Assefa M. Melesse
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Nile River Basin

Ecohydrological Challenges, Climate Change and Hydropolitics

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Preface

Water is vital to life but its availability, distribution, and quality has been dwindling over time with population increase, climate change, and emerging new demands driven by economic and population growth. A large area of the globe is water-stressed. The severity and gravity of this issue is even much greater when water, a common good, needs to be shared among riparian countries. The most famous transboundary river for its rich history and service for over 238 million people in the basin in 11 countries is The Nile. The role of The Nile in human history and civilization has been well documented. The upper section of the basin provides nearly all the water and the lower section of the basin with no contribution is the sole beneficiary. This status quo water use is being challenged by the upper basin countries, mainly Ethiopia as economic growth and population pressure forces for the increased use of water for various consumptive and nonconsumptive uses. The sole historical users of Nile water, Egypt and Sudan, would like to see their use of water unchallenged while many upstream basin countries strive to develop various sizes of water resources development projects.

On the supply end, various studies have shown that flows from tributaries and hence Blue Nile River, a source of 62% of the Nile flow, 82% with Sobat (Baro-Akobo) and Atbara (Tekeze-Setit), has been declining due to population pressure in hydrologically sensitive areas, headwater contraction, land degradation as well as changes in rainfall regimes (quantity, timing, and distribution). The decline in the supply and the ever increasing demand of water in the basin calls for a new formula for water sharing as well as a collaborative effort to enhance water supply through watershed protection and management. Although this necessitates a forum for basin countries to take the lead and address the critical water resources issues the basin is facing on both sides of the water budget, the role of scientific information and reliable data for guiding dialogues and discussion to provide tools for informed decision is critical.

The availability of data and scientific studies on various aspects of the basin is scant and limited mainly to the lower section of the basin. The focus and priority for water resources research, especially in the upper basin is very limited and this contributes to the limited knowledge and understanding about the hydrologic processes in the critical part of the basin.

This book, *Nile River Basin: Ecohydrological Challenges, Climate Change and Hydropolitics*, presents results of various scientific studies ranging from state of the hydrology of the basin to land and water degradation, climate change impacts, watershed services, and transboundary water management. Under seven parts: (I) Hydrology and Water Availability, (II) Soil Erosion and Water Quality, (III) Lakes and Watersheds, (IV) Climate Change and Water Resources, (V) Water Accessibility, Institutional Setup and Policy, (VI) Transboundary Rivers, Water Sharing and Hydropolitics and (VII) Watershed Services and Water Management, 33 chapters are presented. Studies on data needed for stream flow simulation, satellite rainfall reliability, monitoring of surface water using remote sensing, surface and groundwater resources, and environmental challenges of drastic land use and ownership change and conversion of hydrologically sensitive areas to large scale commercial farms in the basin are presented. Various experimental and modeling-based studies on soil erosion estimation, sediment dynamics and impacts of land use change and management, and hydro-epidemiology of the Nile basin are also presented. Satellite-based land disturbance index for biomass mapping, lake bathymetry, spatial evapotranspiration modeling using satellite data and rainfall erosivity index are also discussed. The impact of climate change on water availability, adaptation strategies to cope with climate change and the role of indigenous knowledge to adapt, climate teleconnections of flows in the Nile basin and water management is addressed. Local and basin wide water governance and institutional setup in the basin and management of rainwater for resiliency of dryland areas are presented. International laws and norms that are the basis of transboundary river agreements are presented. Transboundary river management and the need for negotiation and dialogues to avoid unnecessary water conflict are covered. The Grand Ethiopian Renaissance Dam basic design features and simulation on its downstream flow impact during the reservoir filing and operation periods are included. Stakeholders' and institutions' engagement, perception, and willingness for the implementation of payment for watershed services are also presented.

The book contains the works of several water resources experts from the Nile basin and other countries. The book, as shown above, covers a wide range of topics that are timely and can be used by students, educators, researchers, policy makers, water and environmental resources managers, and others.

Assefa M. Melesse
Wossenu Abtew
Shimelis G. Setegn

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Chapter 1
Introduction

A Scarce and Shared Resource: Hydrologic Threats, Trends, and Challenges in the Nile River Basin

Assefa M. Melesse, Wossenu Abtew and Shimelis G. Setegn

Abstract The Nile River basin is home to more than 238 million people covering 11 countries. The basin is characterized by unique ecological systems with varied landscapes including high mountains, tropical forests, woodlands, lakes, savannas, wetlands, arid lands, and deserts. The basin is also characterized by poverty, rapid population growth, environmental degradation, and frequent natural disasters. While the population in the basin is projected to increase significantly over the coming decades, the water resources are projected to decline, with an increase in environmental degradation. This will be a tremendous challenge in a basin where emerging water demands by upstream countries are forcing a new formula for the use of the scarce water resources. Unless a framework of agreement for equitable water sharing is reached soon between all riparian states, the potential for acute water conflict is high. Cooperation is essential for controlling watershed degradation and water quality decline.

Keywords Nile River · East Africa · Blue Nile · White Nile · Nile countries · Transboundary rivers

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1.1 Overview

The Nile River, at about 6,825 km, is the longest river in the world. It comprises two major tributaries, the White Nile and the Blue Nile (known as the Abbay in Ethiopia). The White Nile rises in the Great Lakes region of central Africa, with the most distant source in southern Rwanda and flows north from there through Tanzania, Lake Victoria, Uganda and South Sudan. The Blue Nile starts at Lake Tana in Ethiopia, and flows into Sudan from the southeast. The two rivers meet in the Sudanese capital Khartoum and flow north through Sudan and Egypt to drain into the Mediterranean Sea. The drainage area estimate varies between 3.1 Million km^2 (FAO 2007) to 3.3 million km^2 (CPWF 2007). The variation is due to difficulty in delineation of the sub-basin in the flat slope parts of Sudan and Egypt. Elven countries fall within the Nile basin these include Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. The Nile River basin is home to approximately 238 million people, while over 443 million (based on World Bank 2006) live within the 11 riparian states. The Nile region is characterized by high population growth and considerable development challenges (Awulachew et al. 2008). The benefits of the Nile River need to be shared among these 11 countries, but the issues are hard to encompass.

1.2 Climate and Flow

The Nile River basin exhibits a varied climate and a spatiotemporal variability in precipitation. The northern part of the Nile basin is overwhelmingly described as desert, with little to no rainfall. The central portion of the basin is dominated by occasional, though infrequent, rainfall, and the headwater regions receive significant seasonal rainfall, although with large interseason and interannual variability. Analyzing the regional hydrological dynamics, therefore, requires intensive examination of the processes governing water balances, i.e., involving climatic and ecological forcings and feedbacks as well as population and industrialization pressures, both nationally and basin-wide. It is also evident that parts of the basin that receive lesser precipitation and, hence, contribute little to the basin's flow, utilize more water from the basin.

Hydrologically, flow of the Nile River is very small compared to the major international rivers of the world like that of Amazon but its historical significance and benefits to many people in the basin put the Nile in the forefront. Receiving its major annual flow mainly from the Blue Nile River in Ethiopia, the flow is highly dependent on rainy season runoff from the Ethiopian highlands. Various studies have indicated that these flows have shown a decline over a period of time attributed to factors ranging from poor headwater protection to land degradation to a decline in precipitation.

1.3 Climate Change and Nile Flow

It is projected that the decline in water resources availability will be exacerbated by the projected climate change impact on rainfall pattern and volume over the next century. According to Kim et al. (2008), the increased rainfall and resultant water supply in the upper Blue Nile that are anticipated through the middle of the century are likely to be positive in a region regularly beset by drought. However, according to El Shamy et al. (2009), over the longer term (2081–2098), the Blue Nile basin may become drier. Using the outputs from 17 Global Circulation Model (GCM) for the A1B scenario, their predictions varied between a -15 and $+14\,\%$ change in precipitation, with the ensemble mean suggesting little change. However, the projected increase in temperature and evaporation is expected to reduce the runoff.

According to the analysis by Beyene et al. (2010), much of the precipitation increase in the Blue Nile is anticipated in the winter (December, January and February) months, which may be of less value in this region, where the majority of the agricultural production systems are presently rainfed. However, the projections from Soliman et al. (2009) suggest that by the middle of the century, the annual discharge from the Blue Nile would be similar to recent historic levels, but with appreciable changes in the seasonality and spatial variability. This analysis used the A1B emissions scenario and the ECHAM5 (Max Planck Institute) GCM and considered the 2034–2055 timeframe. It suggested higher flows at the onset of the wet season, and reduction in flows at the end of the wet season and through the dry season.

1.4 Challenges in Sharing a Common Good

As the water resources of the Nile decline, the demand on the other hand is continuously increasing along with per capita demand and population increase. The need for more consumptive water resources development projects by the basin countries is putting the scarce and limited resource under pressure, requiring new thinking and collaboration for efficient use and sharing of the water equitably. This poses a challenge because major historical users of the water, Egypt and Sudan, do not want to accept the new reality but maintain their lion shares of the Nile. Upstream countries currently are progressing in developing a framework of basin management agreement, the Nile Basin Cooperative Framework Agreement. The agreement is signed by Ethiopia, Kenya, Uganda, Tanzania, Rwanda, and Brundi. South Sudan has stated to sign, while Egypt and Sudan have not shown willingness so far. New frame of agreement in sharing the Nile water that reflects the new emerging needs is critical for the transboundary water management that is inclusive and sustainable.

If basin counties are to successfully respond to the multifaceted threats that the next 20–50 years will bring, immediate action is required. Moreover, this action must be multinational, highly coordinated, and must be supported with the best scientific knowledge of the factors and processes responsible for the changes in the hydrology of the Nile River basin. In addition to the role of science in effective water resources management and help in the coordination and utilization of the common good, basin countries need to continue working together and face the new reality of both the supply and demand side of the water resources in the basin. The emerging needs from upstream basin countries as part of their economic development agenda and investment in the water sector will require a new framework of dialogues and understanding in accommodating these needs and rights.

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Part I
Hydrology and Water Availability

Chapter 2
The Nile River Basin

Wossenu Abtew and Assefa M. Melesse

Abstract The Nile River basin is one of the transboundary river basins that is in the forefront of water resource challenges of the century. As the basin's population is growing, water demand is increasing. Focus on basin hydrology, climate change, and water management is critically needed. The Blue Nile subbasin is relatively more efficient in generating runoff contributing most of the flow to the Nile compared to the White Nile. This makes flows susceptible to changes in the watershed. The basin's high rate of population growth is putting stress on natural resources including water. In 25 years, the population of the 11 Nile countries is projected to reach 726 million. A 64 % increase in water demand is projected in the Nile basin countries without factoring increase in per capita water demand. The link between river and watershed is becoming vivid as demand for water and power grows and becomes a source of conflict.

Keywords Nile River · East Africa · Blue Nile · White Nile · Nile countries · Transboundary rivers

2.1 Introduction

The Nile basin is one of the transboundary basins where the livelihood of millions will depend on its hydrology more than ever. The Nile, the longest river, 6,650 km in length, travels from East and East-Central Africa to the Mediterranean Sea with its watershed in 11 countries (Fig. 2.1). Growing population and limited water resources make hydrological variations more important. Historically, the Nile River has shown

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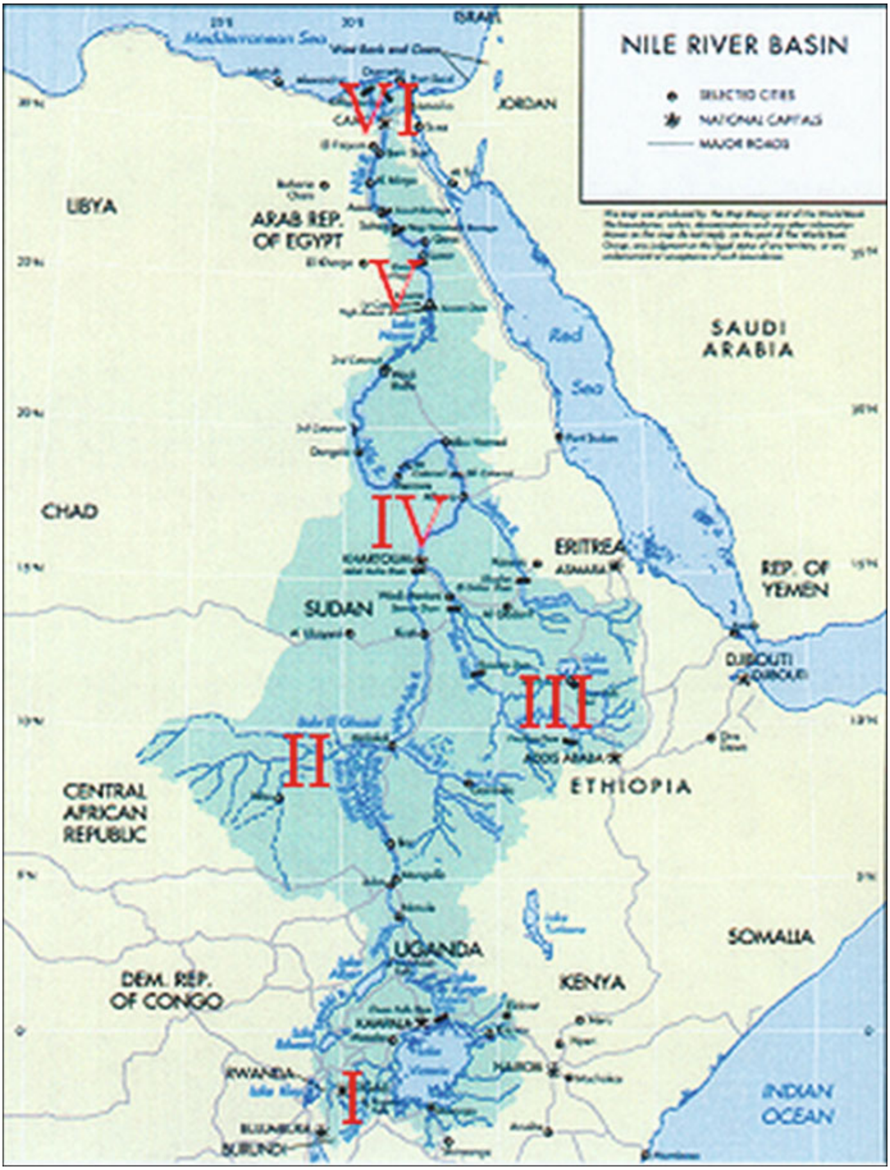

Fig. 2.1 The Nile River basin crosses six hydroclimatic zones: (*I*) lake plateau territory (Burundi, Rwanda, Tanzania, Kenya, and Uganda), (*II*) Sudd freshwater swamp (southern Sudan), (*III*) Ethiopian highlands, (*IV*) Sudan plains (central Sudan), (*V*) northern Sudan and Egypt (from the Atbara and Nile Rivers confluence to Cairo), and (*VI*) Mediterranean zone (coastal region with no measurable rainfall)

significant fluctuations in flow. Record droughts have been documented including the recent Sahelian drought of the 1970s and 1980s. A historical account of the Nile flow fluctuations is documented by Evans (1994). The reason why the Nile flow did

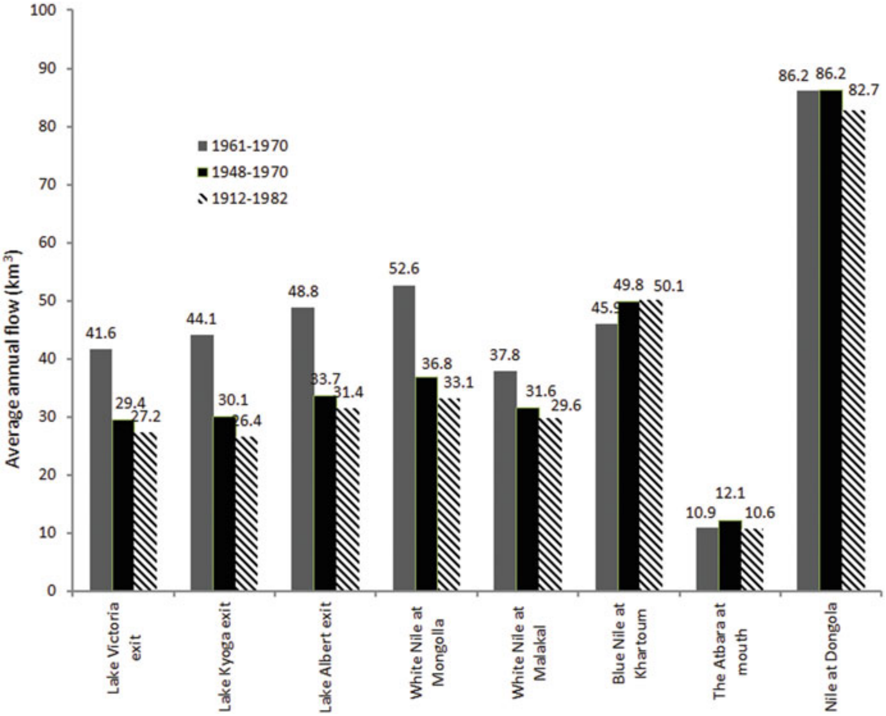

Fig. 2.2 Average annual flow variation for the Nile River system for different recording periods. (Data source: Karyabwite 2000)

not drastically decrease during the Sahelian drought was due to wet conditions in the Lake Victoria basin providing good flow through the White Nile. Historical intense droughts with dire impacts have been recorded by ancient Egyptians. Strontium isotopic and petrologic information indicated that around 4,000 years ago, the Nile flow was so reduced that it resulted in the downfall of a kingdom (Stanley et al. 2003). In recent periods, drastic fluctuation in flow has been reported. An estimated low flow record of 46 km^3 (billion m^3) occurred in 1913. A high flow estimate of 102 km^3 occurred from 1871 to 1898. Current mean flow at Aswan is 84 km^3 (Evans 1994). Flow record variation could be both climatic and measurement discrepancies. Figure 2.2 depicts average annual flow variation for three recording periods at main flow points on the Nile River system.

The Nile River basin drainage area is more than 3 million km^2 with 73 % of the drainage basin in Sudan and Egypt with net consumption of water. The ratio of the producing watershed to consuming watershed is low. Ethiopia, with 12 % of the drainage basin, generates 86 % of the river year-round flow. The remaining 14 % comes from the White Nile which has a larger drainage basin. The White Nile has year-round sustained flow mainly because of a rainfall pattern with less temporal variation. About half of the water generated by the equatorial lakes and watershed is lost in the Sudd marshes (Gedefu 2003). The climate of the Nile basin reflects the

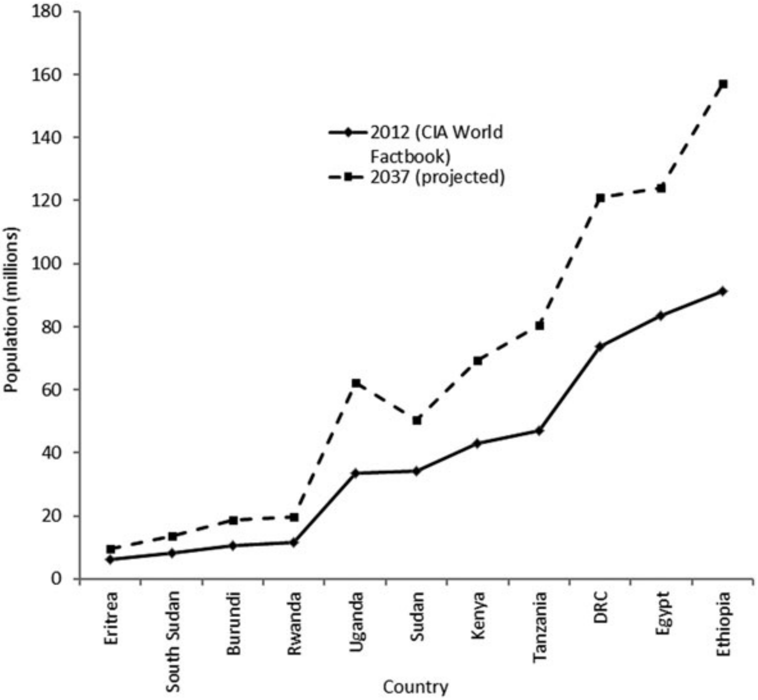

Fig. 2.3 Population of Nile countries. (2012 CIA World Factbook, South Sudan 2008 census)

latitude range (from 4° S to 32° N) and the altitude range (from sea level to more than 3,000 m). The basin extends from Mediterranean climate at the mouth of the Nile to tropical climate at the sources of the Blue and White Nile. In between is a large area with desert and semidesert climate changing into savannah in South Sudan. Rainfall varies from 2,000 mm in the southwest region of the Blue Nile basin to almost no rain in the Sudanese and Egyptian desert. The Rwenzori Mountains in the west rise as high as 4,500 m and annual rainfall can reach 3,000 mm contributing runoff to the White Nile.

The Nile basin countries, Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda, have a combined population of 443 million in 2012 with a projected population of 726 million in 25 years (Fig. 2.3). Overall, the watershed is not efficient in generating enough runoff to overcome losses; only 5 % of the rain results in runoff yield that makes it to the river terminus, 84 km^3 at Aswan. The average flow from all subbasins reaching Sudan is 90 km^3. The water demand in the Nile basin is growing due to population growth and increase in per capita water demand. Due to overpopulation and climate change, stress on water resources in the basin is growing.

Understanding the historical, current, and projected hydrology of the Nile is critical for managing the ever-increasing water demand in the basin with potential interests outside the basin too. Detail work on the hydrology of the Nile is presented by Sutcliffe and Park (1999). The seasonal pattern of rainfall in the Nile basin follows the movement of the intertropical convergence zone (ITCZ) with moisture sources from the Indian and Atlantic Oceans (Mohamed et al. 2005). The major lakes in the Nile basin system are Lake Victoria, Lake Kyoga, Lake Albert, Lake Tana, Lake Edward, and Lake Nasser. Numerous tributary rivers flow into the upper lakes. The major subbasins are the Blue Nile, Tekeze-Setit-Atbara, Baro-Akobo-Sobat, and the White Nile. The hydrology of each subbasin is important as drought in one subbasin may be compensated by wet condition in another subbasin.

2.2 Lakes of the Nile Basin

2.2.1 Lake Victoria

Lake Victoria with an area of 67,000 km^2 at an elevation of 1,134 m above sea level is the largest lake in Africa and the second freshwater lake in the world. It is the source of the Victoria Nile which is a major source of the White Nile and has a drainage basin of 194,000 km^2 (Piper et al. 2009). It is shared by Kenya (6 %), Uganda (45 %), and Tanzania (49 %). The drainage into the Lake is mainly from Kenya and Tanzania. The main inflow is from Kagera River on the west. The main rivers from Kenya are Kuha, Awach, Miriu, Nyando, Yala, Nzoia, Sio, Malawa, and Malikisi and from Tanzania are Mara and Kagera (Degefu 2003). Actually, the Kagera River flows from Burundi with contributions from tributaries in Rwanda and flow along the boundaries of Burundi and Rwanda, and Tanzania and Uganda. The lake has a maximum depth of 82 m with an average depth of 40 m. The Lake outflows at Owen Falls as the Victoria Nile. The Owen Falls has a hydropower dam since 1954. The dam has resulted in increasing the water level and storage of the lake. But in recent years, the water level has shown decline (Fig. 2.4). It has been difficult to provide a hydrological explanation for the sharp rise in water level from 1961 to 1964 (Piper et al. 2009). The Victoria Nile flows into Lake Albert through Lake Kyoga. Annual average (1912–1982) outflow from Lake Victoria is 27.2 km^3, while outflow from Lake Kyoga is 26.4 km^3 (FAO 1997). Periodic variation of flows from Lake Victoria is depicted in Fig. 2.2. The equatorial lakes region is shown in Fig. 2.5.

Rainfall seasonal characteristics in the Lake Victoria drainage basin are different from the Blue Nile basin. The Blue Nile subbasin wet season is distinct and it runs from June through September. Lake Victoria's drainage basin rainfall seasonal variation is smaller except for December, January, and February; the rest of the months have considerable rainfall ranging from 105 to 200 mm. Runoff has also lower seasonal variation with lows in January through March but between 20 and 40 mm from April through December as derived from Khan et al. (2011). Their study was on the major subbasin of Lake Victoria, Nzoia. The highest monthly rainfall is in April and the highest runoff is in May when the Blue Nile basin is in dry season. As a result of this type of rainfall temporal distribution, the White Nile has consistent month-to-month flow when compared to the Blue Nile.

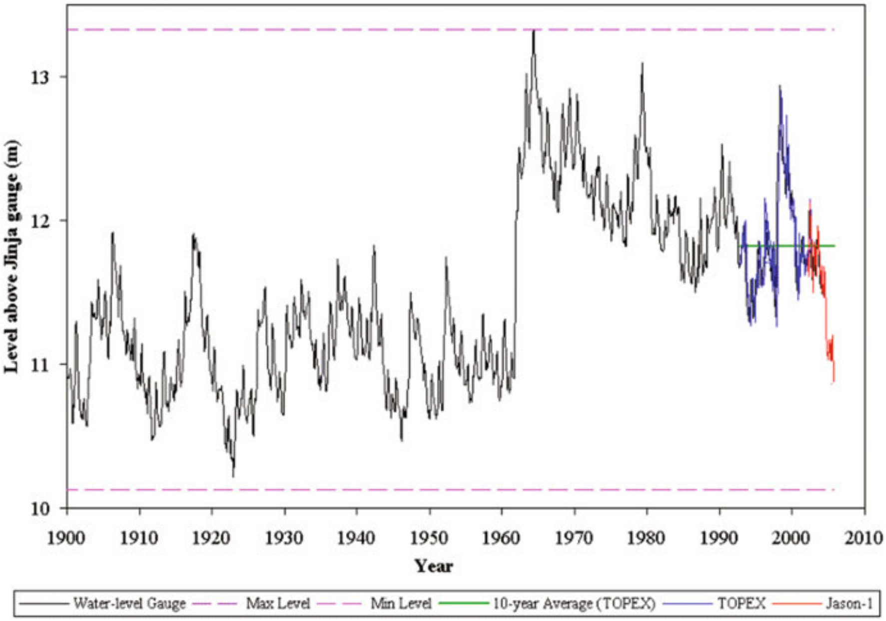

Fig. 2.4 Lake Victoria historical relative water level at Jinja, Uganda. (USDA, Production Estimate & Crop Assessment Division)

Fig. 2.5 Equatorial lakes, source of the White Nile. (Source: USDA)

2.2.2 Lake Albert

Lake Albert lies on the border of Uganda and Democratic Republic of Congo at an elevation of 619 m with an area of 5,374 km^2. When the Victoria Nile enters Lake Albert, the Albert Nile flows out to South Sudan entering the Sudd branching into Bahr El Zafar and Bahir El Jabal later joined by Bahr El Ghazal and local tributaries. At Malakal, the Sobat joins from the east forming the White Nile (Fig. 2.1). Although there are various rivers and streams that join the inflows and outflows of Lake Albert from the Rwenzori Mountains, the Semliki River is the major inflow. The Rwenzori Mountains, with annual rainfall between 2,000 and 3,000 mm, are also considered as source of the White Nile (Eggermont et al. 2009). The highest source of the Nile contributes significant flow to the White Nile from rainfall and glacier melts although not as much as Lake Victoria. Lake Edward in the same drainage basin at an elevation of 920 m and area of 2,325 km^2 flows into Lake Albert. Annual average (1912–1982) flow out of Lake Albert (Albert Nile) is 31.4 km^3 (FAO 1997). Variation in annual flows from Lake Albert is depicted in Fig. 2.2.

2.2.3 Lake Tana

The Blue Nile flows out of Lake Tana in the Ethiopian highlands. Lake Tana at an elevation of 1,786 m above sea level has an area of 3,156 km^2 (Fig. 2.1). It has drainage basin of 16,000 km^2 with inflows mainly from four rivers, Gilgel Abay, Ribb, Gumera, and Megetch (Chebud and Melesse 2000). It is a relatively shallow lake with a mean depth of 7.2 m and a maximum depth of 14 m (Wale 2008). Water level changes are attributed to human activities and changes in climate. Figure 2.6 depicts Lake Tana mean monthly water level fluctuations from a reference point at Bahir Dar. Increasing trend is shown since 1990 but decline started in the 2000s after operation of the weir, built to regulate flow into the Blue Nile. Water level fluctuation for Lake Tana is relatively smaller. A sustained severe drought for 7–8 years is expected to terminate outflow from the lake (Kebede et al. 2006). Lake Tana outflows as the Blue Nile with an estimated mean annual flow of 3,732 million m^3 and a minimum and maximum estimated range of 1,075 and 6,181 million m^3, respectively (Rientjes et al. 2011).

2.2.4 Lake Nasser

Lake Nasser is a man-made lake or reservoir result of the Aswan High Dam built on the Nile River by Egypt covering some territory of Sudan (Fig. 2.1). At a water surface elevation of 175 m, it has an area of 5,168 km^2 with a volume of 121.3 km^3 (Abdel-Latiff 1984). The lake area has no measurable rainfall, and evaporation losses are high, 2.7 m yr^{-1} (Omar and El-Bakry 1981). Mean annual inflow of the Nile at Aswan is 84.1 km^3 (Table 2.1).

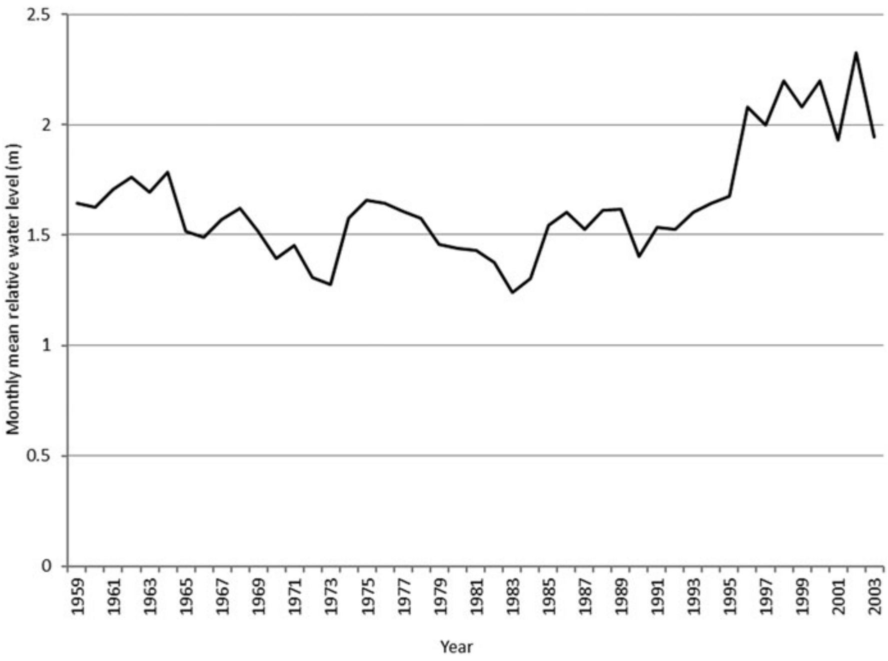

Fig. 2.6 Relative water level fluctuation of Lake Tana (1959–2003)

Table 2.1 Average annual flows of the Nile River system. (Modified from Sutcliffe and Park 1999)

Watershed	Annual flow (km^3)
Nile at Aswan	84.1
Atbara at mouth	11.1
Blue Nile at Khartoum	48.3
White Nile at Khartoum	26.0
Sudd at Malakal	16.1
Sobat at Malakal	9.9

2.3 Watersheds and Tributaries

The source of the Nile is not much of hydrologic significance as most of the flows come from the tributaries. A spring in the Ethiopian highland is the source of the Blue Nile. The Kagera in Burundi or the Rwenzori Mountains at the border of Uganda and the Democratic Republic of the Congo either or both may be referred as the source of the White Nile. The major river systems of the Nile are the Blue Nile, the Sobat, the Atbara, and the White Nile contributing 55, 12, 15, and 18 %, respectively (Sutcliffe and Park 1999).

2.3.1 The Blue Nile

The Blue Nile River basin is the main source of the Nile River with a drainage area of 324,530 km^2 (Peggy and Curtis 1994). The Upper Blue Nile basin is 176,000 km^2

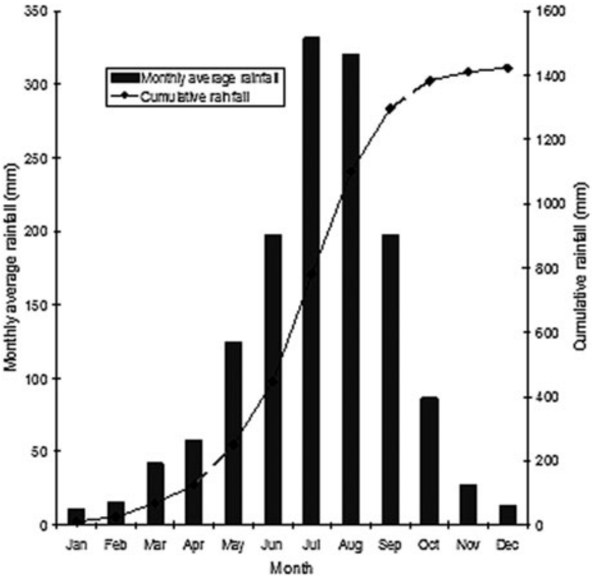

Fig. 2.7 Monthly distribution of rainfall over the Blue Nile basin. (Abtew et al. 2009)

in area (Conway 2000). The major tributaries of the Blue Nile River in Ethiopia are Gilgel Abbay, Megech, Ribb, Gumera, Beshlo, Woleka, Jemma, Muger, Guder, Chemoga, Wenchit, Fincha, Dedessa, Angar, Dura, Rahad, Dinder, Dabus, Gulla, and Beles. The upper Blue Nile River basin is wet when compared to the lower basin (part of the Blue Nile drainage basin outside Ethiopia until it joins the White Nile River).

Rainfall over the Blue Nile basin has distinct seasonal variation with June, July, August, and September being the wet months. May is the transition month from dry to wet season and October is the transition month from wet to dry season. Mean monthly rainfall distribution over the basin is shown in Fig. 2.7. Dry season rainfall variation is high. Annual rainfall ranges from more than 2,000 mm in the southwest of the basin to 800 mm in the northeast (Abtew et al. 2009). Mean annual rainfall is 1,423 mm with a standard deviation of 125 mm. It is a relatively wet basin. The estimated 100-year drought annual basin rainfall is 1,132 mm while the 100-year wet annual rainfall is 1,745 mm. A basin-wide anomaly of ± 300 mm of rainfall would result in extreme drought or high stream flows. Spatial variation of annual rainfall in the Blue Nile basin is depicted in Fig. 2.8.

The mean annual flow of the Blue Nile from Lake Tana at Bahir Dar is 3.7 km^3 with 70 % of the flow occurring from June to September. Seventy-three percent of the rainfall in the basin occurs from May through September (Abtew et al. 2009). With tributaries joining along its journey, mean annual flow at the Sudan border at Roseires reaches 48.7 km^3. At Khartoum, the Blue Nile with a mean annual flow of 48.3 km^3 joins the White Nile to become the Nile (Table 2.1). Periodic variation of the Blue Nile flow is shown in Fig. 2.2.

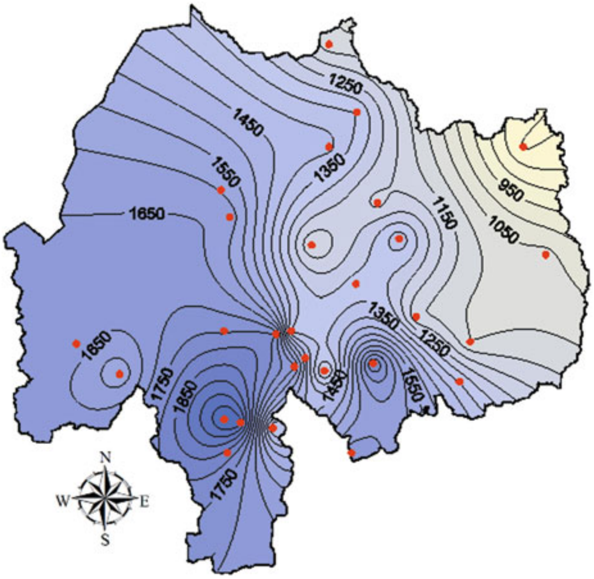

Fig. 2.8 Spatial variation of annual rainfall in the Blue Nile basin. (Abtew et al. 2009)

2.3.2 *The White Nile*

The farthest source of the White Nile is said to be the Kagera River that flows from the mountains of Rwanda and Burundi or streams and glacial melt from the Rwenzori Mountains, a border between the Democratic Republic of the Congo and Uganda (Eggermont et al. 2009; Sutcliffe and Park 1999). The White Nile at Khartoum basin area is about 1.7 million km^2 (Tesemma 2009). From the east, Lake Victoria drains into Lake Albert through Lake Kyoga as the Victoria Nile (Fig. 2.1). The western drainage flows into Lake Albert through Lake Edward and the Semliki River and exits from Lake Albert as Albert Nile. The Albert Nile, also known as Bahr El Zeraf, flows into the flat marshes of the Sudd branching and joining Bahr El Ghasal and local tributaries. The Sobat joins from the east as the White Nile travels north to Khartoum to join the Blue Nile and become the Nile. Later, the Atbara joins from the east, north of Khartoum. Mean annual flow of the White Nile is estimated as 26 km^3 (Table 2.1) and variation of periodic flow is shown in Fig. 2.2.

2.3.3 *The Sudd*

The Albert Nile flows into a large flatland and forms one of the world's largest wetlands extending to 125,000 km^2 of marshes during high flows but averaging 30,000 km^2 in area. Lateral branching forced by flat topography creates the maximum opportunity for evapotranspiration. The slow flow through the vegetated marsh results in as much as 50 % of the water being lost in evapotranspiration and seepage.

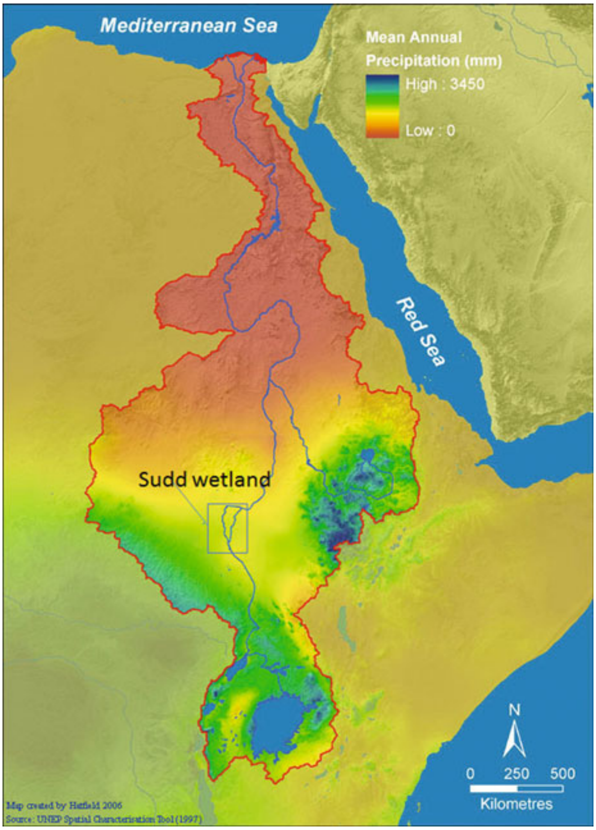

Fig. 2.9 Spatial variation of rainfall on the Nile basin and the Sudd. (Hatfield Group)

Based on data from 1961 to 1983, the annual mean inflow into the Sudd is 49 km^3 and outflow is 21 km^3 (Mohamed et al. 2006). Variation in periodic flows from the Sudd is shown in Fig. 2.2. Annual evaporation is estimated as 1,718 mm for open water and 1,641 for vegetated wetland (Robelo et al. 2012). The Sudd region in South Sudan and the Nile river system are shown in Fig. 2.9. Rainfall over South Sudan and Sudan decreases from the south to the north and the same pattern is seen for the Sudd wetlands with an estimated average annual rainfall of 1,000 mm. Figure 2.9 depicts color-coded spatial variation of rainfall over the Nile basin. The thick vegetation in the Sudd is mainly reeds, grasses, and water hyacinth with tussocks floating around. There are settlements in the marsh with elevated huts accessible with canoes.

2.3.4 *The Baro-Akobo-Sobat*

Drainage from southwestern Ethiopia flows to the west. The Baro-Akobo originates in southwest Ethiopian highlands at an elevation of as high as 3,000 m. The major

Table 2.2 Baro-Akobo subbasin catchment area and runoff. (Grand Ethiopian Renaissance Dam Project 2013)

Subbasin	Area	Mean annual runoff (10^6 m^3)
Baro	30,004	12,784
Akobo Upper	6,036	1,774
Akobo Lower	7,209	2,118
Gilo	12,815	3,224
Alwero	8,019	1,375
Serkole	7,702	1,320
Triatid	2,690	419
Pibor	1,435	224
Total	*75,910*	*23,238*

rivers are Baro with tributaries Birbir, Geba, and Sor; Akobo with smaller tributary Kashu; Alwero and Gilo with tributaries Gacheb, Bitun, and Beg; and Pibor. Other tributaries in Ethiopia are Cechi and Chiarini and in Sudan are Neubari and Ajuba. The Akobo flows west and meets Pibor which flows north on the border of Ethiopia and South Sudan. Smaller tributaries join in South Sudan to form the Sobat. Subbasin areas and estimated runoff in the Baro-Akobo basin are shown in Table 2.2. The Sobat is navigable from June to December. The Sobat contributes an estimated annual flow of 9.9 km^3 (Table 2.1).

2.3.5 *The Tekeze-Setit-Atbara*

The Atbara is the last tributary for the Nile joining 320 km downstream north of Khartoum. The main source of water is the Tekeze or Setit River which originates from the Ethiopian Semene highlands that reach elevations as high as 4,500 m. It is joined by local tributaries in northwestern Ethiopia (former Begemdir and Tigray regions). The major tributaries to the Tekeze are Angereb, Shinfa, Zarima, Guang, and others with numerous small tributaries. The Tekeze-Setit becomes Atbara with tributaries from Eritrea. The Gash from Eritrea joined by the Obel contributes to the Atbara during high-flood periods. The Atbara is 880 km long (Hasan and Elshamy 2011). The drainage basin of the Tekeze/Setit is 68,800 km^2 (Sutcliffe and Park 1999). The Atbara contributes 11 % of the Nile flow. Periodic variation in flow is shown in Fig. 2.2. The watershed area in Ethiopia, Eritrea, and Sudan is 227,128 km^2. Forty percent of the drainage area and 75 % of the population in the basin are in Ethiopia. It is sediment rich due to its topography with 120 million t of soil eroded from Ethiopia annually (Degefu 2003).

The only major dam on the Tekeze is the Tekeze dam that is 188 m tall, completed in 2009, and expected to generate 300 MW hydroelectric power. Built in a canyon surrounded by steep topography, landslide and high rate of sedimentation are already a problem. The Angereb reservoir on the Angereb River was commissioned in 1997 but its life was projected to be 15 years due to sedimentation (Negussie et al. 2012).

Fig. 2.10 Water-use effort for subsistence agriculture in Dawa River basin, a transboundary river

There is a 15-m-high and 300-m-wide earth dam near Addis Nefas, northern Ethiopia, built by local farmers with government assistance. Food shortage is chronic in the region with one in four people living on food aid. The advice to Ethiopia has been more storage of floods for irrigation during dry periods to produce food (Hoering 2006).

2.4 Water Use in the Nile Basin

When the issue of water use in the Nile basin is discussed, riparian rights spring. As a matter of fact, most of the mostly rain-generated water in the basin does not leave the watershed. Most water use in the Nile basin is for agriculture. Rainfed agriculture and forestry use most of the water. The Nile basin covers 10.3 % of the continent of Africa. This watershed holds or uses most of the water in the basin and relatively smaller percentage leaves the basin as runoff. What is not captured or immediately used in the watershed collects in the form of runoff in gullies and streams before joining the river system. Figure 2.10 illustrates effort to satisfy local water demand for small-scale agriculture in a transboundary river basin of Dawa. As population grows, water use in every basin will increase in different forms. From the river system, most of the abstracted water is used for irrigation. Water supply and livestock water use is relatively small. Table 2.3 shows Nile basin countries, area in

Table 2.3 Nile basin countries with drainage area in the basin and irrigated land. (Appelgren et al. 2000)

Country	Area in the Nile basin (km^2)	Percent of country	Irrigated land in the basin (ha)	Irrigable land[a] (ha)
Burundi	13,000	46	50	80,000
D. R. Congo	22,300	1	80	10,000
Eritrea	25,700	21	5,800	150,000
Ethiopia	366,000	32	32,100	2,220,000
Egypt	307,900	33	2,923,200	4,420,000
Kenya	52,100	9	9,800	180,000
Rwanda	20,400	83	3,300	150,000
Sudan and South Sudan	1,943,100	78	1,930,300	2,750,000
Tanzania	118,400	13	14,100	30,000
Uganda	238,700	98	9,100	202,000
Total	3,107,600	414	4,927,830	10,192,000

[a] 8,000,000 ha in the Nile basin (FAO)

the Nile basin, percent of country area in the basin, irrigated lands as of 2000, and potentially total irrigable area in the country. Current area of land under irrigation or planned area should be far higher. Out of the total irrigable area, about 80 % is in the Nile basin.

Water storage is the current measure of water security. According to the World Bank, Ethiopia has only 43 m^3 per capita storage while the goal should be 755 m^3 per capita like South Africa. The Bank's water resource assistance strategy believes water storage has to be the country's priority (Hoering 2006).

2.5 Summary

The Nile basin covers geographically, socially, politically, and ecologically diverse regions from south of the equator to the Mediterranean Sea. The sources of the Nile are also climatically diverse where drought in one basin may be compensated by wet conditions in the other subbasins. Population growth in the basin countries is increasing at an alarming rate and creating water stress. Adverse change in climate will magnify the water stress and create struggle to fulfill water demand in and out of the basin. Food shortage and economic distress in the watersheds will increase water use in the watersheds eventually resulting in decline in river flow and increase in water conflict.

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Chapter 3
Streamflow Data Needs for Water Resources Management and Monitoring Challenges: A Case Study of Wami River Subbasin in Tanzania

Preksedis Marco Ndomba

Abstract Streamflow data collection is a critical part of water resources management in a subbasin, basin, and a country. River and streamflow monitoring provides data needed for water allocation for human and environmental needs and managing hydrologic extremes such as droughts and floods. Streamflow monitoring network implementation at a required density and successful continuous operation demands skilled personnel, sufficient fund, and organization. This necessity in Tanzania is evaluated with a case study of the Wami River subbasin streamflow monitoring program. Monitoring density, continuity, and data quality is evaluated. Existing rating curve representativeness is tested, and new rating curves are proposed. Water information and data gaps are shown as deficiency, and short- and long-term proposals are presented to improve monitoring network, data quality, data storage, and access.

Keywords Stream gauging · Streamflow monitoring · Wami subbasin · Tanzania

3.1 Introduction

In this chapter, the term data denotes hydrological data from surface observations. In most cases, observations are usually taken over longer periods of time. The longer an observation record of a specific station, the more useful and meaningful and credible it becomes. Estimating the total amount of water on earth and the various processes of the hydrologic cycle has been a topic of scientific exploration since the second half of the nineteenth century. However, quantitative data are scarce, and so the amounts of water in the various components of the global hydrologic cycle are still not known precisely (Chow et al. 1988).

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Effective water management can be achieved through sound decision making based on reliable data and information on the status and trends of water resources, including quantity, quality, and statistics on events such as floods (WMO 2009). Development and management of water resources projects and research in developing countries such as Tanzania are often subjected to numerous challenges, with availability of quality and sufficient data being the main challenge. At present, most of the data are being held in hard and/or digital forms, some on databases, and others as textural in word processing and Portable Document Format (PDF) files. Data are constantly collected and processed by various organizations including government agencies, nongovernment organizations, and projects. Project-based data records, normally, are up to 2 years long. In such situations, the objectives of the sampling program are influenced by individuals such as researchers, investors, donors, consultant, and others, solely tailored to project deliverables (Alamgir et al. 2001). In most cases, these initiatives are ad hoc and uncoordinated.

Pursuant to data problems, decisions in water resources management in Tanzania, and many other parts of the world, have been made based on information derived from studies that used inadequate or uncertain hydrologic data. Thus, the main question that is of interest to both scientists and development practitioners is on how uncertainty associated with using unreliable data sets propagates to decision making in water resources management (Harmel et al. 2009; Spence et al. 2007).

Around the world, the need for quality and sufficient observed data sets is ever increasing due to the relatively new and many challenges we are currently facing in water resources management (Harmel et al. 2009; Alamgir et al. 2001). Hydrologic monitoring in many countries was reduced during the mid-1990s in response to fiscal pressures on governments (Spence et al. 2007). Besides, there are many flux dynamics at different scales, than ever before, with multiple feedbacks, of which we require more insight and detail of understanding so that we can develop pragmatic mitigation or adaptation approaches. Water resources management is faced with numerous challenges with regard to both water quality and quantity as a result of various drivers of change, e.g., pollution dynamics, land-use change, climate change, etc. We can only understand such complex dynamics and interaction of these drivers through analysis of relevant, accurate, and appropriate observed data sets, which should be adequately available. Again, due to the complexity associated with flux dynamics at different scales, there is a need to apply other data-gathering approaches that have the potential to capture the flux signatures at the desired scales, of which the conventional techniques have limitations. Some of these techniques have been tested in other parts of the world, and it would be useful to validate them against the institutional and capacity framework in Tanzania. Besides, uncertainty estimates corresponding to measured hydrologic data can contribute to improved monitoring design, decision making, model application, and regulatory formulation. Uncertainty estimates associated with flow discharge measurement, for instance, are rarely made and reported to data users (Harmel et al. 2009; Alamgir et al. 2001).

Therefore, the general objective of this chapter is to present recent data management challenges facing water managers in developing countries such as Tanzania using the Wami River subbasin as a case study. Besides, the chapter also discusses

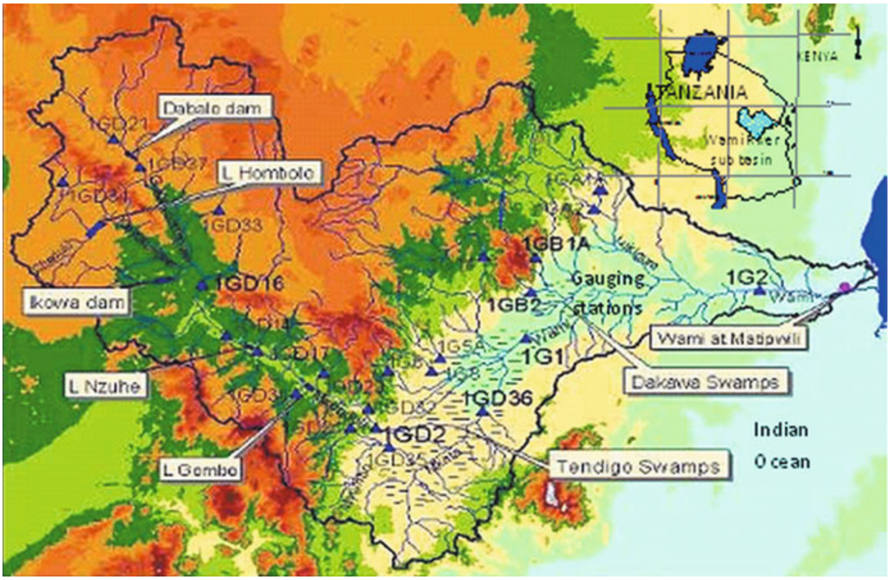

Fig. 3.1 Hydrologic regular monitoring network in Wami River subbasin, Tanzania

the desired framework to debottleneck the challenges while emphasizing the need for adequate, accurate data on water resources in achieving sound decisions for sustainable management and development.

3.2 The Wami River Subbasin Monitoring System

3.2.1 Description of the Study Area

This study uses a case study approach to be able to adequately detail a typical hydrologic monitoring programme in a basin where the author has been involved in various initiatives including training, research, and consultancy services. Besides, it is the case study where data were readily available on the Wami River subbasin. It is located between 5–7 °S and 36–39 °E. The subbasin extends from the semiarid Dodoma region to the humid inland swamps in Morogoro region and Saadani village in the coastal Bagamoyo district (Fig. 3.1). It encompasses an area of approximately 43,946 km^2. The Wami River begins at the Dogwai River which is located approximately 120 km northeast of Dodoma municipality at the Chiole Hill in Chandama highlands. From the Chiole Hill, the river flows down towards the south where it is commonly known as the Kinyasungwe River. The River passes through the Dabalo natural reservoir at an approximate elevation of 1,000 meters above sea level (masl) (Fig. 3.1). The river further flows down in southeast direction and the river name at this point is Mkondoa River. The River passes through Lake Nzuhe and Lake Gombo in the suburbs of Mpwapwa and reaches to Kilosa (Fig. 3.1). At Mkata Plain, downstream of Kilosa, the River turns to the northeast and joins with the Wami tributary which comes from the west–southwest. The river at this point is called Wami River. It meets Kisangata River, Tami River, and Mkundi River and then flows towards the northeast to cross the National Road at Dakawa village. After that, Wami River joins with Mjonga (Diwale) and Lukigula rivers around Kiromo village downstream and flows in the eastern direction. In Mandera, the River crosses the National Road and flows into the Indian Ocean through the estuary in the Wami delta (Fig. 3.1).

The population of both Wami and Ruvu subbasins combined is approximately 5.4 million (Tanzania National Census of 2002). This includes Dar es Salaam (3 million) and the smaller cities of Morogoro, Kibaha, and Dodoma. About 80 % of the basin population lives in urban areas and 20 % in rural areas; thus, the population is very urbanized compared to the rest of the country which is 20 % urban and 80 % rural. Outside of urban areas, population densities are around 30–35 people per km^2. Regional population growth rates are 1.6–4.6 % per annum. Apart from the major urban areas, approximately 75 % of total household income in the basin is earned from agricultural activities. The central part of the basin covers an agricultural region that includes the Mtibwa sugar plantation, Dakawa rice fields, and Ruvu paddy irrigation. It is useful to note that these commercial agricultural activities in the central part of the basin have significant economic importance to Tanzania. Water from the Wami River is used to irrigate these large-scale agricultural operations as well as other smaller farms in the region. The lower parts of the subbasin have a large water supply scheme, the Chalinze Water Supply Scheme at 1G2 gauging station, which provides water for about 60 villages in the Bagamoyo and Morogoro rural districts.

Climatic conditions in the Wami subbasin are both spatially and seasonally variable. Average annual rainfall across the Wami subbasin is estimated to be 550–750 mm in the highlands near Dodoma, 900–1,000 mm in the middle parts of the subbasin near Dakawa, and at the river's estuary in Bagamoyo. Most parts of the Wami River subbasin experience marked differences in rainfall between wet and dry seasons. Although there is some interannual variation in timing of rainfall, dry periods typically occur during July–October and wet periods occur during November–December (first rains) and March–June (long rains). Average monthly minimum and maximum temperatures are almost the same throughout the basin. The coldest month is August (18 °C) and the hottest month is February (32 °C). The annual average temperature is approximately 26 °C. Evaporation is estimated to be 2,500 mm yr^{-1}, a value that exceeds the average annual rainfall in the semiarid region of Dodoma. However, in Morogoro and the coastal regions, evaporation is 1,800 mm with a relative humidity of 50 and 62 %, respectively.

3.2.2 Data Types and Sources

The data used in this study are secondary data on streamflows and gauging (flow velocity, area, stage (gauge), and topographic data). Hydro 1 km resolution Digital

Elevation Model (DEM) is a free downloadable internet source data. The topographic analysis was conducted under a geographic information system (GIS) environment, ArcView 3.1 software. The flow data are readily available as they have been collected by the Wami River subbasin office and other sources. As there were no adequate resources (time and funding) for this study, such data were the only available input as they are cheaper and more quickly obtainable than the primary data. The data record length is significant as it is more than 40 years long. The period is considered adequate enough to capture various hydrological extremes in the subbasin as requirement for good data set. Such periods can also help in analysing trend and change detection, for instance, to assess declining number of gauging stations. However, the secondary data before use were evaluated in terms of four requirements: (1) availability, (2) relevance, (3) accuracy, and (4) sufficiency or adequacy.

3.2.3 Determining Data and Hydrologic Monitoring Network Adequacy

3.2.3.1 Metadata Requirements

In this study, metadata is defined as data about data. Typical metadata content requirements for streamflows data include, but not limited to, the following: (1) date/time and time zone; (2) quality that has been assigned to the observations; (3) the numerical value or character representation used to indicate missing observations; (4) the instrument used to record the observation and instrumentation history; (5) measurement techniques or procedures, including calibration and conversion details; (6) the name and specialization of the observer; (7) structural data, e.g., roughness length, rating curve, and cross-sections; (8) full details of the gauging station; (9) description of the site and surroundings and changes with time; (10) site plans, construction details, and photographs; and (11) weather.

In many instances, the value of the data is enhanced if the user can relate it to the details of the history of its collection as part of the routine production of metadata (WMO 2008). The best way to avoid misinterpretation and confusion among users and to foster exchange of data with other users or water stakeholders is to adopt accepted standards. These are typically provided by authoritative national and international organizations. The standards for the present scope are ISO/TC133 standards for practices in hydrology (WMO 2008). The term network in this chapter refers to surface-water network. Data collection sites included in this network might have disparate uses for the data being collected (WMO 2008). These requirements, together with expert judgments, were used to assess data reliability, data source dependability, and sufficiency or adequacy.

Table 3.1 Recommended minimum densities of streamflow station, area in km^2 per station. (As modified from WMO 2008)

Physiographic unit	Area per station (km^2)
Coastal regions	2,750
Mountainous regions	1,000
Interior plains	1,875
Hilly/undulating regions	1,875
Small islands	300
Polar/arid regions	20,000
Urban areas	–

3.2.3.2 Determining Minimum Network Density for Streamflow-Gauging Stations

The main objective of the stream-gauging network is to obtain information on the availability of surface-water resources, their geographical distribution, and their variability in time. Magnitude and frequency of floods and droughts are of particular importance in this regard. The concept of network density is intended to serve as a general guideline if specific guidance is lacking (WMO 2008). In practice, when no abundant existing measurements are available for specific guidance, a minimum network can be designed to avoid deficiencies in development and management of water resources. Criteria for a minimum network, as used in this study, are outlined in Table 3.1 and focus on the concept of network density, the number of stations per area for a specific type of measurement. The guidelines for minimum network design are based on distinction of different climatic and physiographic zones (WMO 2008). A limited number of larger zones have been defined for the definition of density norms in a somewhat arbitrary manner adopting some general rules. A detailed network analysis as presented in WMO (2008) was substituted by a rule of thumb approach as tabulated in Table 3.1.

In addition to streamflow observation locations, extra sites may be required where only water levels are measured. Such stations are mostly useful for flood-monitoring and flood-forecasting purposes. Cautiously, it should further be noted that even if the installation of a station is adequate, its records may be of little value if it is not operated correctly. That is why in this study conditions of hydrologic monitoring stations were assessed and documented as well.

3.2.4 Rating Curve Analysis

The existing and readily available current meter measurement data and stage–discharge relationships for the Wami River subbasin were analyzed in order to justify their application in various ongoing and future water resources planning and development projects. Both qualitative and quantitative methods were used to assess validity and reliability of the rating curves. Qualitative analysis entailed reviewing rating plots of current meter measurements from various periods in monitoring history. Quantitatively, statistical performance indicators were used to assess the reliability of the rating curves. It is worth to note upfront that only three gauging stations 1G1, 1G2, and 1GD16 were analyzed rigorously. This is partly because the stations represent various geomorphologic and flow regimes expected in the Wami River subbasin as detailed later in this chapter and also due to data adequacy and quality issues.

3.2.4.1 Rating Curve Validity Assessments

The analysis emphasizes on identification of data outliers, gauge shifts, and validity period. An outlier is an observation that lies outside the overall pattern of a distribution (Moore and McCabe 1999). Usually, the presence of the outlier indicates some sort of problem. This can be a case where data do not fit the model under study or an error in measurement. Statistics and information derived from data sets that include outliers could often be misleading. However, deletion of outlier data is a controversial practice frowned upon by many scientists. While mathematical criteria provide an objective and quantitative method for data rejection, it does not make the practice more scientifically or methodologically sound, especially in small sets or where a normal distribution cannot be assumed. Rejection of outliers is more acceptable in areas of practice where the underlying model of the process being measured and the usual distribution of measurement error are confidently known. Because of this, outliers usually demand special attention, since they may indicate problems in sampling or data collection or transcription errors. Alternatively, an outlier could be the result of a flaw in the assumed theory, calling for further investigation by the researcher (Rantz et al. 1982; URT 1979).

Shifts in the discharge rating reflect the fact that stage–discharge relations are not permanent but vary from time to time, either gradually or abruptly, because of changes in the physical features that serve as the hydraulic controls for the station (Rantz et al. 1982; URT 1979). The crest of the hydraulic control defines the stage of zero flow. If a specific change in the rating stabilizes to the extent of lasting for more than a month or two, a new rating curve is usually prepared for the period of time during which the new stage–discharge relation is effective. If the effective period of a specific rating change is of shorter duration, the original rating curve is usually kept in effect, but during that period shifts or adjustments are applied to the recorded stage, so that the “new” discharge corresponding to a recorded stage is equal to the discharge from the original rating that corresponds to the adjusted stage. Normally, sites with pronounced and stable hydraulic controls are preferred gauging stations. The stage–flow relationship at this site would always be stable, hence minimizing or avoiding shift problems. When a site without stable hydraulic control is wanted as a gauging station, the practice has been to construct an artificial structure for the purpose.

If a group of consecutive measurements subsequently plot to the right or left of the average fitted rating curve, it is usually clearly evident that a shift in the rating has occurred. An exception to that statement occurs where the rating curve is poorly defined or undefined in the range of discharge covered by the subsequent measurements. In that circumstance, the indication is that the original rating curve was in error and requires revision (Rantz et al. 1982; URT 1979). However, based on the author's experience, uncertainty is inevitable when one tries to extrapolate the rating curves beyond the measured data, especially to hydrological extremes. A relative error of more than 100 % could be recorded.

Stage–discharge relations are usually subject to minor random fluctuations resulting from the dynamic force of moving water, and because it is virtually impossible to sort out those minor fluctuations, a rating curve that averages the measured discharges within close limits is considered adequate. In some few cases as research projects, uncertainty of the developed rating curve is rigorously determined. Furthermore, it is recognized that discharge measurements are not errorfree, and consequently an average curve drawn to fit a group of measurements is probably more accurate than any single measurement that is used to define the average curve (Rantz et al. 1982; URT 1979).

3.2.4.2 Checking the Reliability of Developed Rating Curves

A number of methods are available in the literature to check the reliability of discharge rating curves. This study used mainly two approaches: determination of required number of discharge measurements for establishing a reliable rating curve and application of statistical tests to rating curves for absence of bias and goodness of fit (URT 1979).

For the first method, it is required that the number of data points used to develop rating curve, N, be greater than the statistically derived number of required measurements, n (Eqs. 3.1–3.3). Besides, on a statistical ground, it is recommended that n should never be less than 6 for any one interval of the range (URT 1979):

$$n > \left(\frac{2S_D}{E}\right)^2 \tag{3.1}$$

$$S_D = \sqrt{\frac{\sum (P - \bar{P})^2}{n-1}} \tag{3.2}$$

$$P = \frac{Q_m - Q_r}{Q_r} \times 100\%, \tag{3.3}$$

where

n = number of required measurements;
S_D = standard deviation in percent ($2S_D$ is allowable width of scatter band);
E = a specified precision expressed as a percentage, in this study is taken as 5 %;
P = percentage deviation;
$\bar{P}$ = mean percentage deviation;
Q_m = measured discharge; and
Q_r = discharge estimated by rating curve.

The second method encompasses three statistical testing criteria: the paired t-test, the sign test, and the run of sign test. The first two criteria are commonly used to test a rating curve for absence of bias and the third tests a rating curve for random fluctuations or goodness of fit. This study used the sign test and the run of sign test criteria for the purpose (Eqs. 3.4 and 3.5).

The sign test is performed by counting the observed points falling on either side of the fitted rating curve. Then, assuming the successive signs to be independent of each other, the sequence of the differences may be considered distributed according to the law $(p + q)^n$, where n is the number of observations, and p and q the probabilities of occurrence of positive and negative values, 0.5 each:

$$t = \frac{|n_1 - np - 0.5|}{S_E} = \frac{|n_1 - np - 0.5|}{\sqrt{npq}}, \tag{3.4}$$

where

n = total number of observations;
n_1 = number of positive signs;
p = probability of sign being positive;
q = probability of sign being negative;
np = expected number of positive signs; and
S_E = standard error of np.

The run of sign test is based on the number of changes of sign in the series of deviations of measured discharges from the established rating curve. It is carried out by detecting the presence of possible abnormally long runs of positive or negative deviations. Starting from the second number of the series, we write under each a “0” if the sign is the same or “1” if the sign is not the same as the immediate preceding sign. If there are n deviations in the original series, there will be (n – 1) numbers in the derived series. Assuming the deviations can be regarded as arising from random fluctuations about the estimated values from the curve, probability of a change in sign may be taken to be 0.5. If n is large, this will be a reasonable assumption and the derived series was assumed to follow the binomial distribution (Eq. 3.5):

$$t = \frac{|n_1 - (n-1)p - 0.5|}{S_E} = \frac{|n_1 - (n-1)p - 0.5|}{\sqrt{(n-1)pq}}, \tag{3.5}$$

where

n = total number of observations;
n_1 = number of changes in sign;
p = probability of change in sign;
q = probability of no change in sign;
$(n-1)p$ = expected number of changes in sign; and
S_E = standard error of $(n-1)p$

The bias or no random fluctuations hypotheses are disproved when the test criterion t is less than the corresponding t table value at 5 % level of significance.

3.3 Streamflow Monitoring Network Evaluation

3.3.1 *Adequacy of Stream-Gauging Stations Network*

The network densities for streamflows with respect to drainage area were assessed based on recommended minimum densities as stipulated in Table 3.2 (WMO 2008). For the Wami River subbasin, coastal, interior plains, and hilly/undulating regions, a minimum drainage area of 2,750 km^2 was considered satisfactory (S), otherwise unsatisfactory (U). One will note that out of 21 streamflow stations, 14 (67 %) have satisfactory network densities. Furthermore, it should be noted that stations with large network densities such as 1G1 and 1G2 are located in the main Wami River and nesting upper sub-catchments. For instance, the intervening catchment area between 1G1 and 1G2 is only 4,440 km^2. It could be deduced that most of the stations gauge allowable drainage area sizes as recommended by WMO guidelines. Such a good performance is based on the total number of gauging stations in the network with both functional and nonfunctional status. If nonfunctional stations were removed from analysis, then the network densities would have been unsatisfactory. This problem is not uncommon especially to other basins in Tanzania. It is also acknowledged in WMO (2008) that continuous operation of a network may be difficult—especially over a period of 20 years or more. A minimum network, in which stations are abandoned or irregularly observed, will have its effective density reduced and is, therefore, no longer an adequate minimum network.

A bar diagram, presented in Fig. 3.2, was drawn for the eight flow-gauging station (1G1, 1G2, 1G5A, 1G6, 1GA1A, 1GB1A, 1GD2, and 1GD36) from Table 3.2. The vertical and horizontal axes are gauging station dummy number and time in years, respectively. These are key gauging stations in the regular monitoring network of the Wami River subbasin. This diagram shows the length of data that are available for each gauging station and the extent of missing data. It is possible to view stations with availability of concurrent data. This information is of vital importance in river flow analysis and in data gap-filling prioritization initiatives.

From the plot, it could be observed that, literally, every station has missing data. Further qualitative spatial analysis indicates that most of the flow-gauging stations used have been monitored with nonconcurrent observation periods. Consequently, available flow data have different lengths, periods of observation, and quality which is related to the size of missing observations. Most of the available records span between the 1970s and early 1980s. The ongoing efforts to revive the river flow-gauging network in the subbasin have necessitated rehabilitation works of some of the nonoperational gauges. As a result of such initiatives, to date, relatively new water-level records are available since 2006 for some of the gauging stations. This suggests that at many gauging sites there is exceptionally a large gap of missing information between the early 1980s and 2006. Missing data filling is, therefore, inevitable. In order to fill the gaps, one has to conduct a rapid water resource assessment programme that entails the collection and processing of existing hydrological, hydrogeological, and auxiliary data required for their areal interpolation (WMO 2009). In some instances,

Table 3.2 Status of stream-gauging stations for Wami River subbasin. (WRBWO 2007)

Station code	Catchment	River	Location	Period of record		Status		Catchment area	Network density (WMO 2008)
				Historical	Recent	Manual	Automatic		
1G1	Wami	Wami	Dakawa	1954–1988	2006–2010	Functional	Not functional	35,786	
1G2	Wami	Wami	Mandera	1954–1984	2005–2009	Functional	Functional	40,227	U
1G5A	Wami	Tami	Msowero	1964–1994	2006–2010	Functional	Functional	741	U
1G6	Wami	Kisangata	Mvumi		2006–2009	Functional	Functional	140	S
1G11	Wami	Chogoali	Difulu Village	Not in database	Not in database	Not functional	Not functional	294	S
1GA1A	Wami	Lukigura	Kimamba Rd.Br	1964–1987	2006–2009	Functional	Functional	953	S
1GA1	Wami	Mziha	Mziha	Non	2006–2009	Not functional	Functional	86	S
1GB1A	Wami	Diwale	Ngomeni	1980–1990	2006–2009	Functional	Functional	173	U
1GD2	Wami	Mkondoa	Kilosa	No data in database	No data	Not functional	Not functional	10,930	U
1GD14	Wami	Kinyasungwe	Gulwe	1957–1982 (sparse)	No data	Not functional	Not functional	9,846	U
1GD16	Wami	Kinyasungwe	Kongwa/Dodoma	1958–1959 (sparse)	No data	Functional	Not functional	7,965	U
1GD17	Wami	Kinyasungwe	Godegode	1978–1979 (sparse)	No data	Not functional	Not functional	14,006	S
1GD21	Wami	Kinyasungwe	Itiso	Not in database	Not in database	Functional	Not installed	900	U
1GD29	Wami	Mkondoa	Mbarahwe	1969–1991 (ok)	No data	Not functional	Not functional	477	S
1GD30	Wami	Lumuma	Kilimalulu	1969–1990	No data	Not functional	Not functional	595	S
1GD31	Wami	Mdukwe	Mdukwe	1969–1979	No data	Not functional	Not functional	497	S
1GD 32	Wami	Mkondoa	Railway Brg.	1975 (1 month)	No data	Not functional	Not functional	792	S
1GD33	Wami	Masena	Ibumila	No data in database	No data in database	Not functional	Not functional	664	S
1GD34	Wami	Kinyasungwe	Mayamaya	No data in database	2006–2008	Functional	Notfunctional	172	S
1GD36	Wami	Mkata	Mkata	1973–1978	2006–2009	Functional	Functional	20,974	U
1GD37	Wami	Kinyasungwe	Ikombo	No data in database	2006–2009	Functional	Functional	951	S

S satisfactory, *U* unsatisfactory

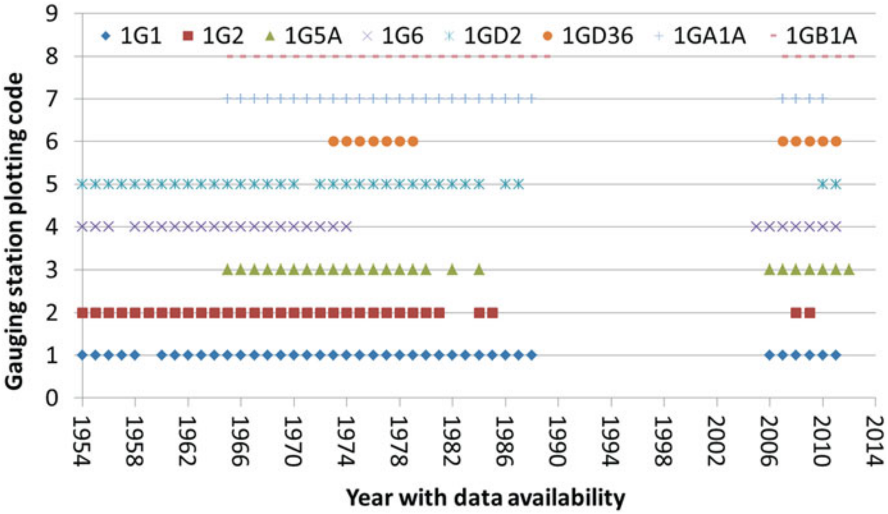

Fig. 3.2 A bar diagram showing the span and availability of flow data in the eight stations used in the study

skilled labor-intensive approaches such as rainfall-runoff modeling techniques would be applied. To the best of the knowledge of the author, the resources required such as funding and skilled personnel are limited and, if not, unavailable. There are hardly such capabilities in academic and research institutions.

A sample of recent current meter spot measurements data is presented in Table 3.3. It is the typical sample size from the Wami River subbasin office flow-sampling programmes. For some stations such as 1GD16, only one set of flow measurements is reported. Besides, the sampled flows do not represent well the flood regime at the flow-gauging stations. Few spot measurements (one or two) for some of these stations would hardly be useful for typical hydrologic data analysis such as verification of rating curve validity. As supported by other researchers such as Rantz et al. (1982), even if these recent measurements depart significantly from a defined segment of the rating curve, there may be no unanimity of opinion on whether a shift in the rating has actually occurred, or whether the departure of the measurements results from random error that is expected occasionally in any measurement.

The physical descriptions of the gauging stations in the regularly monitoring network characterize the stations into two categories. Firstly, the gauging stations with pronounced hydraulic controls are 1G2, 1G1, 1GD14, 1G5A, 1GA1A, 1GD29, and 1GD30. Secondly, those with fair or poor hydraulic controls are1G6 and 1GD31 (Table 3.4). Besides, the first category could further be grouped into stations with ease of accessibility, 1G1, 1G2, 1G5A, 1GA1A, 1GD29, and 1GD30, and those which are poorly accessed from nearby cities such as Morogoro town or Dar es Salaam (Ndomba 2007). It should be noted that flow-sampling programmes at a site with poor accessibility and poor hydraulic control may potentially result in inadequate and inaccurate data. It should be emphasized that a station with unstable hydraulic

Table 3.3 Sample spot current meter measurements for Wami River subbasin for year 2007. (WRBWO 2007)

Date	Station no.	Name of station	Location	Stage, H (m)	Streamflow, Q $m^3\ s^{-1}$	Cross-section flow area, A (m^2)
10/1/2007	1G1	Wami	Dakawa	4.51	94.273	131.89
12/3/2007	1G1	Wami	Dakawa	2.7	37.388	56.206
20/03/2007	1G1	Wami	Dakawa	3.33	43.363	72.49
11/4/2007	1G1	Wami	Dakawa	2.752	32.266	48.03
18/04/2007	1G1	Wami	Dakawa	3.21	38.667	63.75
15/05/2007	1G1	Wami	Dakawa	2.69	35.872	54.574
13/06/2007	1G1	Wami	Dakawa	2.1	27.368	43.32
10/1/2007	1G5A	Tami	Msowero	0.678	6.464	11.657
10/3/2007	1G5A	Tami	Msowero	0.39	3.474	6.76
10/1/2007	1G6	Kisangata	Mvumi	1.5	5.698	7.083
10/3/2007	1G6	Kisangata	Mvumi	1.2	3.961	8.263
11/1/2007	1GD	Mkondoa	Kilosa	0.6	33.395	26.542
14/03/2007	1GD	Mkondoa	Kilosa	0.705	27.697	18.99
11/4/2007	1GD	Mkondoa	Kilosa	0.961	6.945	9.11
11/1/2007	1GD36	Mkata	Mkata	5	43.061	59.985
10/3/2007	1GD 36	Mkata	Mkata	2.84	16.584	20.64
13/03/2007	1GD35	Myombo	Kivungu	2.18	9.572	22.29
15/03/2007	1GD1A	Diwale	Ngomeni	1.69	8.249	17.8
9/1/2007	1GA2	Mziha	Mziha	0.9	1.506	6.017
14/02/2007	1GA2	Mziha	Mziha	1.135	3.764	9.808
9/1/2007	1GA1A	Lukigura	Kimamba	1.51	6.587	12.9
14/03/2007	1GA1A	Lukigura	Kimamba	1	1.729	8.24
1/4/2007	1GD16	Kinyasungwe	Kongwa Rd.	0.067	2.035	4.375

control has a variable stage at zero flow. Therefore, the relationship between stage and flow is also unstable. This means that for the same stage at different times one observes different streamflows. The analysis also suggests that the uncertainty in streamflow measurements for the Wami River subbasin gauging sites with unstable hydraulic controls is inevitable.

In order to complement the physical characteristics as reported in Table 3.4, the Wami River system was further characterized to assess flow-gauging station representation in terms of hydraulic regime and geomorphologic zonation. The physical properties were derived from topographic data as described in Sect. 3.2. It gives a general idea on spatial variation and not exact figures. In a typical application, slope data would have to be smoothed or averaged. The derived information along the main channel includes distance from the Indian Ocean (zero chainage), elevation, and river channel slope (Fig. 3.3). Based on both elevation and slope properties, one would note that the Wami main river channel is divided into three hydraulic–geomorphologic zones. Zone 1 is coastal plains and rejuvenated cascade in the first 100 km from the Indian Ocean shoreline. Zone 2 is inland plain between 100 and 220 km. Zone 3 is mountain streams and upland plateau beyond 220 km. This analysis found that the flow stations in the regular monitoring network are installed and gauge runoff in different geomorphologic and topographic environments of Wami River.

Table 3.4 Physical descriptions of the flow-gauging stations. (As compiled from URT 1976)

Station code	Catchment	Station details	Extreme hydrological events
IG1	Complex catchment containing a wide range of altitudes slopes, vegetation and climate	Types of gauges: standard vertical; benchmark: installed at the top of an angle iron concreted into the ground on the left bank and benchmark assumed datum is at 6.121 m; a hydraulic control is fairly stable open channel with clay bed and grassy banks; the site is accessible throughout the year, 48 kilometers from Morogoro/Kilosa Road	Max. recorded discharge is 157.59 $m^3\ s^{-1}$ on 9/4/68 with WL of 5.95 m; min. recorded discharge is 2.89 $m^3\ s^{-1}$ on 2/12/70 with WL of 0.59 m
IG2	Upper part highly grassland and wooded grassland the remainder intermediate bush and wooded	Types of gauges: standard vertical; benchmark is a concrete beacon on left bank near staff gauges and benchmark assumed datum is at 2.633 m; a hydraulic control is permanent formed by rock outcrop and rapids 61 meters d/s of the gauge; the site is accessible throughout the year on the main road from Dar es salaam to Handeni about 184 kilometers from Dar es salaam	Max. recorded discharge is 1,798.02 $m^3\ s^{-1}$ on 7/4/68 with WL of 4.28 m; min. recorded discharge is 3.83 $m^3\ s^{-1}$ on 30/11/70 with WL of 0.77 m
IG6	Steep catchment well wooded, with vegetation actively induced by natives	Types of gauges: standard vertical; benchmark is a bolt on bridge wall painted red on L/B and benchmark assumed datum is at 8.510 m; a hydraulic control is steep catchment well wooded, with vegetation actively induced by natives; The site is accessible throughout the year, 96 kilometers from Morogoro along Morogoro/Kilosa Road	Max. recorded discharge is 73.47 $m^3\ s^{-1}$ on 30/3/70 with WL of 3.20 m; min. recorded discharge is 0.31 $m^3\ s^{-1}$ on 31/1/67 with WL of 0.34 m
IGD14	Consists chiefly of lightly wooded grassland with some bushland and thickets grassland, actively induced vegetation	Types of gauges: standard vertical; benchmark is an iron bolt concreted to an old concrete structure at the corner of Gulwe shops and benchmark assumed datum is at 6.181 m; a hydraulic control is permanent control consisting of bridge foundation slab 75 m together with two abutments; the site is accessible throughout the year, 152 kilometers from Dodoma.	Max. recorded discharge is 71.68 $m^3\ s^{-1}$ on 29/3/70 with WL of 3.66 m; min. recorded discharge is 0.0 $m^3\ s^{-1}$ on 31/1/65 with WL of 0.00 m
IG5A	Fairly steep upper part of the catchment, small medium wooded grassland approx, 30 % vegetation actively induced by natives	Types of gauges: standard vertical; benchmark is a concrete beacon with a nail on top installed on the left bank a few meters from 4–5 m, and it is painted red and benchmark assumed datum is at 5.444 m; a hydraulic control is a rock barrier across the river bed and some rapids further downstream; the site is accessible throughout the year, from Morogoro along Kilosa Road some 80 kilometers from Morogoro	Max. recorded discharge is 1,134.02 $m^3\ s^{-1}$ on 8/4/68 with WL of 3.24 m; min. recorded discharge is 0.59 $m^3\ s^{-1}$ on 22/3/65 with WL of 0.40 m

Table 3.4 (continued)

Station code	Catchment	Station details	Extreme hydrological events
IGA1A	Mainly wooded and wooded grassland	Types of gauges: standard vertical; benchmark: screw in concrete block on L/B and benchmark assumed datum is at 3.673 m; a hydraulic control consists of a rock barrier horizontally and vertically; the site is accessible throughout the year, along Morogoro/Handeni Road	Max. recorded discharge is 468.69 $m^3\ s^{-1}$ on 15/12/67 with WL of 3.95 m; min. recorded discharge is 0.00 $m^3\ s^{-1}$ on 17/1/65 with WL of 0.0 m Note: This station is a new station, though when it was established, it was thought that it could replace the 1GA1 gauging station, but it was found that the river regime at 1GA 1A is completely different from that at 1GA 1
IGD29	Steep mountainous slopes covered by forest, bushland and thickets, woodland, grassland, and low hills	Types of gauges: standard vertical; Benchmark: 6″ bolt concreted in huge rock on the right bank about 3 m d/s the cableway post and benchmark assumed datum is at 4.858 m; a hydraulic control is permanent big boulder on big rocky bar across the river with some water falls; the site is accessible through Morogoro/Kidete railway and then Kidete/Mbarawe Road	Max. recorded discharge is 319.90 $m^3\ s^{-1}$ on 15/1/70 with WL of 3.60 m; min. recorded discharge is 1.04 $m^3\ s^{-1}$ on 28/11/70 with WL of 0.36 m
IGD30	Woodland and wooded grassland and some intensive native cultivation	Types of gauges: standard vertical; benchmark: bolt embedded in rock on right bank and benchmark assumed datum is at 2.750 m; a hydraulic control consists of rocks across the river channel is located near a bridge built on rocks, a fall 1 m it is permanent for all stages; the site is accessible through 124 kilometers from Morogoro by train to Kidete on Central Railway line, then further 7 kilometers	Max. recorded discharge is 6.95 $m^3\ s^{-1}$ on 25/3/69 with WL of 1.10 m; min. recorded discharge is 0.16 $m^3\ s^{-1}$ on 30/11/70 with WL of 0.41 m
IGD31	The upper catchment is mainly woodland and lower catchment is vegetation actively induced by natives.	Types of gauges: standard vertical; benchmark: bolt embedded in rock on right bank and benchmark assumed datum is at 4.780 m; a hydraulic control: for low and medium stages consists of rock bar and higher flows consists of waterfalls together with a gorge d/s; the site is accessible through 147 kilometers from Morogoro/Kilosa main and a further 18 kilometers on foot from Kilosa	Max. recorded discharge is 74.90 $m^3\ s^{-1}$ on 16/3/70 with WL of 3.60 m; min. recorded discharge is 0.83 $m^3\ s^{-1}$ on 10/12/70 with WL of 0.36 m

WL water level

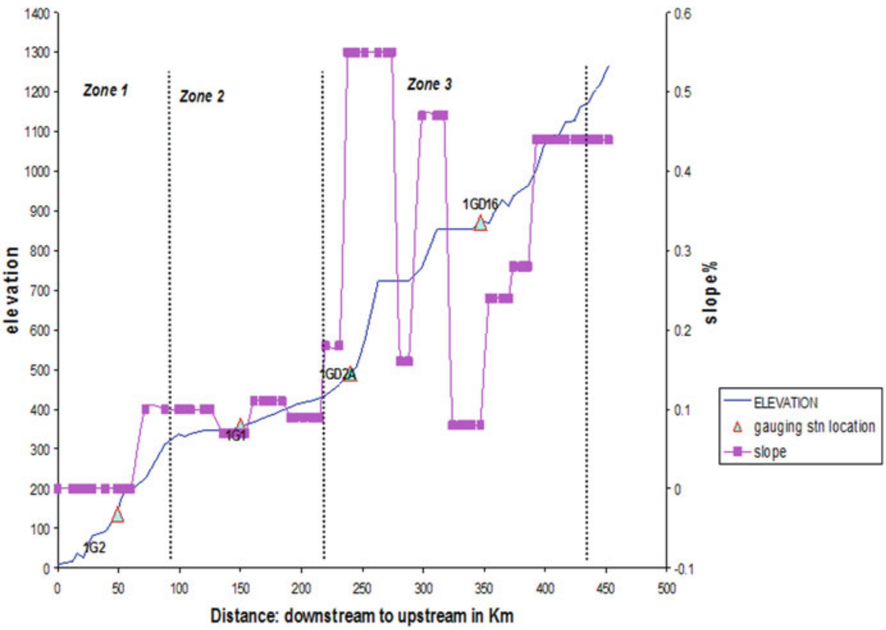

Fig. 3.3 Longitudinal bed profiles of elevation and slope for Wami River with selected flow-gauging stations

It is noted from Fig. 3.3 that gauging stations 1G2, 1G1, and 1GD16 are representing zone 1, zone 2, and zone 3, respectively. Based on this analysis, it can be deduced that the flow-gauging stations in Wami River are located in three flow hydraulic regimes that are frequently inundated, seasonally inundated, and flow within the channel banks as represented by river reaches at 1G2, 1G1, and 1GD16 gauging stations, respectively. Besides, with regard to average riverbed slope in zone 3, 1GD16 gauging station is located in steep terrain and, thus, represents flow regime of headwater regions (flash floods) in the Wami River subbasin.

Literally, such observed differences in flow regimes as represented by various flow-gauging stations would require zone tailor-made flow-sampling program. For instance, flash floods river reaches as represented by Kinyasungwe (1GD16) would require frequent sampling visits than downstream river reach that is frequently or seasonally inundated. This is meant to capture the high temporal variability in the headwater river flows as it is known that the discharge of small rivers is strongly influenced by local factors. In practice, it is difficult to adequately sample the entire flow range in these rivers. For monitoring purposes, that is why one would resort to automatic water-level recorders in flash floods river reaches. It is not apparent from the network analysis conducted in this study whether the sampling programmes are tailor-made to respective geomorphologic–hydraulic zones.

Table 3.5 Compiled existing information on stage–discharge relationships for gauging stations in the Wami River subbasin. (WRED 2013; URT 1976)

Station code	Rating parameters $Q = K\ (H\text{-}Ho)^n$ H in m, Q in $m^3\ s^{-1}$, data available			Validity period		Range for H
	Stage of zero flow, Ho	Coefficient, K	Exponent, N	Start	End	
IG1	0	6.3106	1.5997	1953	1983	H: 0.0→4
	3.02	51.5772	1.7641	1953	1983	H: 4→10
IG2	0.24	36.2012	2.9832	1954	1973	H: 0.24→10
	0.73	129.481	2.0716	1973	1975	H: 0.73→10
	0.53	53.2324	1.9884	1975	1977	H: 0.53→10
	0.34	26.3967	2.6913	1977	1979	H: 0.34→10
	0.61	65.8118	2.5931	1979	1984	H: 0.61→10
IG6	0.2	5.3856	1.891	1959	1964	H: 0.2→10
	− 0.11	3.9752	2.5362	1964	1970	H: − 0.11→10
	0.04	6.9846	1.8914	1970	1980	H: 0.04→10
	0	0.7454	3.4764	1982	1990	H: 0.0→10
IGA1	0.24	4.3693	1.9262	1961	1970	H: 0.24→10
IGD2A	− 0.12	30.0643	2.9351	1981	1981	H: − 0.12→10
IGD14	0.06	13.8933	1.6163	1962	1968	H: 0.06→1.0
	0	11.5555	1.2166	1962	1968	H: 1.0→10
	0.05	7.5944	1.2329	1971	1972	H: 0.05→10
	0.06	3.7229	1.2715	1972	1974	H: 0.06→10
	0	0.4064	3.3606	1976	1977	H: 0.00→10
IGD16	0.09	6.45366	1.7021	1958	1984	H: 0.09→10
IG5A	− 0.05	13.6046	4.076	1965	1977	H: − 0.05→10
	0.61	70.2361	1.163	1979	1979	H: 0.60→10
	0.41	34.908	1.046	1982	1983	H: 0.41→10
IGA1A	0.05	13.3617	2.9648	1966	1970	H: 0.05→10
	0	3.7778	3.0219	1970	1981	H: 0.00→10
IGA2	0.05	9.7672	2.4129	1965	1990	H: 0.05→10
IGD29	− 0.02	5.8305	1.5754	1969	1982	H: − 0.02→0.8
	− 0.1	5.7921	2.7688	1969	1982	H: 0.8→10
IGD30	0.24	7.6363	2.0739	1969	1975	H: 0.24→10
IGD31	− 0.5	1.682	2.722	1969	1990	H: − 0.5→10
IGD36	0.67	7.049	1.3005	1973	1981	H: 0.67→10

3.3.2 *Validity of Rating Curves*

Most of the rating relationships are valid up to the early 1980s and a few up to 1990. With the exception of a few gauging stations, 1GA1, 1GD16, 1GA2, 1GD30, 1GD31, and 1GD36, stage–discharge relationships are fitted using more than one rating curve or segment (Table 3.5). In particular, 1G2 flow regime is represented by period-based five rating curves. As pointed out earlier, some of these stations such as 1G1, 1G2, and 1GD16 are located in the main Wami River. Another observation is that rating parameters such as stage of zero flow, Ho, for some gauging stations, 1GA1A and 1GD14, are comparable to field observations of 17/1/1965 and 31/1/1965, respectively, as reported in URT (1976). This is one of the stations with pronounced stable hydraulic control as noted earlier.

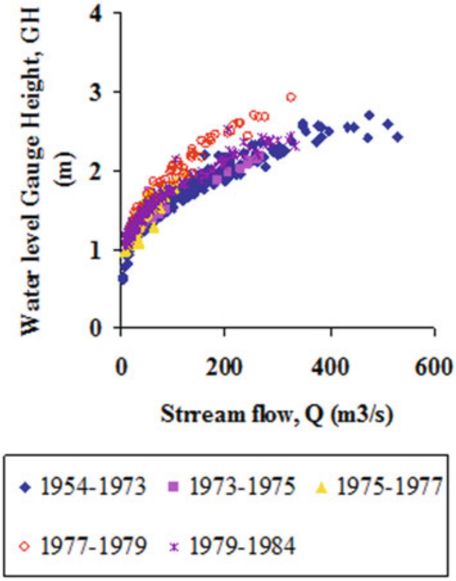

Fig. 3.4 Scatter plot of streamflow, Q, versus water levels (GH) at 1G2 gauging station

As an example, the rating curve at 1G2 gauging station presented in Fig. 3.4 is discussed in detail. The data points in the figure are grouped according to period of measurements. It can be noted that the data points for flows greater than 100.0 $m^3 s^{-1}$ for the period between 1977 and 1979 lie outside the overall pattern of a distribution. However, it could be seen that the data set for the following period that is between 1979 and 1984 plots closely to the distribution.

This is probably suggesting that the data set for the period 1977–1979 is an outlier. In most hydrological analyses, such a data set is screened out and never used in further analysis. There is no indication of evident breaks in log-transformed data points in Fig. 3.5. This suggests that only one segment average fitting curve is adequate. However, the data points appear in a wider band. As suggested by Rantz et al. (1982), probably this type of distribution pattern of data is a result of changes in the physical features that form the control for the station. The same analysis was repeated for 1G1 and 1GD16 stations and the following were deduced. There are two rating equations developed for the 1G1 station, one for the 0–4 m and another for the 4–10 m gauge height ranges. This is a justification of constructing different rating equations for the two rating segments. It should be noted that recent flow spot measurements as reported in Table 3.5 plot well with an average rating curve. Analysis of 1GD16 gauging station rating curve and current meter measurements indicates that there is neither a shift nor a break.

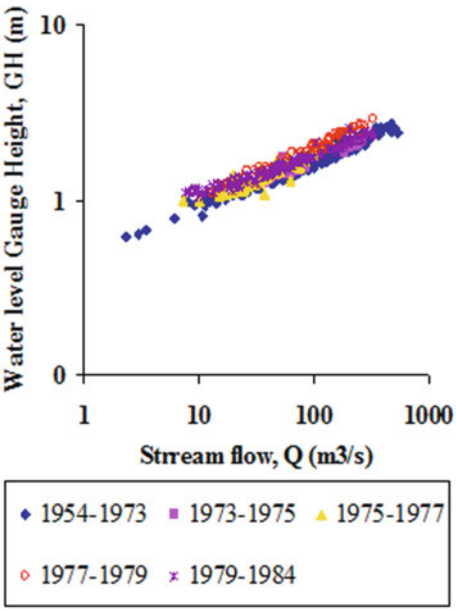

Fig. 3.5 Log-transformed data points of streamflow, Q, against water levels (GH) at 1G2 gauging station

3.3.3 *Reliability of Rating Curves*

As mentioned in Sect. 3.2, this study used mainly two approaches for analyzing the reliability of a rating curve determination of required number of discharge measurements for establishing a reliable rating curve (Table 3.6) and application of statistical tests to rating curves for absence of bias and goodness of fit (Tables 3.7 and 3.8).

It is noted from Table 3.6 that only 1G2 gauging station passes the test and, therefore, the rating curve is considered reliable based on this method. Probably, this is attributed to the lower percentage standard deviation (SD) and greater number of data points, N, used to develop the rating curve. This result was expected as 1G2 is one of the flow-gauging stations located in the lower main river reach of Wami with frequent or seasonal inundation and low temporal flow variability. It is also located at the trunk road bridge site where all-year-round accessibility is guaranteed.

Generally, the results in Table 3.7 suggest absence of bias in the rating curves. However, one would note that the test criterion t in Table 3.8 is consistently greater than t critical two tail (t table values) at 5 % significance level. This suggests that the assumption of random fluctuations as the basis of this test has been disapproved. Therefore, the test has detected the presence of abnormal long runs of positive or negative deviations. Probably, the test shows that there is a systematic trend in the deviations with time, indicating that the rating curves need adjustment for shift in control.

Table 3.6 Required number of discharge measurements for establishing a reliable rating curve

S/N	Gauging station	Data points used, N	Percent Standard deviation, S_D	Width of scatter band, $2S_D$	Number of required measurements, n	Stage ranges (m)
1	1G1	70[b]	43.2	86.4	299	H: 0→ 4
		26[b]	17.5	35	49	H: 4→10
2	1G2	503[a]	34.9	69.8	195	H: 0→10
3	1GD16	71[b]	96.2	192.5	1,482	H: 0→10

The analysis used a specified precision expressed as a percentage, E of 5 %
[a]pass, [b]fail

Table 3.7 Sign test for unbiased observations

S/N	Gauging station	Total number of observations, n	Number of positive signs, n1	Expected number of positive signs, np	Standard error of np, SE	Test criterion, t	T_table at 5 % level of significance	Remarks
1	1G2	503	258	252	11	0.54	1.96	Unbiased
2	1G1	96	47	48	5	0.31	1.96	Unbiased
3	1GD16	71	38	36	4	0.47	1.96	Unbiased

Table 3.8 The run of sign test for random fluctuation

S/N	Gauging station no.	Number of deviations, n	Number of changes in sign, n1	Expected number of changes in sign, (n − 1)p	Standard error of (n − 1)p, SE	Test criterion, t	t_table at 5 % level of significance	Random fluctuation
1	1G2	502	258	250	11.2	39.2	1.96	No
2	1G1	95	30	47	4.8	13.3	1.96	No
3	1GD16	70	10	35	4.2	14.3	1.96	No

Table 3.9 Parameters of author's developed flow rating curves

S/N	Gauging station	Rating curve segment No.	Rating curve parameters			Gauge heights range
			K	Ho	N	
1	1G1	1	5.0	− 0.11	1.80	H: 0→4
		2	50.0	3.06	1.85	H: 4→10
2	1G2	1	84.0	0.605	2.30	H: 0→10
3	1GD16	1	8.0	0.19	1.41	H: 0→10

3.3.4 Performance Evaluation of Existing and Author's Developed Rating Curves

As the flow-sampling programmes in the Wami River subbasin could be characterized as adhoc and intermittent, it was decided to evaluate the possibility of developing new rating curves for selected gauging stations 1G1, 1G2, and 1GD16 (Table 3.9).

Table 3.10 Performance evaluation of the various rating curves

S/N	Gauging station code	Standard error of estimate, STEYX	
		Existing rating curves	Author's developed rating curves
1.	1G1	20.84	9.74
2.	1G2	21.75	24.49
3.	1GD16	1.25	1.15

In this attempt, the physical parameters such as stage at zero flow, Ho, were assumed not measured or unknown. It is worth noting that the same historical data set with its uncertainty was used in this analysis. The rating equation parameters (K, Ho, and n) were estimated using an optimization algorithm built in FORTRAN programming developed by the author. The sum of square of residuals (SSQ) is used as objective function. The parameters of these relationships are presented in Table 3.9. In Table 3.10, both existing and author's developed rating curves are compared using quantitative approach on statistical grounds. The standard error of estimate, STEYX, is used as a performance indicator (Table 3.10). Lower value of STEYX indicates better performance.

Generally, with the exception of the 1G2 gauging station, there is noticeable performance improvement in the author's developed rating curves based on standard error of estimate statistic (Table 3.10). However, there is not much gain in developing a new rating curve for 1G2 gauging station as its performance is poorer than the existing rating curve. It should be recalled that 1G2 gauging station flow regime is represented by period-based rating curves. Based on the experience of the author, the new rating relationship is more reliable as it would capture a wide range of flow variation. It is worth noting that other researchers such as Rantz et al. (1982) have a similar opinion.

3.4 Conclusions

3.4.1 Adequacy of Monitoring Network

Although network density meets the standards when both functional and nonfunctional flow-gauging stations are considered, it has been established that the subbasin is poorly gauged. Besides, the study has revealed that only a few of the functional flow-gauging stations in the monitoring network are placed at a geomorphologically and hydraulically ideal site, a river reach with strong or stable hydraulic control and accessibility all year round. Some flow stations are installed at river reaches with ill-defined collapsing banks and meanders.

The author, based on personal working experience, would like to assert that the findings for this case study are true reflections of the status of the existing regular flow discharge-monitoring networks for all the basins in Tanzania. It is clear that there is a need to enhance the commitment and determination in increasing the monitoring and observatory network in all basins in the country due to the rate at which most of the key hydrologic networks are collapsing. In this account, Tanzania is not an exception as studies in other regions, such as South Africa, Australia, and Canada, have clearly highlighted the downward trend in hydrometeorological monitoring and the decline of motivation for the relevant authorities, and the lack of purpose to maintain and increase the hydrologic monitoring networks (Spence et al. 2007; WMO 2009). However, unlike other countries as demonstrated by this study, in Tanzania, data are inadequate, inaccurate, and poorly documented. There are no compelling quality assurance (QA) and quality control (QC) protocols in place. Besides, data management initiatives are uncoordinated. It is not uncommon to find key water stakeholders or institutions using streamflow data of different quality and quantity from the same gauging station. It is, therefore, imperative to note that in order to reverse the situation, sector-wide and countrywide collective approaches must be adopted.

3.4.2 Validity and Reliability of Rating Curves

This study has demonstrated that most of the flow rating curves in the Wami River subbasin are outdated with inadequate number of data points used to develop the rating relationships. The study has also identified outliers in data records and systematic trend in the deviations with time. The latter could probably be attributed to poor measurement techniques, use of uncalibrated current meter or sampling equipment, inexperienced sampling technicians, transcription,and computational errors. These are incapability-based problems. The author considers that other factors have a lesser role in explaining the deviations. It is worth noting that inadequacy and inaccuracy of data observed in the Wami River subbasin is not a special case. It is also common to find key water stakeholders or institutions using different rating curves for the same gauging station. On the basis of the findings of this case study, the author recommends that the flow rating curves need to be updated by adequate and accurate new current meter measurements by skilled personnel.

3.4.3 Implication to Sustainable Management and Development of Water Resources

Given inadequate monitoring network, data inaccuracy, inadequacy, and unreliable flow rating curves, the author would like to raise questions to the Wami Ruvu basin office and other basins managers in Tanzania: (1) How do you allocate available water resources for various users? (2) How do you operate hydropower reservoirs? (3) How do you formulate policies? (4) How do you make bold decisions such as conflict resolutions as agriculture vs hydropower? (5) In view of the fact that many types of hydrological forecasts are compiled on the basis of data from inadequate monitoring networks, how do you make operational forecasts, irrigation schedules, and climate change predictions? As reiterated in WMO (2008), the perpetual nature of the principal stations in the basic network provides a basis for monitoring long-term trends in hydrological conditions in the region caused, for instance, by land-use changes or by increases in stratospheric greenhouse gases (WMO 2008). By no means, in data-poor regions such as Tanzania, decisions on water resources management would have to be made on an ad hoc basis. In some circumstances, decisions shall be based on project motivation or individual influence. In incidences where the decisions are based on available data, information, and analysis, then the uncertainty inherent from inaccurate data will not be a factor.

At the present time, water managers, water basin officers (WBOs), water resources development practitioners, and other water sector stakeholders in Tanzania and the region at large may not consider it important to emphasize the vital role of adequate, accurate data in decision making. Such notions have affected many developing countries, including Tanzania, to the extent that crucial data are no longer collected for an extensive time or more than 10 years. The reason or purpose to increase the monitoring system is not recognized as shown by decline in the number of sampling or gauging stations. The finding in this case study is evident. Inaccurate and outdated flow rating curves are some of the reasons for discharge data inaccuracy. Literally, no one knows for certain how much water is flowing in the stream. It might, therefore, explain why water conflicts in the Wami River subbasin and other basins in Tanzania at large could not be resolved promptly and permanently.

Data for planning purposes have been collected from different sources in many different formats (digital and paper) and on maps in different scales and projections, all stored in different locations. To increase the usefulness of this data, data need to be put into a relational database format and stored in a centralized, secure, and easily accessible location. Access of data for all users should be created (Alamgir et al. 2001). It is worth noting that studies elsewhere have shown that, if information is used properly, it can be expected to contribute to the economic worth resulting from a data-based decision making. It goes without saying that the more credible the information, the better the decision.

3.5 Recommendations

The chapter is concluded by discussing the desired framework to debottleneck the data management challenges while emphasizing the need for adequate, accurate data of water resources to achieve sound decision making for sustainable management and development. Therefore, it presents the proposed way forward in reversing the situation in three work packages: training, research, and data management. Each package addresses a specific theme within the context of the proposed study as discussed in Sects. 3.5.1–3.5.3. There is a need, for instance, for conducting a sector-wide training on data QC and data QA as a prerequisite programme for a sound data management system (nationwide information system with integrated databases) centrally administered at the headquarters of sector ministry, the Ministry of Water. It is also critical through research to ascertain and document reliability of hydrologic data sets, at different scales, and uncertainties associated with using unreliable hydrologic data sets in water resources management, and validation and entrenching of the new data-gathering approaches in hydrologic monitoring programmes in Tanzania.

3.5.1 Training on Water Resources Data Collection and Processing

In order to have sound decision making, there is a need to collect water resources data that will be credible and acceptable by all water sector stakeholders in Tanzania. The subtheme of training, therefore, intends to conduct a data QA and control training for the hydrologists and technicians of the basins. The general objective of the training is to impart and improve knowledge on data QA and control for the water sector stakeholders to assist in the collection and quality-assuring hydrologic data from their workstation. The trained personnel will assist in the collection and QA of hydrologic data from their respective basins. Basically, the proposed training is intended to improve the way the Ministry of Water staff and other water stakeholders handle data that are used as inputs to decision making or planning developments. Among others, the training should aim at orienting the participants to be able to understand the complete QA/QC process, understand different techniques for data QC, and use simple tools to carry out data QC process. At the moment, the data gap is exceedingly large; probably, the training should introduce some rapid water resources assessment approaches. In this case, trainees should be able to prioritize primary gauging stations to start with a rapid sampling programme initiative. The training should also guide participants in choosing the size of the hydrologic monitoring network. It is without emphasis that sampling programmes in main river gauging stations would give immediate results than those in small tributaries. Besides, the training shall instill the sense of importance of recording and keeping good data in the technicians and hydrologists in the respective river basins. The participants of the training would be sensitized to understand that what they are doing (data collection and keeping) is of great importance to the national development.

3.5.2 Research on Data Quality and Adequacy in Tanzania

Not surprisingly, this study has found that the Wami River subbasin is poorly gauged as WMO (2008) puts it clearly that adequate flow-gauging stations monitoring networks are not common. For that reason, care should be taken not only in establishing but also in providing for the continuing operation of these stations and for monitoring the reliability and accuracy of the collected records. Research on data quality and adequacy in Tanzania is essential as evidenced earlier at many gauging sites. There is an exceptionally large gap of missing information. For most gauging sites, the data gap is concurrent. Therefore, records cannot be reconstructed at the discontinued site by means of the base-station records and the interstation relationship (WMO 2008). In order to fill the gaps, it might require skilled labor-intensive approaches such as rainfall-runoff modeling techniques. This is only possible where a valid or reliable rainfall-runoff model has been calibrated during times when all gauges (rainfall and streamflows) were functioning properly. In the case of Tanzania, for instance, it is unclear which modeling framework would suit the purpose in the study area. Therefore, supplementary studies are also required for enhancing the present monitoring programmes (WMO 2008).

This theme package also highlights a possible paradigm shift in attitude and reason of purpose with regard to hydrologic monitoring, data management, and value addition to various hydrologic data sets in Tanzania. Such an approach targets not only the authorities in charge of the data sets but also the clients (e.g., researchers) who could add value to the hydrology monitoring by sharing their scientific findings, packaged in the desired products, for the benefit of the various stakeholders. As supported by other researchers elsewhere, such as Harmel et al. (2009), the reliability of hydrologic data sets, at different scales, needs to be ascertained and documented and a case study needs to be undertaken to highlight uncertainties associated with using unreliable hydrologic data sets in water resources management. New data-gathering approaches need to be validated and entrenched in hydrologic monitoring programmes in Tanzania. All this information will be captured and linked in the data management system as discussed in Sect. 3.5.3. It is noteworthy that each work package should be oriented towards both research and development, of which the latter shall target building capacity through training and enhancement of resource base in the pilot river basin.

3.5.3 Data Management: A Nationwide Integrated Centralized Database

As acknowledged by others elsewhere, water resource planners need access to reasonably accurate spatial data and time series data in order to assess resources, demands, and constraints, evaluate options, and formulate alternative strategies (Alamgir et al. 2001). A centralized (nationwide) information system with integrated databases is, therefore, required to document all collection and processing operations to ensure that standards are continually maintained, beginning with equipment used, staff training, field measurement procedures, data processing techniques, and final computer archiving. QA/QC should be defined at different levels, namely data level, workflow level, system level, and IT level.

A nationwide information system with integrated database can be implemented as a Decision Support System (DSS). The DSS implementation can be architecturally distributed where different stakeholders own and manage their data, and the information is only used on a shared basis via predefined agreements. It can also be architecturally centered where all core processing services and data are found at one location within the organization. It is possible to implement a DSS which is datacentric where data from disparate sources such as water basins, Tanzania Meteorological Agency, Ministry of Agriculture, academic institutions, Ministry of Water,

Table 3.11 Proposed data management activities plan

SN	Implementation phase	Activity descriptions	Timelines (months)
1	Very short term	Ministry of Water in liaison with stakeholders identifying data requirements and availability	3
		Collect and compile available data in a form of hydrological yearbook	6
2	Short term	Convene stakeholders consultative meeting to deliberate on implications of data inadequacy in decision making	9
		Develop training materials as manuals on data quality control and assurance	12
3	Medium term	Conduct capacity building training workshops on data collection technologies, processing, and quality control and assurance	18
4	Long term	To conduct research aiming at ascertaining and documenting reliability of hydrologic data sets, at different scales, and uncertainties associated with using unreliable hydrologic data sets in water resources management; and validation and entrenching of the new data-gathering approaches in hydrologic monitoring programmes in Tanzania	24
		Development of a nationwide information system with integrated databases centrally administered at the headquarters of Ministry of Water	36

and governmental and nongovernmental institutions are processed in an inclusive manner by a central agency preferably by the Ministry of Water where analysis is performed to drive decisions on a national scale.

The end user who is a vitally important part of the system interactively communicates with the system through its utilities to obtain information. DSS users have well-defined boundaries when it comes to data or information accessibility based on their roles in the system or organizational structure. For instance, the general public will only have access to the information delivered by the agency following a decision made internally, whereas system administrators and management may have a much more fine-grained access to data governed by a well-defined policy setup unanimously by the stakeholders while adhering to national policy. As acknowledged by others, the purpose of this activity is to improve water resources planning at all levels.

3.5.4 Proposed Way Forward

Considering the existing capabilities and available manpower and inadequate allocated resources in water sector, a plausible action plan is proposed. Four phases, very short term, short term, medium term, and long term of data management activities, are presented in Table 3.11.

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Chapter 4
Satellite Rainfall Products and Their Reliability in the Blue Nile Basin

Ayele Almaw Fenta, Tom Rientjes, Alemseged Tamiru Haile and Paolo Reggiani

Abstract In the Upper Blue Nile (UBN) basin, there is very sparse and uneven distribution of ground-based meteorological stations which constrain assessments on rainfall distributions and representation. To assess the diurnal cycle of rainfall across the UBN basin, satellite observations from Tropical Rainfall Measuring Mission (TRMM) were used in this study. Data of 7 years (2002–2008) of Precipitation Radar (PR) and TRMM Microwave Imager (TMI) were processed, with analyses based on geographic information system (GIS) operations, statistical techniques, and harmonic analysis. Diurnal cycle patterns of rainfall occurrence and rain rate from three in-situ weather stations are well represented by the satellite observations. Harmonic analysis depicts large differences in the mean of the diurnal cycle, amplitude, and time of the amplitude across the study area. Diurnal cycle of rainfall occurrence has a single peak in Lake Tana, Gilgel Abbay, and Jemma subbasins and double peaks in Belles, Dabus, and Muger subbasins. Maximum rain rate occurs in the morning (Gilgel Abbay, Dabus, and Jemma), afternoon (Belles, Beshilo, and Muger), and evening (Lake Tana and along the river gorges). Results of this study

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indicate that satellite observations provide an alternative source of data to characterize diurnal cycle of rainfall in data-scarce regions. We noticed, however, that there are a number of constraints to the use of satellite observations. For more accurate assessments, satellite products require validation by a network of well-distributed ground stations. Also, we advocate bias correction.

Keywords Upper Blue Nile · Satellite rainfall · Remote sensing · TRMM · TMI

4.1 Introduction

In recent decades, tropical rainfall variability at sub-daily time scales has been extensively studied by data from various sources. In developing countries like Ethiopia, in-situ observations of rainfall by meteorological stations often are sparse, because of terrain inaccessibility and remoteness, and economic constraints. Further, most stations are rainfall collector stations for which observations are taken once per day. However, for effective water resources management and hydrologic applications, it is eminent that rainfall can be well represented in space and time dimensions. This also applies to the Upper Blue Nile (UBN) River basin, which is one of the two major runoff source areas of the Nile River.

In the UBN basin, there is very sparse and uneven distribution of ground-based meteorological stations which, as such, constrain assessments on rainfall distributions and representation. An alternative approach to observe rainfall and to represent rainfall over space and at sub-daily time intervals is by satellites that may be geostationary or in orbit. Satellites have the potential to systematically acquire data over large spatial domains with specific revisit intervals. Therefore, a time series of satellite images provides the opportunity to assess the diurnal rainfall cycle over space, which also applies to poorly gauged areas such as the UBN basin area. Since 1997, the Tropical Rainfall Measuring Mission (TRMM) satellite observes rainfall for tropical areas. The satellite has two main sensors on board which are the TRMM microwave imager (TMI) and precipitation radar (PR). Sensors rely on passive and active microwave remote sensing, respectively. Simpson et al. (1988) described that one of the priority science questions that led to the launch of the TRMM satellite was "What is the diurnal cycle of tropical rainfall and how does it vary in space?" TRMM is a non-sun synchronous orbiting satellite and thus revisits certain areas at different local times of a day. In practice, any specific geographic location for any specific local time is revisited only once in 46 days. The low revisit frequency is a major constraint for detailed analysis at sub-daily time scales (see Bell and Reid 1993). However, the fact that regions are visited at different local time is the premise to assessments on the diurnal cycle of rainfall using TRMM observations. In this chapter, we assess diurnal variability of rainfall across the UBN basin using data of 7 years (2002–2008) of PR-2A25 and TMI-2A12 rainfall. Constructed PR- and TMI-based diurnal cycles are compared to counter parts from ground-based meteorological stations.

Many studies have shown that TRMM can provide sufficient observations at different local times to study the diurnal cycle of rainfall. Negri et al. (2002)) used 3 years of TMI and PR data to describe the rainfall diurnal cycle for 5° × 5° and 10° × 25° windows in the tropics. The study indicated that TMI and PR observations show some differences in terms of magnitude and phase of both rain rate and rainfall occurrence and that, over land, TMI estimates of rain rate tend to be higher than PR estimates. Bowman et al. (2005) also reported that TMI rain rates are higher than PR rain rates over land surfaces and tropical oceans. Also, TMI results indicate larger diurnal variation whereas differences in phase between the diurnal cycles of rain rates by the sensors were not consistent. Hirose et al. (2008) aggregated 8 years of TRMM data over a 1° × 1° grid box and found that TMI rain rates and rainfall occurrence were significantly smaller than PR counterparts over western and central Tibet. In addition, rainfall amount and occurrence over areas in eastern Tibet showed morning to early-afternoon peaks for TMI data and evening peaks for PR data. Kishtawal and Krishnamurti (2001) studied the diurnal cycle of rainfall using 5 months of TMI observations for the entire Taiwan. Results were validated by ground observations and showed that the diurnal patterns of TMI rain rates reasonably matched ground observations, although TMI consistently indicated higher rain rates. Ikai and Nakamura (2003)) on the other hand reported that PR rain rates (2A25) are higher than TMI rain rates (2A12) in mountainous regions over land, such as the RockyMountains, the Andes, and the Himalayas. The authors aggregated and spatially averaged the data over an area of size 5° × 5° to overcome sample size limitations. Using 6 years of TRMM data, Yamamoto et al. (2008) found systematic shifts in peak time relative to the diurnal cycles derived from the two sensors over western North America, the Tibetan Plateau, and oceanic regions, such as the Gulf of Mexico. The systematic shifts are particular to regions with high convective frequency and large rain event depth and large amplitude of diurnal variation. Using 8 years of TMI and PR estimates, Ji (2006) made a comparison of mean hourly rainfall and diurnal cycles from PR and TMI and ground observations over Florida (USA) and sites in Darwin (Australia). It was shown that the diurnal cycles from PR and TMI are comparable to the gauge-based counterparts, with small amplitude differences between PR and gauge data. Such differences were much larger for TMI. Furuzawa and Nakamura (2005) report that over land surface, PR rain rate estimates better matched ground observations than TMI. They attributed this to PR's superior vertical and horizontal resolutions. Such elements allow observation of smaller scale precipitation features which, by themselves, cannot be unambiguously observed and resolved by TMI.

Conway (2000) reported on high rainfall variability in the UBN by analyzing monthly rainfall data. Rainfall is influenced by three mechanisms: the Intertropical Convergence Zone (ITCZ) which drives the summer monsoon during the wet season, the Saharan anticyclone that generates dry warm northeasterly winds during the dry season, and the Arabian heights that produce thermal lows during the mild season. Aspects of large-scale wind circulation over the source region of the Nile were studied in Camberlin (1997). Results indicated that during the rainy season a general southwesterly monsoon flow can be noticed, whereas in eastern Africa, as a whole, wind flows are distinctly affected by topographic features. In Camberlin (2009), it is described that topography is the most important factor which affects the general circulation pattern. Mountain ranges generate local wind circulation patterns which result in specific local climate conditions. Rientjes et al. (2013) came to similar conclusions when using PR and TMI data when assessing aspects of rainfall variability in the UBN. Haile et al. (2009, 2012) showed that large water bodies such as Lake Tana tend to develop their own local circulation patterns in the form of lake breezes. Circulation is induced by differences in diurnal temperature variations of the lake and the surrounding land areas. In these studies, it is described that daytime breezes diverge from lakes to the warmer surrounding land, whereas nighttime land breezes converge to the warmer middle part of the lakes.

The aim of this study is to assess the rainfall diurnal cycle for the UBN basin by TRMM PR and TRMM TMI observations. For such an assessment, diurnal cycles of rainfall occurrence and rain rate are constructed. The study reported in this chapter uses 7 years of data which provide a larger sample size than most of the aforementioned studies. Haile et al. (2009, 2011) and Rientjes et al. (2013), in detailed studies on rainfall variability in the Lake Tana basin and the UBN, respectively, indicated that rainfall properties are affected by a number of topographic and meteorological factors, which signify that accurate estimation is a major challenge in the UBN basin.

4.2 TRMM Satellite Overview

The launch of the TRMM satellite was motivated by considering the basic importance of rainfall on the Earth's climate system, to overcome constraints of rainfall observation by inadequate networks, and by the vital role of tropical rainfall in global climate dynamics and the global hydrologic cycle. TRMM was launched on 27 November 1997 as a joint space project between the National Aeronautics and Space Administration (NASA) of the USA and the Japan Aerospace Exploration Agency (JAXA) of Japan. The space segment of TRMM is a satellite in a 350 km circular orbit with a 35° inclination angle. According to Kummerow et al. (1998), TRMM was designed for a lifetime of 3–5 years. Based on TRMM's excellent performance and promise, NASA and JAXA decided in 2001 to extend the mission. Various options were studied for extending the mission lifetime, and the decision was made to boost the operating altitude from 350 to 402.5 km to reduce drag and to conserve fuel (Bilanow and Slojkowski 2006; TRMM 2006). The primary TRMM instruments, their swath width, ground resolution, and orbital period before and after the change of the satellite average operating altitude are given in Table 4.1. The time period before 7 August 2001 is referred to as pre-boost and the time period after 24 August 2001 is referred to as post-boost.

Compared to polar orbiting environmental satellites, TRMM orbital characteristics of altitude (402.5 km), inclination (35°), and orbit itself (non-sun-synchronous) provide multiple benefits with regard to sampling of space and time domains. In this respect, Simpson et al. (1988) and TRMM (2006) describe that the low-altitude orbit provides rapid updating and high spatial resolution in the tropical belt. The inclined nature of the orbit allows the satellite to overpass a given location at different times

Table 4.1 An overview of TRMM rainfall measurement sensors' overview. (Source:http://trmm.gsfc.nasa.gov/)

TRMM instrument	Pre-boost	Post-boost	Pre-boost	Post-boost	Pre-boost	Post-boost
	Swath width (km)		Ground resolution (km)		Orbital period (minutes)	
PR	215	247	4.3	5		
TMI	760	878	4.4	5.1	91.5	92.5
VIRS	720	833	2.2	2.4		

every day and enables the sampling of the diurnal variation of tropical rainfall (Simpson et al. 1988; Kummerow et al. 2000). In its rainfall measurement capacity, TRMM has the PR, the TMI, and the Visible and Infrared Radiometer System (VIRS). Due to its complementary suite of active and passive sensors, the TRMM satellite has been called a "flying rain gauge" by TRMM (2006).

As described by Simpson et al. (1988) and Kummerow et al. (1998, 2000), the main scientific goals of TRMM are to determine the distribution and variability of rainfall and energy (latent heat of condensation) exchange of tropical and subtropical regions, to advance knowledge of the global energy and water cycles. This is important for improving short-term climate models, general circulation modeling, and in understanding the hydrological cycle, particularly as it is highly affected by tropical rainfall and its variability (after Simpson et al. 1988). Since 1998, TRMM has provided data for a wide range of applications in the scientific community. These include applications in: (1) enhancing our basic scientific knowledge by descriptive and diagnostic studies, (2) monitoring weather features notably tropical cyclone activity, (3) weather prediction and assimilation of TRMM data in forecast operations, and (4) climate monitoring and climate model development. We refer to TRMM (2006) for a complete description of these applications.

4.3 Study Area and Data

The UBN basin is the source region of the Blue Nile River and drains a large area of the central and southwestern Ethiopian Highlands. It is the largest river basin in Ethiopia in terms of volume of discharge, and it provides a vital source of freshwater to the downstream users in Sudan and Egypt. The basin is characterized by complex topography, consisting of rolling ridges and flat grassland areas with twisting streams along the sides of the gorge. Topographic grades are steepest in the highland region and become flatter along the lowlands. Much of the highland areas have elevations above 1,500 m with maximum of around 4,200 m in the Choke Mountain. The total drainage area of the UBN basin is about 175,000 km^2 as extracted from 90 m resolution digital elevation model (DEM) from Shuttle Radar Topography Mission (SRTM; see Fig. 4.1). The area is located between 7°44′32″ to 12°45′19″ north latitude and 34°29′20″ to 39°48′17″ east longitude. The livelihood of

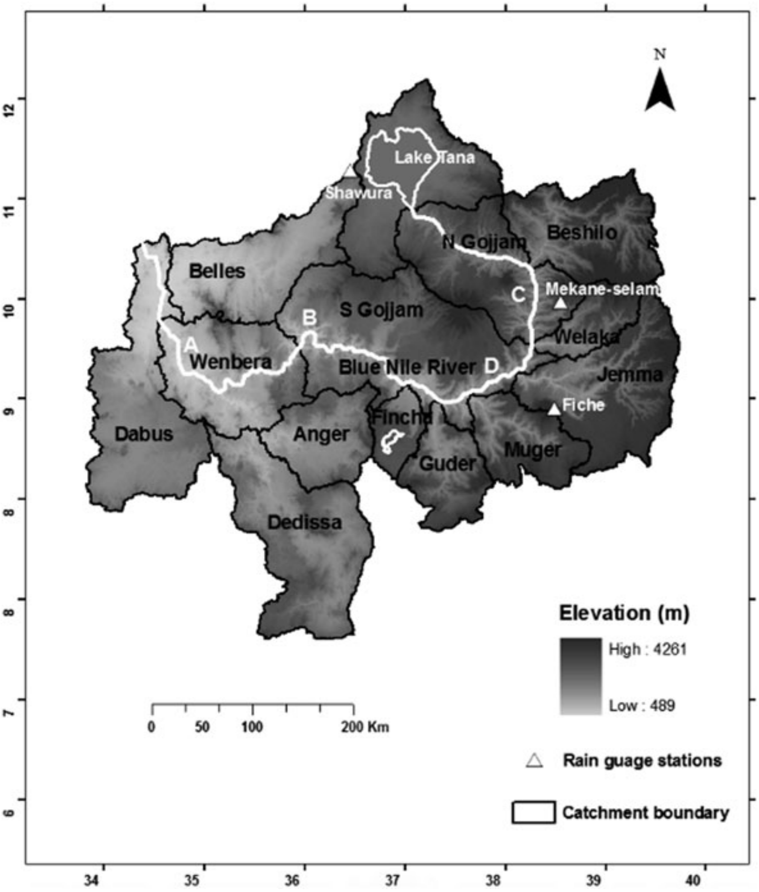

Fig. 4.1 Digital elevation model of the UBN basin extracted from Shuttle Radar Topography Mission (SRTM). Major subbasins, rain gauges, gorge locations A–D, and the main stream of the Blue Nile River (in *white*) are indicated. (Projection: UTM-zone 37 N, Datum: WGS1984, Ellipsoid: WGS84)

Table 4.2 Latitude and longitude of the stations

Station name	Latitude	Longitude	Elevation (m)	Type
Fiche	9°48′N	38°42′E	2750	Recording
Mekane Selam	10°45′N	38°45′E	2600	Recording
Shawura	11°56′N	36°52′E	2232	Recording

the people in the basin is heavily dependent on rain-fed agriculture and small-scale irrigation schemes.

For this study, we selected the TRMM level-2 products PR-2A25 and TMI-2A12 to assess the diurnal cycle for rainfall occurrence and mean rain rate. Diurnal cycle estimates are compared with counterparts by ground observations from Fiche, Mekane Selam, and Shawura meteorological stations (Table 4.2).

4.4 Methodology

The processing of PR-2A25 and TMI-2A12 products involved the extraction using the TRMM Orbit Viewer at ftp://disc2.nascom.nasa.gov/software/trmm_software/Orbit_Viewer/, and the conversion of the TRMM image samples in American Standard Code for Information Interchange (ASCII) table format using the Integrated Land and Water Information System (ILWIS) (http://52north.org/communities/ilwis/overview). Since the TRMM satellite is orbiting the earth with an inclination of 35 to the equator, the data are rearranged using Universal Traverse Mercator (UTM) projection system with datum WGS84. The processing of the image samples in ILWIS involved geo-locating the images and inverse distance interpolation of the image sample points to yield raster maps. For both PR and TMI, inverse distance weighting (power 2) is applied and samples are interpolated to maps with resolution of 5 km × 5 km. Such unified resolution allows comparison of results by map overlay. Next, images that are acquired at similar moments in local time are stratified by their Local Standard Time (LST) at 1-hourly time interval to assess the diurnal cycle. By use of ILWIS, we analyzed the TRMM sampling frequency, rainfall occurrence, and mean rain rate. Summary statistics that include count, sum, mean, standard deviation, and coefficient of variation are used for assessments.

4.5 Statistics of the Diurnal Cycle

We evaluated the frequency and uniformity (i.e., sampling) of the TRMM satellite overpasses in the study area to conclude on representativeness. In the procedure, the number of TRMM observations is counted for each pixel for each LST. Uniformity is assessed by estimating the coefficient of variation (*Cv*) for each pixel where lower *Cv* values indicate more uniform sampling. Results show adequate sampling and refer to Rientjes et al. (2013) for further description and presentation.

For assessing spatial distributions of rainfall occurrence and mean rain rate, rainfall events are identified using a rainfall detection threshold of 1 mm h^{-1}(see Kummerow et al. 1998; Nesbitt and Zipser 2003; Haile et al. 2010). In the following, the number of instances rainfall is detected by TRMM at each LST is referred to as rainfall occurrence (*RO*) in % and is defined as

$$RO = \frac{\sum N_1}{TN} \times 100, \tag{4.1}$$

where N_1 is 1 at selected LST if the rain rate $\geq$ 1 mm h^{-1}; *TN* is total number of TRMM observations for a selected LST.

To eliminate the effect of non-rainy periods on the statistics, the mean rain rate (*RR*) in mm h^{-1} is conditioned on the detection threshold of 1 mm h^{-1} and reads

$$RR = \frac{\sum rain\ rate}{N_1} \tag{4.2}$$

4.5.1 Harmonic Analysis

The nature of the diurnal cycle of rainfall occurrence and mean rain rate is examined using harmonic analysis, which gives information about the amplitude and phase (i.e., timing) of the peak in LST. The analysis is used to determine the diurnal (first harmonic) and semi-diurnal (second harmonic) variations of rainfall occurrence and mean rain rate. As described by Dai (2001), the percentage of the total daily variance explained by the sum of the first two harmonics is a measure for the representativeness of the diurnal variation. The procedure applied in this study follows the procedure in Dai (2001), Haile et al. (2009), and Vondou et al. (2009). The diurnal cycle is expressed by the following form of Fourier series expansion:

$$F(t) = m + S_1 + S_2 + \ldots + S_n, \quad (4.3)$$

where $F(t)$ = the fitted series, m = the mean value of the diurnal cycle, and S_n = the nth harmonic of the diurnal cycle. In rainfall studies, the interest commonly is on the first two harmonics (see Dai 2001; Haile et al. 2009; Lim and Suh 2000) which read:

$$S_1 = a_1 \cos(\omega t - \phi_1), \quad (4.4)$$

$$S_2 = a_2 \cos(2\omega t - \phi_2), \quad (4.5)$$

where a and ϕ are the amplitude and phase angle of the cosine function, ω equals 2π/24 since the number of hours in a day is 24. The variance explained by each harmonic can be determined from the fraction of variance of each harmonic (${\sigma_i}^2$) and standard deviation of the observations (σ).

$$\mathit{Variance\ explained} = {\sigma_i}^2/\sigma^2, \quad (4.6)$$

where ${\sigma_i}^2$can be determined from $a_i/2$.

The harmonic analysis is applied to three subsets. The first application is for the time series of the three meteorological stations. The second application is for subbasin-averaged TRMM observations. The third application is for four satellite pixels that overlay gorge locations (Fig. 4.1) along the main stream of the Blue Nile River.

4.6 Results and Discussion

The Fourier series expansion in the form of Eqs. 4.3–4.6 served to assess rainfall occurrence and conditional mean rain rate for the three applications indicated earlier.

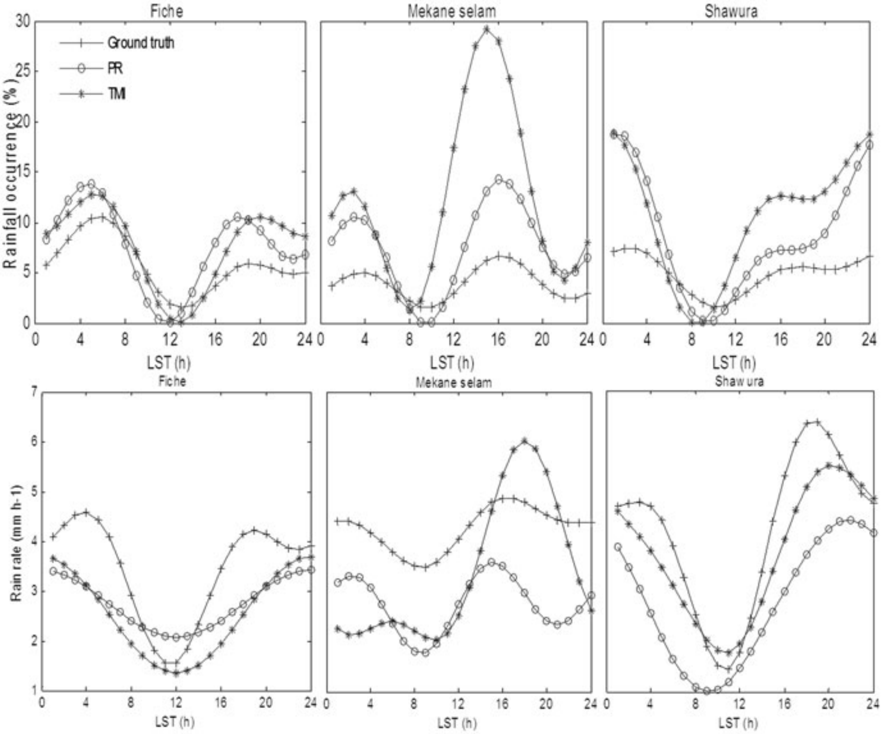

Fig. 4.2 Fitted sum of the first two harmonics for the three station sites

4.6.1 Diurnal Cycles at Meteorological Stations

The sum of the two harmonics fitted to the time series (i.e., ground truth) by Fiche, Mekane Selam, and Shawura meteorological stations and satellite observations (PR and TMI) are shown in Fig. 4.2. Results are for rainfall occurrence and mean rain rate. The gauge data at Fiche station show that rainfall occurrence has a diurnal cycle with two peaks (Fig. 4.2). The major peak ($\sim 10\,\%$) was observed in early morning and the minor peak ($\sim 5\,\%$) was observed in late afternoon, indicating that most rain events occur in morning hours. Gauge data at Mekane Selam station indicate that the diurnal cycle of rainfall occurrence also has two peaks. A major peak ($> 5\,\%$) was observed in the afternoon, whereas a minor peak ($< 5\,\%$) was observed in the morning LST. The diurnal cycle at Shawura was not as pronounced as those of the two other stations with highest occurrence in midnight to morning LST. For Fiche and Mekane Selam stations, the diurnal cycle of mean rain rate (mm h^{-1}) shows similar distribution and amplitudes to the cycle of rainfall occurrence. For Shawura station, a clear diurnal cycle is shown with relative large amplitudes for 0400 LST and 1600 LST.

At Fiche, diurnal cycles for PR and TMI did not show much difference in pattern of rainfall occurrence. We note that midnight to late morning rainfall occurrence derived by the gauge data of this station was well reproduced by both TRMM sensors. A weakness at Fiche station was observed in the afternoon as both PR and TMI substantially overestimated rainfall occurrence by the gauge recordings. In addition, the afternoon rain by PR shows a phase shift of some hours earlier in time than indicated by the rain gauge. At Mekane Selam station, PR and TMI well captured the diurnal pattern of rain occurrence, although diurnal cycles were found more pronounced when compared to the gauge-based diurnal cycle. Both PR and TMI substantially overestimated rainfall occurrence at this station with the largest overestimation made by TMI. For Shawura station, both TRMM sensors poorly represented the diurnal cycle of rainfall occurrence, particularly in terms of magnitude.

The mean rain rate by PR and TMI at Fiche shows a distinct diurnal cycle with similar patterns to the gauge data. Both sensors somewhat underestimate observed rain rate with PR rain rates slightly higher than TMI rain rates. The highest rain rate was observed in the morning which was followed by slightly smaller rates in the afternoon. For Mekane Selam and Shawura, the rain rate diurnal cycle was poorly represented by PR and TMI, with significant underestimation for most hours of the day. An exception is the very high TMI rain rate (6 mm h^{-1}) at Mekane Selam in the afternoon. PR shows a much lower peak rain rate in the afternoon but exhibits a much higher rain rate during the night hours (0000 LST–0400 LST). Rain rates at Shawura show two peaks which occurred in the morning and late afternoon. Although the diurnal cycle of rainfall rate is fairly well represented, for all hours of the day, both PR and TMI underestimate the rain gauge-based rain rates.

Statistics on the harmonic analysis are shown in Table 4.3 and further described later. Both gauge and TMI observations show that the distribution of rainfall occurrence at Fitch is dominated by diurnal variation, with the variance explained by the first harmonic that slightly exceeds 50 %. PR observations indicate that rainfall occurrence at this station is characterized by a semi-diurnal cycle. At Mekane Selam, all three data sources show that semi-diurnal variation mostly explains the sub-daily variation of rainfall occurrence. At Shawura, the semi-diurnal variation is the most pronounced according to results from the three data sources. The amplitude of the diurnal cycle of rainfall occurrence is quite similar for rain gauge and for satellite observations. Satellite observations reported larger amplitude than rain gauge observations at Mekane Selam and Shawura with largest amplitude for TMI observations. The amplitude of PR observations occurred earlier (by a maximum of 1 h). For TMI, a shift of 2 hrs earlier in time occurred as compared to the ground truth-based amplitude.

The observed rain rate diurnal cycle at Fiche is characterized mainly by diurnal variation. However, the satellite observations suggest that the semi-diurnal variation dominates the rain rate of these stations. At Mekane Selam, PR agrees reasonably well with the ground truth which indicates that the diurnal variation dominates rain rate. TMI indicates that the semi-diurnal variation is most dominant. According to both gauge and satellite observations, the rain rate at Shawura can be predominantly explained by the first harmonic indicating the dominance of diurnal variation. PR

Table 4.3 Results from the harmonic analysis for the three station sites

Station	Observation	Variance explained (%)		Mean of the diurnal cycle	Amplitude (%)	LST of the amplitude (h)
		First harmonic	Second harmonic			
Rainfall occurrence						
Fiche	Ground truth	55	34	6	3	600
	PR	32	45	8	4	500
	TMI	52	29	8	4	500
Mekane-selam	Ground truth	14	57	4	1	1600
	PR	22	56	7	3	1600
	TMI	39	45	12	8	1500
Shawura	Ground truth	48	17	5	2	300
	PR	49	12	8	6	200
	TMI	50	15	11	9	100
Rain rate						
Fiche	Ground truth	42	17	3	2	400
	PR	4	37	3	2	100
	TMI	20	27	3	1	100
Mekane-selam	Ground truth	23	8	3	2	1600
	PR	43	9	3	2	1500
	TMI	9	45	2	1	1800
Shawura	Ground truth	52	14	5	1	1800
	PR	63	0	2	2	2200
	TMI	51	2	3	2	2000

LST local standard time

captured both the daily averaged rain rate and amplitude at Fiche and Mekane Selam, whereas TMI underestimated the amplitude at the two stations. The observations from both satellite sensors underestimated the average rain rate at Shawura. The amplitude from the satellite observations showed a time shift earlier in time than that from the gauge at Fiche. For PR, the amplitude of rain rate showed a shift of 1 hour earlier and 4 hours later than LST as compared to gauge-based amplitudes at Fiche and Shawura, respectively. TMI-based amplitude of rain rate shows a time shift of 2 hrs later in time compared to the gauge-based rain rate at Mekane Selam and Shawura.

4.6.2 Diurnal Cycles at Subbasin Scale and Blue Nile Gorge Locations

For harmonic analysis at subbasin scale, we selected Lake Tana, Belles, Beshilo, Dabus, Jemma, Gilgel Abbay, and Muger subbasins that have fair distribution over the UBN basin. Analysis is applied for subbasin-averaged PR observations as estimated for pixels that overlay respective subbasins. To further assess aspects of rainfall diurnal cycle variability, we selected four river gorge locations along the main stream of the Blue Nile River for which analyses by PR observations are performed. Gorge locations selected are used by Rientjes et al. (2013), who showed

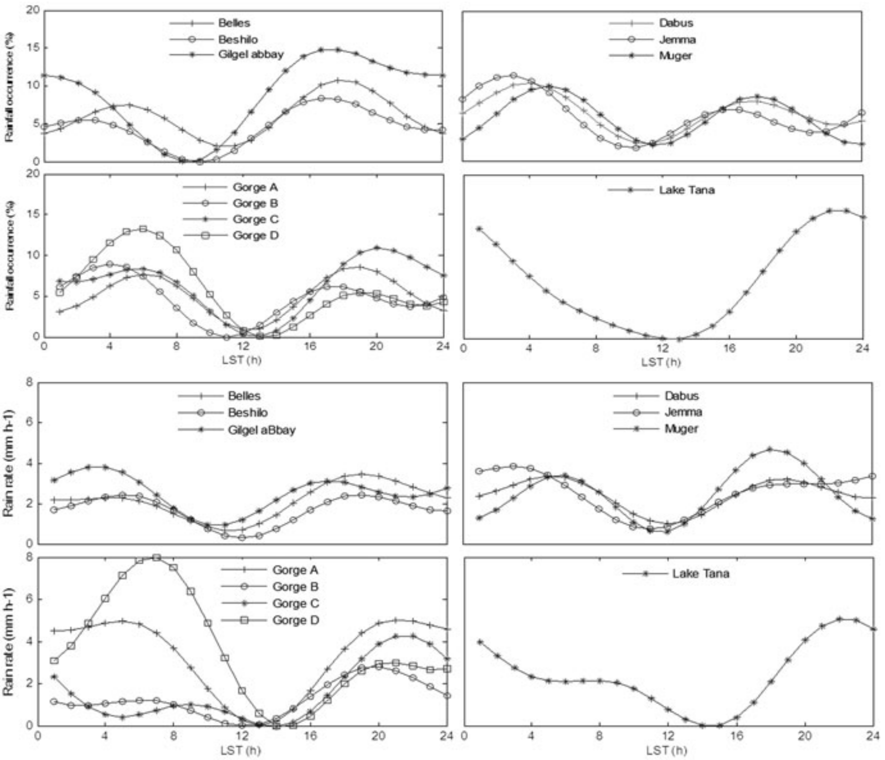

Fig. 4.3 Sum of the first two harmonics for the selected subbasins for rainfall occurrence (*top*) and rain rates (*bottom*)

that rainfall variability at these locations is affected by orography and large-scale topographic variability. Results on diurnal cycles for the subbasins and at the four gorge locations are jointly described and graphically presented in Fig. 4.3. For presentational purposes, the rainfall diurnal cycles at the subbasins and at the gorge locations, respectively, with approximately similar time to maximum rain rate and rainfall occurrence are shown in the same plot. Results on rainfall occurrence for respective subbasins show that diurnal cycles have similar characteristics for Dabus, Jemma, and Muger subbasins which cover the southwestern part of the UBN. For 0400 LST and for 1700 LST highest rainfall occurrence is shown, whereas lowest occurrence is shown at 1100 LST. For Beles, Beshilo, and Gilgel Abbay that cover the northern part of the UBN basin, relatively large variations in the diurnal cycles are shown. Highest and lowest rainfall occurrences differ for respective LST, but also magnitudes differ substantially. The diurnal cycle of rainfall occurrence for Lake Tana largely deviates from any of the subbasins described. Occurrence is highest during evening and nighttime hours (2000 LST–0100 LST) and lowest around 1300–1400 LST. For the four gorge locations also some variability is shown with two periods of relatively high occurrence. For all locations, high and low occurrences are shown for approximately the same night and evening LSTs. From the results, gorge

Table 4.4 Results from the harmonic analysis. Hatched rows indicate that diurnal variation is characterized by a single peak (first harmonic)

Rainfall occurrence

Subbasin/gorge	Variance explained (%)		Mean of the diurnal cycle	Amplitude %	LST of amplitude (h)
	First harmonic	Second harmonic			
Belles	14	39	6	3	1700
Beshilo	31	23	4	3	1600
Gilgel Abbay	51	10	9	6	1600
Dabus	14	39	6	3	500
Jemma	50	31	8	5	400
Muger	1	31	6	3	600
Lake Tana	59	2	7	7	2200
Gorge A	2	11	6	2	1900
Gorge B	18	11	5	2	400
Gorge C	11	7	6	4	2000
Gorge D	19	11	6	4	600
Rain rate					
Belles	35	15	2	1	1900
Beshilo	14	16	2	1	1900
Gilgel Abbay	10	13	3	2	400
Dabus	19	28	2	1	500
Jemma	40	9	3	1	300
Muger	9	41	3	2	1800
Lake Tana	53	16	2	2	2200
Gorge A	56	13	2	1	2100
Gorge B	9	4	1	1	2000
Gorge C	21	9	2	2	2100
Gorge D	16	6	4	3	700

locations B and D show highest rainfall occurrence in the night hours (0400–0600 LST), whereas for locations A and C this is shown during evening hours (1900–2100 LST).

For the rain rate diurnal cycle, for Beles, Beshilo, and Gilgel Abbay subbasins, similar cycles are visible which are characterized by two periods with relatively high rain rates. Consistent deviations between the cycles are visible during the afternoon (1200–1800 LST). For Dabus, Jemma, and Muger, largest deviations are visible for night hours (0000–0600 LST). For Muger, a relatively large deviation with high rain rate is visible for 1600–2000 LST. For the gorge locations, a very large variability is evident. Gorge locations A and D show very high rainfall rates during daytime. All locations show lowest rain rate in the afternoon (1300–1500 LST). Gorge locations B and C show highest rain rates for the evening hours. Gorge location A is the only location that shows high rain rates for both periods. The diurnal rain rate cycle for Lake Tana shows a similar cycle for rainfall occurrence, with highest rain rates during evening and night hours (2000–0100 LST) and very low rain rates around 1300–1500 LST.

Table 4.4 shows that the rainfall occurrence of Gilgel Abbay and Jema subbasins and Lake Tana is characterized by pronounced diurnal variation (variance explained by first harmonic is > 50 %). The semi-diurnal variation of rainfall occurrence is the largest at Belles, Dabus, and Muger. At Beshilo subbasin, both the first and second harmonics are required to characterize rainfall variation as the variance explained by both harmonics is 54 %. At the gorge locations, the variance explained by the first and second harmonic is quite small (13–30 %), suggesting that rainfall variation at these sites cannot be satisfactorily represented by only the first two harmonics. In the study area, rainfall occurrence has the highest amplitude (5–7 %) in correspondence of the subbasins, for which variation of occurrence is mostly explained by the first harmonic. These subbasins apparently have the highest mean rainfall occurrence (7–9 %) as well. Rain mostly occurs between late afternoon and midnight LST at Lake Tana and gorges locations A and C; in the afternoon at Belles, Beshilo, and Gilgel Abbay; and in the morning at Dabus, Muger, and at gorge locations B and D. Overall, differences in the mean of the diurnal cycle, the amplitude, and the timing of amplitude are observed for the four gorge locations along the river. This suggests that there is substantial variation in the rainfall diurnal cycle along the river.

Diurnal variation of rain rate of Jemma, Lake Tana, and Gorge A is mainly explained by the first harmonic (diurnal cycle), whereas the second harmonic (semi-diurnal cycle) dominates the rain rate of Muger. Nearly 50 % of the variation of rain rate of Dabus and Belles is explained by both the first and second harmonics. However, the contribution of the first and second harmonic was very small (13–30 %) at Bashilo, Gilgel Abbay subbasins, and Gorges B, C, D. This suggests that diurnal and semi-diurnal cycles are not the only modes of rainfall variation at these subbasins and locations. The amplitude of rain rate shows small variation across space in the Blue Nile basin, whereas the LST of the amplitude varies noticeably across space. The LST of the amplitude can be divided into three: morning (Gilgel Abbay, Dabus, Jemma, and Gorge D), afternoon (Belles, Beshilo, and Muger), and evening (Lake Tana, and Gorges A, B, and C).

4.7 Conclusions

In this study, we showed that both PR and TMI are suited to capture the diurnal pattern of the observed rainfall occurrence and rain rate in the rainy season (June–September) of the UBN basin. The phase of the rain occurrence signal derived from the satellite sensors was shifted by 1–2 hrs back compared to counter-parts from gauge observations. The phase of the rain rate signals was shifted forward in time by 2–4 hrs compared to those from gauge observations.

In the analysis, we showed that estimates from the two satellite sensors can be successfully used to evaluate diurnal or semi-diurnal variation in the UBN basin. Results show that time–space rainfall variability in the UBN can be represented by TRMM reasonably well. Rainfall diurnal cycles of rainfall occurrence and rain rate vary across the UBN basin. For some basins, cycles have similar characteristics. Diurnal variation (single peak) as indicated by the first harmonic characterizes the rainfall occurrence in Lake Tana, Gilgel Abbay, and Jemma subbasins. Rainfall occurrence of Belles, Dabus, and Muger subbasins is characterized by semi-diurnal variation with two peaks that occur in the morning and afternoon, respectively. Along the main gorge of the UBN River, semi-diurnal and diurnal variations are not the only modes that cause variation of rainfall occurrence. We also showed that the mean of the diurnal cycle, the amplitude, and LST to the amplitude of rainfall occurrence vary along the main river.

For the Lake Tana subbasin, analysis of PR rain rates showed a diurnal cycle that has a single peak rain rate. Results indicate that variation in rain rate cannot always be represented by the diurnal and semi-diurnal cycle patterns. The amplitude of the rain rate signal varies only slightly across the UBN but timing in LST of the amplitude shows substantial spatial variation. Maximum rain rate occurs in the morning (Gilgel Abbay, Dabus, Jemma, and Gorge D), afternoon (Belles, Beshilo, and Muger), and evening (Lake Tana and Gorges A, B, and C).

Overall, results of this study suggest that the PR and TMI observations are suitable to assess the spatial variability of diurnal rainfall cycles across the UBN basin. We noticed, however, that there are a number of constraints with respect to the accuracy of our findings.The first constraint is the resolution of the satellite images where observations are at the scale of the image pixels (i.e., the foot print area). Also, observations only are available at discrete (and limited) moments in time. Therefore, the longer the observation period, the more reliable the assessments are on PR and TMI in representing rain rate diurnal cycles. We used an observation period covering 7 years which, based on our findings, we consider of suitable length. Yamamoto et al. (2008) indicated the various sources of error for TMI and PR. TMI underestimates precipitation water path in mid-latitudes; TMI rain rates depend on storm height and rain type. Also, the TMI algorithm imposes assumptions about freezing level. PR underestimates the precipitation water content in tropical zones, whereas the PR algorithm inadequately represents the radar reflectivity factor to weaken the rain rate relationship. Nesbitt et al. (2004) discuss that rain rate estimates from TMI (2A12) and PR (2A25) show differences due to various factors associated with the sensor characteristics and surface properties. Some of the factors include: (a) the differences in the physics of the retrieval approaches (active vs. passive microwave retrievals and their inherent assumptions) and (b) the differences in sensitivity of the sensors, type of surface, and type of rain. In this study, we did not evaluate possible effects of these aspects since we aimed at assessing rainfall variability across the UBN area. In this study, observations from stations and satellite pixels were directly used without any procedure to validate the satellite observations and to apply bias correction. To reduce errors, we advocate proper validation of satellite observations by an in-situ network of well-distributed meteorological stations. We also advocate bias correction to improve performance of the satellite products.

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Chapter 5
Africa-Wide Monitoring of Small Surface Water Bodies Using Multisource Satellite Data: A Monitoring System for FEWS NET

Naga M. Velpuri, Gabriel B. Senay, Henok Alemu, James Rowland and James P. Verdin

Abstract Continental Africa has the highest volume of water stored in wetlands, large lakes, reservoirs, and rivers, yet it suffers from problems such as water availability and access. With climate change intensifying the hydrologic cycle and altering the distribution and frequency of rainfall, the problem of water availability and access will increase further. Famine Early Warning Systems Network (FEWS NET) funded by the United States Agency for International Development (USAID) has initiated a large-scale project to monitor small to medium surface water points in Africa. Under this project, multisource satellite data and hydrologic modeling techniques are integrated to monitor several hundreds of small to medium surface water points in Africa. This approach has been already tested to operationally monitor 41 water points in East Africa. The validation of modeled scaled depths with field-installed gauge data demonstrated the ability of the model to capture both the spatial patterns and seasonal variations. Modeled scaled estimates captured up to 60 % of the observed gauge variability with a mean root-mean-square error (RMSE) of 22 %. The

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data on relative water level, precipitation, and evapotranspiration (ETo) for water points in East and West Africa were modeled since 1998 and current information is being made available in near-real time. This chapter presents the approach, results from the East African study, and the first phase of expansion activities in the West Africa region. The water point monitoring network will be further expanded to cover much of sub-Saharan Africa. The goal of this study is to provide timely information on the water availability that would support already established FEWS NET activities in Africa. This chapter also presents the potential improvements in modeling approach to be implemented during future expansion in Africa.

Keywords Water monitoring · Surface water · Hydrologic modeling · Remote sensing · Multisource satellite data · Africa · Water resources management

5.1 Introduction

Africa has the highest volume of surface water (up to 30,000 km^3) stored in wetlands, large lakes, reservoirs, and rivers (Shiklomanov and Rodda 2003). However, most parts of sub-Saharan Africa suffer from economic water scarcity, i.e., human, institutional, and financial capital limit access to water, even though water in nature is available locally to meet human demands (Comprehensive Assessment of Water management in Agriculture 2007). About 40 % of the African population is experiencing water stress and/or drought-related stress (Vörösmarty et al. 2005). Furthermore, most people live in rural areas and heavily depend on surface water resources, yet, knowledge of changes in the volume of water stored and flowing in rivers, lakes, and wetlands is poor (Alsdorf and Lettenmaier 2003).

Humans and climate have substantially affected the hydrologic cycle and water availability (IPCC 2007). The hydrologic cycle has intensified (Huntington 2006; Wild et al. 2008), with uneven distribution of precipitation and increased evaporation around the globe. This has resulted in increased frequency of floods and droughts. During the first half of the twenty-first century, water shortages will be among the world's most pressing problems, and will affect food and national security (Vörösmarty et al. 2000; Vörösmarty et al. 2005). Climate change is likely to further increase stress on water resources in many regions of the world. The problems of climate change will be more severe in arid and semiarid regions in sub-Saharan Africa characterized by limited water resources and very fast demographic growth.

Recently, the third United Nations World Water Development Report recognized the importance of water availability and water quality as a key to sustainable development and the prerequisites for Africa's human capital development as well as social, economic, and environmental development (World Water Assessment Program (WWAP) 2009). The major obstacle to poverty alleviation and sustainable development in Africa is the availability of water resources (UN-Water/Africa 2006).

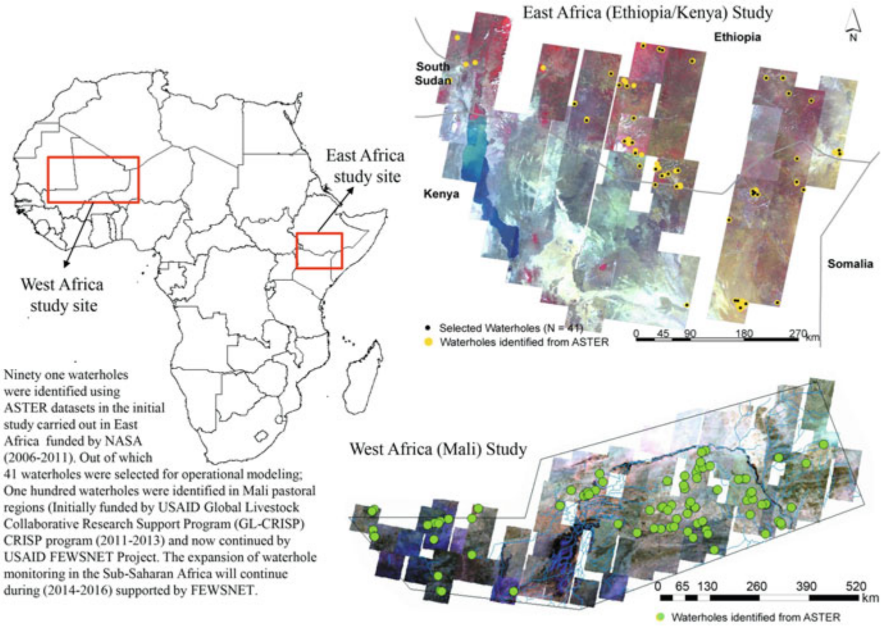
The future global commitments on climate change measures—both mitigation and adaptation are crucial in order to secure future water resource availability (World Water Assessment Program 2009). However, due to limited infrastructure in managing water resources and poor monitoring infrastructure, African countries are among the most vulnerable to the impact of water-related problems. Monitoring surface water (detecting when surface water sites are filled by rainfall and when they dry out) is key information for the assessment of water availability and for deriving indicators of environmental assessment, providing alerts on vector-borne diseases, or managing sedentary and pastoral human activities (Combal et al. 2009).

Several databases exist and provide information on the location of water resources and availability at global to continental scales such as the Global Lakes and Wetlands Database (Lehner and Doll 2004), Global Lakes database (Birkett and Mason 1995), World Register of Dams (ICOLD 1998), Digital Chart of the World (ESRI 1993), Global Wetland map (WCMC 1993), African Water Resources Database (Jenness et al. 2007), surface water body features from GEOnet gazetteer, and the Shuttle Radar Topography Mission (SRTM) water body data that provide information on the location of water resources and availability. High-resolution optical remote sensing satellite data have also been used to map small water bodies over sub-Saharan Africa (Haas et al. 2009). However, information in real to near-real time on the water level and storage is not available from existing datasets which makes them less useful for managing water resources.

Recently, remote sensing data have been providing global information on water level and storage variations in near-real time (Birkett 1995; Cretaux et al. 2011). However, so far, only large to very large lakes lying beneath the satellite orbit are being monitored. The majority of small surface water bodies globally are not being monitored. Remote sensing and global weather datasets are available at coarse- to medium-resolution that can be integrated into a hydrologic modeling framework to model the variability of water levels in remote surface water bodies. Furthermore, it is possible to use satellite-based estimates of rainfall and modeled runoff and evapotranspiration (ETo) data to estimate the changes in the surface water resources using the water balance approach (Velpuri et al. 2012; Velpuri and Senay 2012; Senay et al. 2013). This approach can be used to monitor surface water resources daily.

Small surface water bodies are addressed by different names such as water ponds, water pans, waterholes, water points, water tanks, water pockets, etc., depending on the region of the world. FEWS NET has adopted "water points" as the name for small surface water bodies in Africa. These water points are not just point locations of water availability (such as tap/well locations) but represent natural or man-made surface water bodies with a surface area of around 1 km^2 that supply water for household consumption, livestock use, or provide other sources of livelihood such as fisheries.

The goal of this study is to present an approach that uses readily available satellite-based products to monitor water points fed by surface water in data-scarce regions of sub-Saharan Africa. The objective of this research is to provide informatino for the FEWS NET program, in near-real time on the seasonal patterns and daily variations of water point water levels so that nongovernmental organizations (NGOs), governmental organizations, or communities (such as subsistence farming or pastoralists)



Ninety one waterholes were identified using ASTER datasets in the initial study carried out in East Africa funded by NASA (2006-2011). Out of which 41 waterholes were selected for operational modeling; One hundred waterholes were identified in Mali pastoral regions (Initially funded by USAID Global Livestock Collaborative Research Support Program (GL-CRISP) CRISP program (2011-2013) and now continued by USAID FEWSNET Project. The expansion of waterhole monitoring in the Sub-Saharan Africa will continue during (2014-2016) supported by FEWSNET.

Fig. 5.1 Study area illustrating location of East African and Mali study sites. Insights show Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery and location of water points identified in this study

that depend heavily on surface water resources can use the information for timely decision making and drought early warning purposes. Such information would enable communities that are vulnerable to a changing climate to build resilience to changing climate.

5.2 Study Area

The water point monitoring project is planned to cover entire sub-Saharan Africa. The initial study was performed over East Africa. The first phase of monitoring was taken up in the West Africa (Mali) region. The East African study area extends from southern Ethiopia through northern Kenya (Fig. 5.1) covers approximately 150,000 km^2 and encompasses Moyale, Yabello, Filtu, and Arero districts in southern Ethiopia and the Marsabit, Moyale, Wajir, and Mandera districts in northern Kenya. The area is characterized as arid to semiarid, with harsh weather conditions—low rainfall and high desiccating factors for most of the year. The rainfall pattern is bimodal in the region, with short rains occurring between October and December and the long rains occurring between March and May followed by a long dry season. Rainfall ranges from 300 to 800 mm with an average of 500 mm per annum. The West Africa (Mali) study site extends across the central Mali region and covering the Koulikoro, Segou,

Table 5.1 Satellite data, products, and other ancillary datasets used in this study

No	Data	Satellite sensor/source	Frequency	Resolution/ scale	Reference
1	ASTER	VNIR and SWIR	Multiple dates	15 m	–
2	Elevation data	SRTM V 4.0	Single date	90 m	Farr et al. 2000
		ASTER GDEM	Single date	30	
3	Satellite rainfall estimate	TRMM 3B42	Daily	0.25° x 0.25°	Huffman et al. 1995
4	Runoff coefficient data for Africa	SCS curve number method	Single date	10 km	Senay and Verdin 2004
5	Global GDAS reference ET	Model assimilated satellite data	Daily	0.1° x 0.1°	Senay et al. 2008
6	Water point water level	Field data collection	2008–2010	–	Senay et al. (2013)

ASTER Advanced spaceborne thermal emission and reflection radiometer, *SWIR* shortwave infrared, *VNIR* visible and near-infrared, *GDEM* Global digital elevation model, *SCS* soil conservation service, *SRTM* Shuttle Radar Topography Mission, *TRMM* Tropical Rainfall Measuring Mission

Mopti, Timbuktu, and Gao regions. The study site is approximately 350,000 km^2 and accounts up to a third of Mali. The rainfall is highly variable with scarce rainfall (around 200 mm) in northern region and high rainfall up to 1,000 mm annual rainfall in the southern region of the study site mostly occurring during June to October months. Soil type varies from loamy to sandy loam. Both the study sites are dominantly pastoral, characterized by limited water resources, frequent droughts, and flooding.

5.3 Data Used

The list and characteristics of the datasets used in this study are shown in Table 5.1.

5.3.1 ASTER

A total of 70 and 91 ASTER images were used to map the water points in the East and West African study sites, respectively, spanning over the years 2000–2010 (Fig. 5.1). Table 5.2 shows the temporal distribution of ASTER imagery used. The visible and near-infrared (VNIR) bands and shortwave infrared (SWIR) bands were used for the identification of surface water points such as natural ponds springs and man-made pans. To identify the maximum number of water points, images were collected

Table 5.2 Temporal distribution of ASTER imagery used in this study including East African and Mali study sites

Years	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W
2000	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–	16	–
2001	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	2	–	–	2	–	–	4
2002	–	–	–	–	–	–	–	–	–	–	–	–	–	–		–	–	1	–	1	–	3	–	–
2003	–	–	–	–	–	–	2	–	–	–	–	–	–	–	3	–	3	–	–	4	1	–	–	–
2004	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	–	3	1	–	–	–	3	–	–
2005	–	–	–	–	–	–	–	–	–	–	–	–	1	–	4	–	3	–	2	–	2	–	8	–
2006	–	–	–	–	–	–	–	–	–	–	1	–	2	1	–	–	–	7	1	6	–	12	2	–
2007	–	2	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	4	–	5	–	3
2008	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	–	1
2009	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	–	2	–	7	–	13
2010	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–

E East Africa (Ethiopia/Kenya), *W* West Africa (Mali) regions

following two criteria: (a) $< 10\,\%$ cloud cover and (b) no dry season images. As a result, a complete wall-to-wall coverage of the images was not found for the study sites. Except for few pockets, the ASTER images covered much of the study area ($> 85\,\%$) in East Africa and Mali.

Cloud and cloud shadows were initially masked out from the analysis. Two types of water bodies were mapped: (a) clear-water and (b) water-like points. The clear-water points are those water bodies filled with relatively clear water; they are often deep and are easily visible as darker features on a false color composite (FCC) of ASTER imagery. On the other hand, water-like points are commonly small or filled with a lot of sediments, or clear evidence of vegetation activity in the surrounding area and were seen in lighter blue to green shades in the ASTER FCC.

5.3.2 Satellite-Based Precipitation

A suite of sensors onboard a variety of satellites are providing reliable global information on precipitation. In this study, rainfall estimates derived from the Tropical Rainfall Measuring Mission (TRMM) 3B42 merged high-quality infrared precipitation product (Huffman et al. 1995) were used. These estimates are available from the National Aeronautics and Space Administration (NASA) website. The US Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center distributes processed data (gridded daily rainfall data in readily usable geographic information system (GIS) formats) through an anonymous file transfer protocol (FTP) site in readily usable formats. The rainfall estimates are available since December 1997 at 0.25° x 0.25° grid resolution globally. The data subset for the African region was used in this study.

Several researchers have validated TRMM rainfall estimates with rain gauge data (Nicholson et al. 2003a, b; Ji 2006; Hazarika et al. 2007; Harris et al. 2007) over different parts of the world and found that TRMM rainfall estimates (1) capture the trends in rainfall patterns, (2) show reasonable comparison with rain gauge estimates where there are higher number of rain gauges within a grid, and (3) slightly overestimate, where there are few or no rain gauge stations (Nicholson et al. 2003b; Hazarika et al. 2007). Furthermore, Dinku et al. (2008) extensively evaluated TRMM-3b42 rainfall estimates using rain gauge data from Ethiopia and found that satellite estimates compare reasonably well with rain gauge data with an overall correlation coefficient of 0.72. Satellite-based rainfall estimates are used to model the surface runoff contribution to each water point and to quantify direct rainfall contribution over the water point.

5.3.3 ETo Data

Reference daily ETo data are produced using 6-hourly meteorological data from the National Oceanic and Atmospheric Administration (NOAA) Global Data Assimilation System (GDAS) using the standardized Penman–Monteith equation (Senay et al. 2008). The ETo data are available with a 1° x 1° spatial resolution from the USGS EROS website. The GDAS ETo data were validated by Senay et al. (2008), and were found to have a high correlation coefficient of 0.99 with the ETo derived from observations made at weather stations, demonstrating the usability of GDAS ETo in large-scale hydrologic modeling studies and early warning applications.

5.3.4 Other Ancillary Data

The SRTM digital elevation model (DEM) data are freely distributed at 90 m spatial resolution for Africa. The data have 16-m absolute vertical height accuracy, 10-m relative vertical height accuracy, and 20-m absolute horizontal circular accuracy (Rodriguez et. al. 2005). The digital elevation model derived from the SRTM is used in this study to derive several hydrological derivatives such as (a) streams and river networks and (b) catchment areas for each water points.

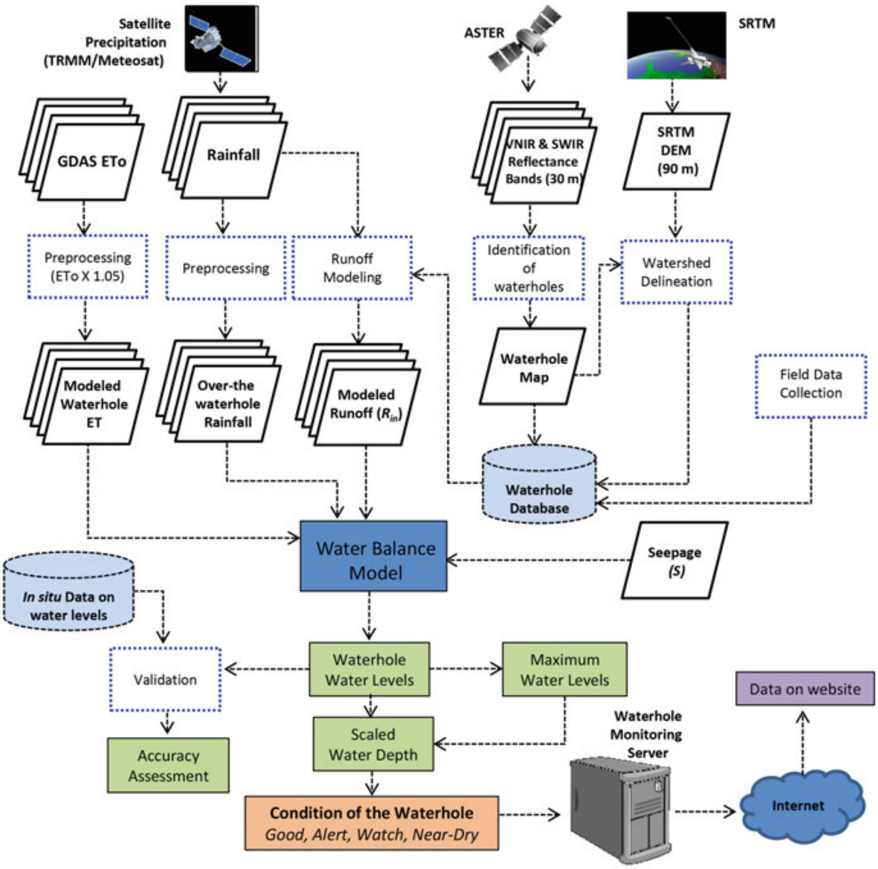


Fig. 5.2 Integration of multisource satellite-driven data for modeling water point water levels and to build an operational water monitoring system

5.4 Methodology

A broad framework of datasets and methods used in this study and integration of satellite-driven data and hydrologic modeling approach used in this study is illustrated in Fig. 5.2.

5.4.1 Water Point Identification, Watershed Delineation, and Characterization

The first step toward building a water monitoring system is to build a geo-database of water points. A schematic representation of the processes involved to build a water point database is shown in Fig. 5.3. First, water points are identified using ASTER

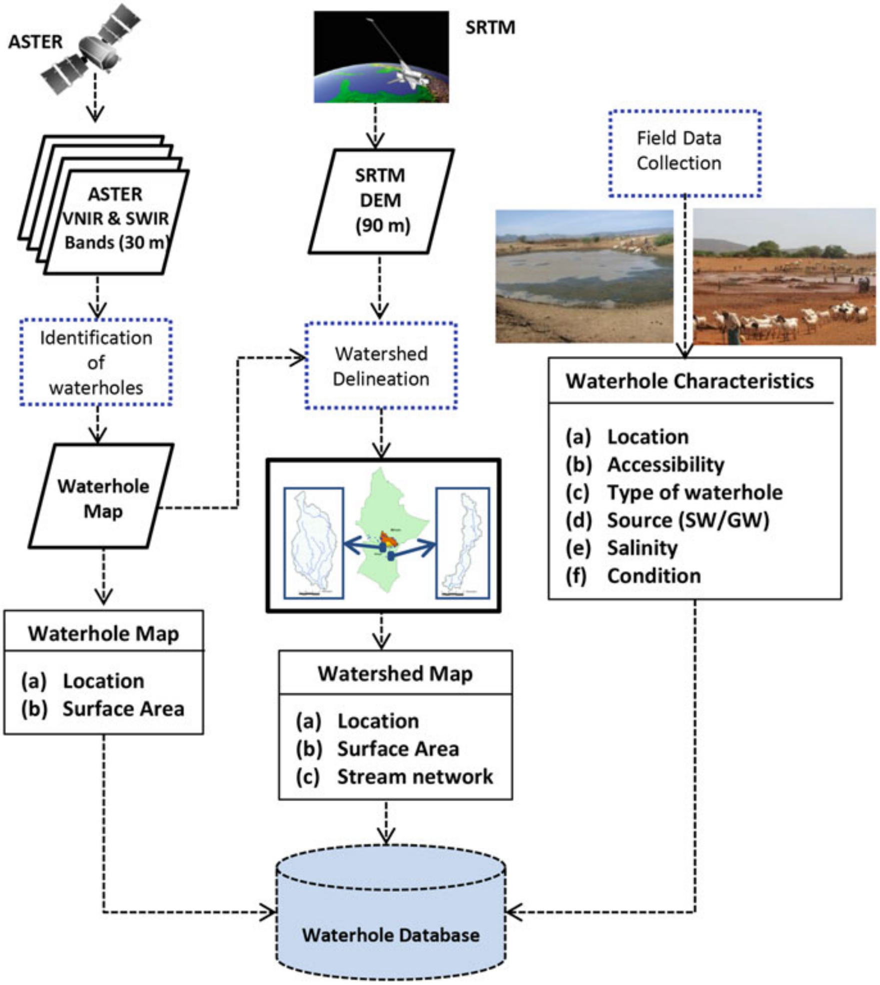


Fig. 5.3 Steps involved in water point identification using ASTER data; watershed delineation using Shuttle Radar Topography Mission (SRTM) digital elevation data and field characterization of water points

imagery. Second, the watershed for each water point is identified using the SRTM DEM. Water point characteristics can be collected through a field campaign.

5.4.1.1 Water Point Identification Using ASTER

Spectral analysis of VNIR and SWIR bands is performed to identify the water point. To delineate surface water bodies from the ASTER imagery, different approaches were adopted to map two kinds of water points (clear-water point and water-like water point) as suggested by Senay et al. (2013). A detailed description of these approaches is provided here.

Identification of Clear-Water Points

The clear-water points are those water bodies that are relatively deep and have good water quality. These water points are seen as dark objects and are distinctly different from other land cover types in an FCC of ASTER imagery. In the case of such clear-water points, Senay et al. (2013) suggested that a simple band ratio (SBR) of near-infrared (NIR) and red would be sufficient to map clear-water points as shown in Eq. 5.1. An SBR value ≤ 1.0 was used to extract clear-water points, whereas a value > 1.0 would be considered a non-water feature:

$$\mathrm{SBR} = \frac{\mathrm{NIR\_Band}}{\mathrm{RED\_Band}} \tag{5.1}$$

where NIR and red bands are band 3 and band 2 from the ASTER data.

Identification of Water-Like Points

On the other hand, water-like points are often small or filled with a lot of sediments, which is a clear evidence of vegetation activity in the water point, often seen as light blue to green shades in the ASTER FCC. To identify and classify water points that were shallow or had poor water quality, different approaches were used. First, the mean absolute deviation (MAD) that uses all the VNIR and SWIR bands was used to identify water-like points. A dynamic threshold was used to identify water-like features. The threshold varied depending on date of image acquisition and geographic location. The MAD is given in Eq. 5.2:

$$\mathrm{MAD} = \frac{1}{N}\sum_{j=1}^{N}\left|x_j - \overline{x}\right| \tag{5.2}$$

where x_j represents ASTER band reflectance value, $\overline{x}$ denotes average value for all bands for a pixel, and N is the total number of bands used.

In regions where the MAD approach was not entirely successful, other well-developed indices for identifying water bodies such as the normalized difference water index (NDWI) and the modified NDWI (MNDWI) were used. NDWI was first introduced by McFeeters (1996) and is expressed as

$$\mathrm{NDWI} = \frac{\mathrm{Green} - \mathrm{NIR}}{\mathrm{Green} + \mathrm{NIR}} \tag{5.3}$$

where Green and NIR bands are bands 2 and 3 of the ASTER imagery. NDWI maximizes reflectance (in green) from a water feature by taking advantage of low reflectance of water in the NIR band. The NDWI band shows water as positive values and other land cover types (vegetation and soil) as negative values. However, water points delineated using NDWI can sometimes be mixed up with surrounding land cover classes especially when surrounding land features have low reflectance in NIR such as either wet soil or built-up land (Xu 2006). Therefore, Xu (1996) proposed the use of MNDWI which can be expressed as

$$\mathrm{MNDWI} = \frac{\mathrm{Green} - \mathrm{MIR}}{\mathrm{Green} + \mathrm{MIR}} \tag{5.4}$$

where Green and MIR (middle infra-red) bands are bands 2 and 5 of the ASTER imagery.

5.4.1.2 Watershed Delineation Using SRTM DEM

The water points identified from the ASTER images were rasterized into 30-m grid cells. These grid cells corresponding to the water points were used as discharge points and catchment for each water point identified were delineated from the SRTM 90-m digital elevation data resampled to 30-m. Other hydrologic parameters such as streams and river networks were also delineated from SRTM digital elevation data.

5.4.1.3 Water Point Characterization

Field characterization of the water point identified from ASTER imagery is important for (a) verification of the water point locations and (b) collection of a number of parameters that are required for modeling water point water levels. Water points were visited during the field campaign and parameters such as accessibility, type of the water point, the source of the water (either surface water or groundwater fed), salinity of the water, usability, and condition of the water point were collected. This information also identified water points that are not accessible, not usable, and difficult to model. Such water points were eliminated from further analysis and modeling. A field campaign was carried out over the East African study site during August 2007. Hand-held global positioning system (GPS) units were used for the verification of the location of the water points identified.

5.4.2 Runoff Modeling

Both the study areas in East Africa and Mali are characterized by sparse vegetation and dry conditions. Most of the rainfall is either infiltrated or lost due to evaporation, which is common in arid and semiarid regions (Xu and Singh 2004). Because of the arid to semiarid nature of the study sites, a small portion of the rainfall over the catchment is converted to surface runoff and it finally reaches the water bodies. In this study, surface runoff was estimated according to the runoff model setup suggested by Senay et al. (2013). The runoff is estimated from the Soil Conservation Service (SCS) curve number procedure (SCS 1972). Senay and Verdin (2004) generated gridded annual runoff estimates for Africa at a 10-km spatial resolution. The annual runoff coefficients were summarized for the study area and were found to vary from 0.02 to

0.1 with an average coefficient of 0.05. In this study, the average runoff coefficient in combination with TRMM rainfall to estimate catchment runoff contribution was used. The volume runoff contribution to each water point was estimated as

$$R_v = c \times P \times WA \tag{5.5}$$

where R_v is the volume runoff contribution (m^3), c represents the rainfall–runoff coefficient for each water point ($c = 0.05$), P is the spatial mean TRMM rainfall received over the contributing area or the watershed of the water point, and *WA* is the surface area of the watershed (in m^2). According to Senay et al. (2013), the use of a uniform runoff coefficient makes the modeling approach simple and easy to model especially considering the objective of this study and homogeneous and dry landscape; the use of a constant runoff coefficient produces runoff estimates with a reliable precision. Furthermore, the objective of this study is to model the variability in the water levels in the surface water point over Africa. Then, runoff contribution to each water point in depth is estimated as

$$R_d = \frac{R_v}{\mathrm{WPA}} \tag{5.6}$$

where R_d is the runoff depth (m) and *WPA* is water point area (m^2).

5.4.3 Modeling Evaporation Losses from the Water Point

GDAS ETo is the sum of evaporation from the soil surface and transpiration from a standardized reference clipped grass surface fully covering the ground (Allen et al. 1998). However, evaporation from open water bodies (E) in small water points and shallow ponds is generally slightly higher than the reference *ETo* (m) and, hence, can be represented by evapotranspiration fraction (ETf) value of 1.05 (Allen et al. 1998). Therefore, over-the-water-point evaporation is estimated as

$$E = 1.05 \times ETo \tag{5.7}$$

where E is the over-the-water-point evaporation losses (m).

5.5 Modeling Water Point Water Depths Using Water Balance Approach

Generally, water levels can be modeled using a water balance approach Velpuri et al. (2012); Senay et al. (2013) as

$$\Delta D = P + R_{\mathrm{in}} + G_{\mathrm{in}} - E - R_{\mathrm{out}} - G_{\mathrm{out}} - S \tag{5.8}$$

where P is the direct rainfall (m) into the water point; R_{in} is the runoff contribution or inflows (m) into the water point, G_{in} is the groundwater influx (m), E is the over-the-water-point evaporation (m), R_{out} is the outflow (m) from the water point, G_{out} is the groundwater outflow (m), and S represents seepage losses (m) from the water point. The precision of modeled water levels using this approach depends on the accuracy of each parameter in Eq. 5.8. However, the water points considered in this study are located in remote areas where ground truth data on these parameters are mostly unavailable. Remote sensing satellites offer a reliable estimate of some hydrologic variables required to water balance modeling of surface water points in remote areas. As modeling groundwater fluxes (G_{in} and G_{out}) is a challenging task using remote sensing data (Velpuri et al. 2012), we excluded water points where groundwater fluxes were dominant. Furthermore, R_{out} can be ignored as many of the water points identified in the two study sites do not have substantial outflows (as they were not part of the main stream or river system). Hence, Eq. 5.8 was simplified as

$$\Delta d = P + R_{\text{in}} - E - S \tag{5.9}$$

A constant seepage (S) value of 0.002 m per day was used Senay et al. (2013). Once the change in water level for each day was estimated, the water level for each water point was estimated daily as:

$$L_i = L_{i-1} + \Delta d_i \tag{5.10}$$

where L is the water level in the water point and subscripts i and i–1 denote the current and previous time step, respectively. Water level was set to zero when L was found to be negative.

Since the objective of the study reported in this chapter was to present an approach to monitor the patterns and variations in water points rather than the absolute levels, modeled water level data for each water point were converted to scaled depth (L_s) from 0 to 100, where 0 denotes minimum depth and 100 denotes the maximum depth of the water point:

$$L_s = \frac{L_i}{L_{\max}} \times 100 \tag{5.11}$$

where L_i represents the current depth and $L_{\max}$ the maximum depth; values for each water pointwere obtained from the modeled water levels over 1998–2011. The $L_{\max}$ values were up to 3 m for East African water points and up to 2 m in Mali.

The model (Eqs. 5.5–5.11) was run since January 1, 1998, and daily information on the variations in the water point water levels was estimated. Considering the fact that most of the water points are seasonal and since January is a dry month in both the study sites, the initial water level was assumed to be zero.

5.5.1 Validation of Water Point Water Levels

Modeled water point water levels were validated using ground truth water level data. As water points in East Africa and Mali are unmonitored and ungauged, in situ observations of the water levels were collected. Due to accessibility and other logistical

Fig. 5.4 Staff gauge installation efforts carried out in some of the Kenyan water points

reasons, only a few water points were selected in Ethiopia and Kenya for collecting in situ data. A total of eight water points in Kenya and seven in Ethiopia were chosen for staff gauge installation and data collection. Staff gauges were installed with the help of the International Livestock Research Institute in Kenya and Oromiya Agricultural Research Institute (OARI) in Ethiopia. However, monitoring efforts at five water points in Kenya and two in Ethiopia were abandoned as these gauges were removed or vandalized, leaving only three water points in Kenya and five in Ethiopia for in situ monitoring. Data on the water levels from these water points were collected on a weekly to monthly basis. Figure 5.4 shows gauge installation activities in the Kenyan water points. Comparison and validation of modeled water point water levels were performed using the in situ data from three Kenyan and five Ethiopian water points. To compare the trends with the modeled scaled depths, in situ observations were converted to scaled depths using Eq. 5.11. Data used for each water point for validation are shown in Table 5.3. Due to instability in Mali and other safety reasons, validation data were not collected. Thus, the validation exercise was limited to some Kenyan and Ethiopian water points.

5.5.2 Condition of the Waterpoint

The main goal of this research is to provide information on the seasonal patterns and variations of the water point water levels so that NGOs, governmental organizations,

Table 5.3 Description of field-installed gauge data for the water points used for validation of modeled water levels in the East African study

ID	Water point	Lat	Long	Local name	Data used for validation	
					From	To
58	KEN-14	E 38.7441	N 3.5079	Dabala Fachana	Apr 2009	July 2010
59	KEN-15	E 39.0640	N 3.4815	Holale	Apr 2009	July 2010
82	KEN-36	E 40.8705	N 3.9013	Olla	Dec 2009	Aug 2010
23	ETH-03	E 38.7509	N 3.7437	Wirwita	Jan 2010	Aug 2010
45	ETH-05	E 38.8434	N 3.6409	Dembi Korba	Sept 2008	Aug 2010
5	ETH-13	E 38.2019	N 5.0018	Beke	Sept 2008	Aug 2010
19	ETH-26	E 38.4010	N 4.1402	Dimtu	Jan 2010	Aug 2010
22	ETH-29	E 38.4471	N 3.9814	Jilo Dokicha	Jan 2010	Aug 2010

and other stakeholders can use the information for early warning and decision making and to build resilience to climate change. To provide information on the general condition of the water availability in the region, water points were classified into four categories based on their current condition as *Good*, *Watch, Alert*, and *Near-Dry*.

A water point is said to be in *Good* condition when the mean scaled depth over the previous 10 days is greater than the long-term median depth. A water point is in a *Watch* condition when the scale depth over the previous 10 days is between 50 % and 100 % of the long-term median depth. An *Alert* condition means that the scaled depth over the previous 10 days is between 3 % and 50 % of the long-term median depth. A water point is *Near-Dry* when the scaled depth over the previous 10 days is less than 3 % of the median depth. A long-term median water level for each water point was computed using data from 1998 to 2011. Information on the water point condition is easy to understand and would enable stakeholders to identify the general trend in water levels in the region and would aid in early warning and decision making for livestock movement and government intervention.

5.6 Results and Discussion

5.6.1 Water Point Identified from ASTER Imagery

Water points in the East African study were identified using two indices (SBR and MAD). Figure 5.1 shows the spatial distribution of 90 water points identified from ASTER imagery. Out of the 90 water points, 47 clear-water points were identified using the SBR, and 43 water-like points were identified using the MAD. Surface area of each water point was extracted and found to vary from less than a hectare (ETH-50) to 150 ha (ETH-40). The area of the catchments for these water points delineated using SRTM varied from 2 (ETH-46) to 28900 ha (ETH-13) with a mean of 2900 ha. With respect to geographic location, 52 of those water points were identified in Ethiopia, 36 in Kenya, and 2 in South Sudan.

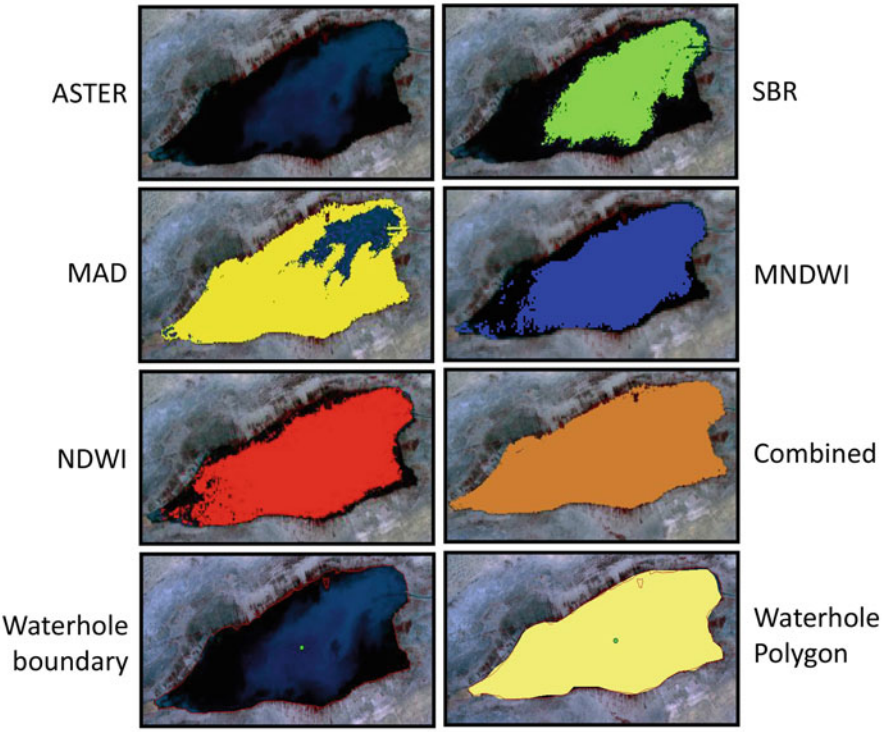


Fig. 5.5 Demonstration of a combination approach used to identify water points using ASTER imagery in Mali region

Though two band indices (SBR and MAD) were able to identify location of the water points, they were not able to extract the total surface area of the water points. The reasons for this were (a) water quality was different within the water point, and (b) spectral mixing of portions of the water points with surrounding land pixels. In order to delineate total surface area accurately, NDWI and MNDWI were used. However, none of the individual band indices were able to delineate the total surface area of the water points. Hence, a combination approach (adding the pixels identified as water by all the approaches) from all the water points was adopted (Fig. 5.5).

5.6.2 *Characteristics of East African Water Points*

A total of 66 water points were visited during the field campaign. However, 2 water points in Sudan and 22 in Ethiopia were not visited due to inaccessibility and security reasons. During the field campaign, the locations of the water points identified from ASTER were verified using handheld GPS units. Except for three water points in Kenya, the locations of all the water points were verified. Information on general

Table 5.4 Characteristics of water points identified using ASTER imagery

No	Water point characteristic	No. of water points	
		Kenya	Ethiopia
1	No of water points visited	36 (100 %)	30 (58 %)
2	Error in mapping water points	3 (9 %)	0 (0 %)
3	Dams/earthen dams	8 (23 %)	20 (67 %)
4	Ponds/pans	26 (76 %)	14 (33 %)
5	Dry at time of visit	14 (41 %)	17 (57 %)
6	Recharged from groundwater	11 (32 %)	0 (0 %)
7	Saline	6 (18 %)	0 (0 %)
8	Water for human + livestock use	26 (76 %)	50 (97 %)
9	Water point used only by wildlife	11 (32 %)	2 (3 %)
10	Deteriorating condition	13 (38 %)	47 (90 %)

hydrology, physical properties, and usability of water points was also gathered. Based on the information collected, 11 water points in Kenya had major contribution to and from the groundwater systems. A total of 40 water points (13 in Kenya and 27 in Ethiopia) were found to have very poor water quality. Six water points were classified as saline and undrinkable. Information on other characteristics of water points gathered during the field campaign is shown in Table 5.4. Based on the information gathered, 41 water points identified as useful were chosen for modeling and monitoring. Characterization of West African water points was not performed due to instability and insecurity issues in Mali.

5.6.3 Water Point Water Levels

Water point water levels were modeled using Eqs. 5.5–5.11. The model was run daily on the selected set of 41 water points in the East African study and on all 101 water points in the Mali region from January 1, 1998. Information on direct precipitation, evaporation, and scaled depth and condition of each water point were produced. Figure 5.6a, b illustrates the dynamics of the water point water levels modeled in the East African and Mali studies.

5.6.4 Validation of Results

Results of the validation performed on eight water points (three Kenyan and five Ethiopian) are shown in Fig. 5.7. Validation results indicate that the modeled water levels reasonably matched the field-installed gauge measurements in patterns and variations, with some differences in magnitude. To estimate model accuracy, a simple Pearson's correlation coefficient and root mean squared error (RMSE) were estimated for each of the eight validated water points. When compared to the in situ observations, correlation coefficients for the eight water points ranged from 0.18 to

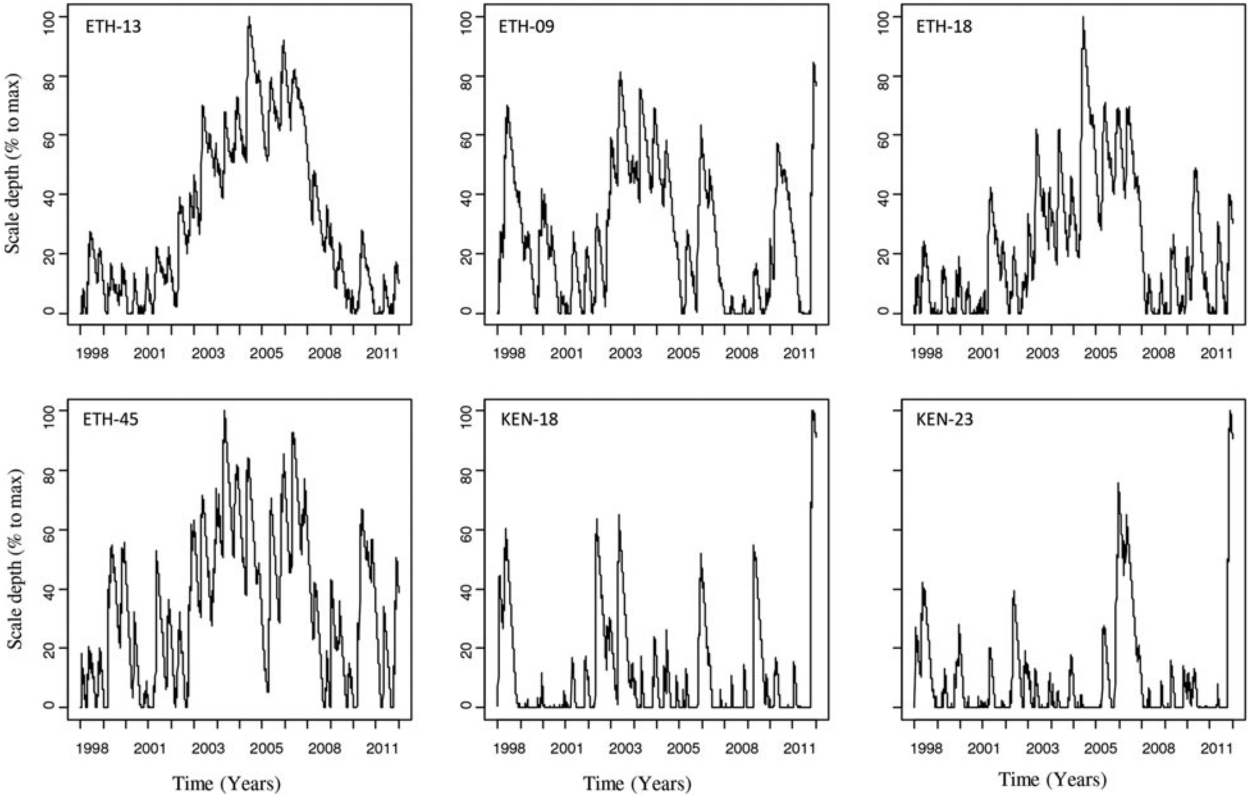


Fig. 5.6 Illustration of the modeled scaled water depths (Jan 01, 1998, till the end of 2011). **a** East African water points. **b** Mali water points

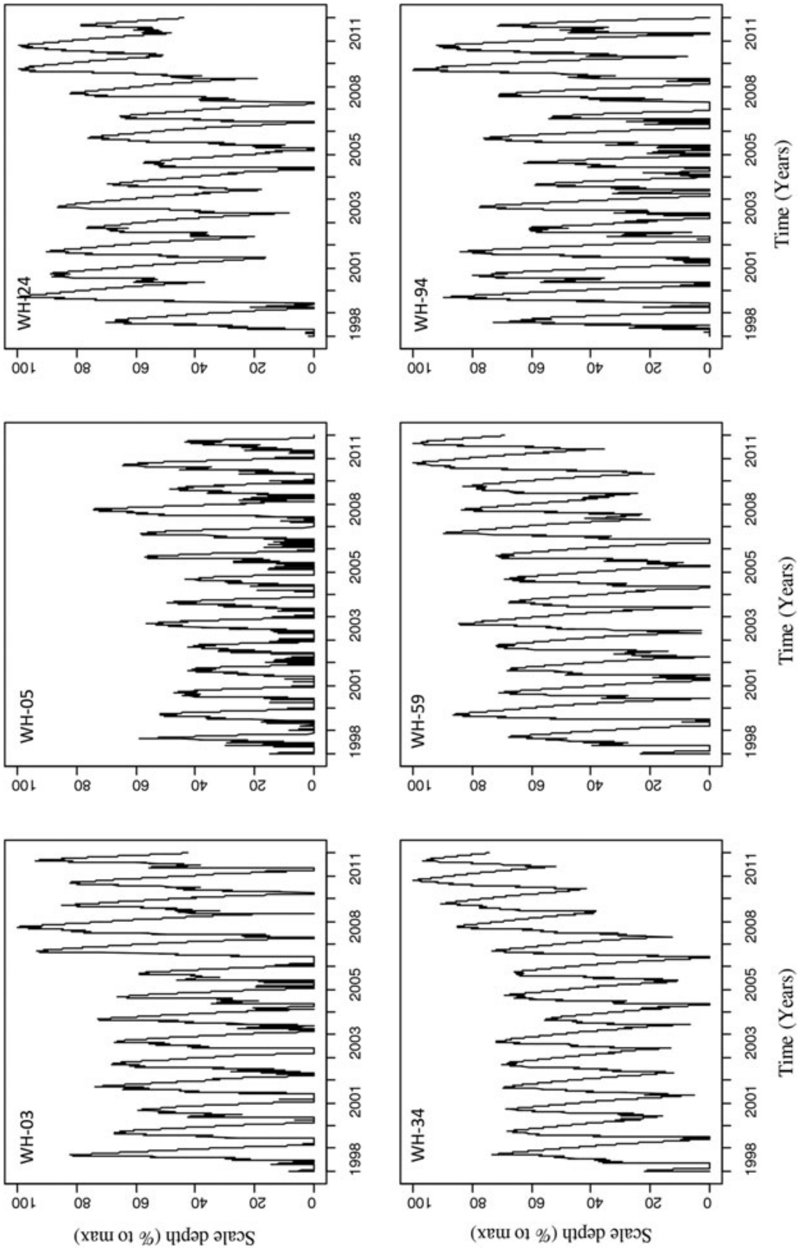


Fig. 5.6 (continued)

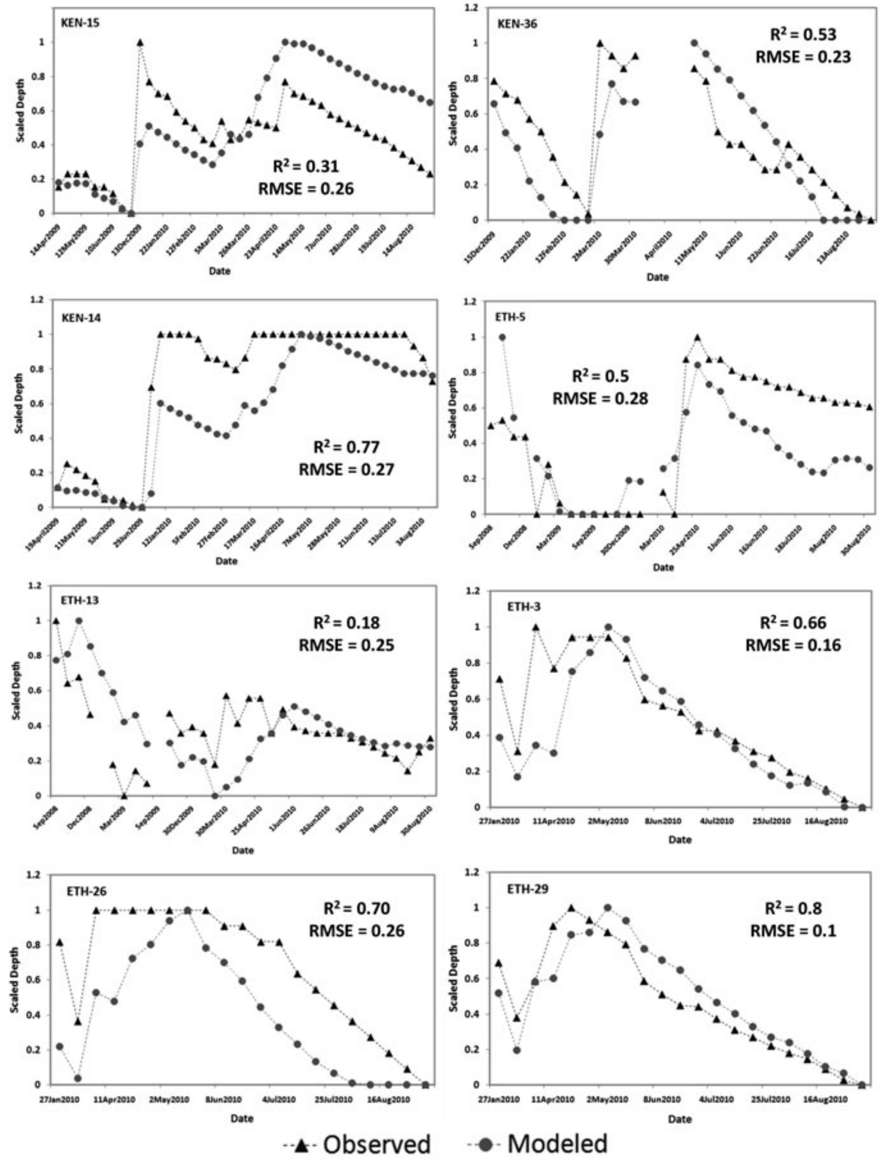
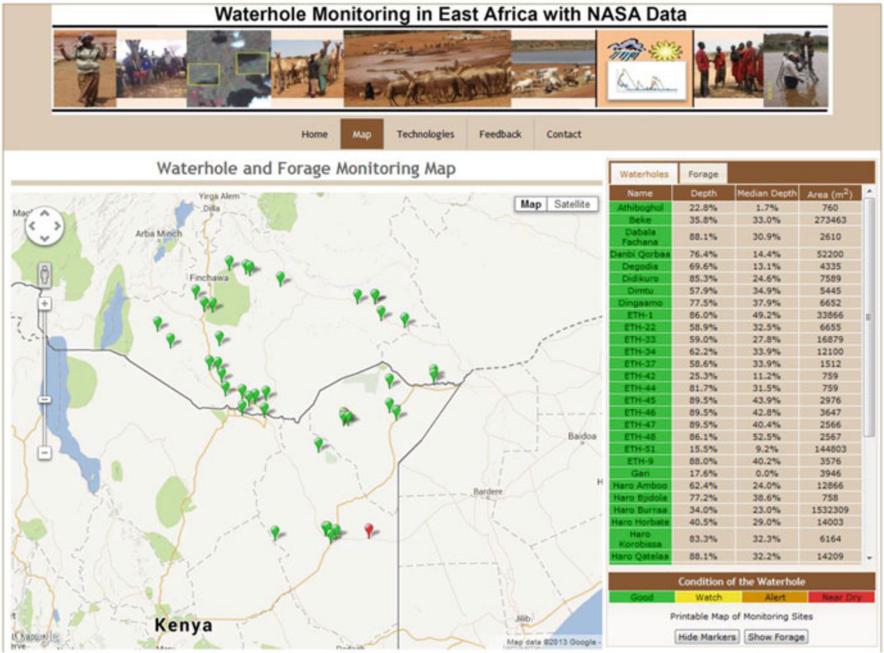


Fig. 5.7 Validation of modeled water point water levels using gauge data for various water points

0.8. RMSE values (on a scale of 0–1) were estimated and found to range from 0.1 to 0.28 with a mean RMSE of 0.22. A major source of error was the difference in magnitude, which can be attributed to the model simplicity. However, the model was found to capture the general direction or trend in water level variations. Such information is sufficient for most drought monitoring or flood monitoring programs



Name	Depth	Median Depth	Area (m^2)
Athiboghol	22.8%	1.7%	760
Beke	35.8%	33.0%	273463
Dabala Fachana	88.1%	30.9%	2610
Danbi Qorbaa	76.4%	14.4%	52200
Degodia	69.6%	13.1%	4335
Didikuro	85.3%	24.6%	7589
Dimtu	57.9%	34.9%	5445
Dingaamo	77.5%	37.9%	6652
ETH-1	86.0%	49.2%	33866
ETH-22	58.9%	32.5%	6655
ETH-33	59.0%	27.8%	16879
ETH-34	62.2%	33.9%	12100
ETH-37	58.6%	33.9%	1512
ETH-42	25.3%	11.2%	759
ETH-44	81.7%	31.5%	759
ETH-45	89.5%	43.9%	2976
ETH-46	89.5%	42.8%	3647
ETH-47	89.5%	40.4%	2566
ETH-48	86.1%	52.5%	2567
ETH-51	15.5%	9.2%	144803
ETH-9	88.0%	40.2%	3576
Gari	17.6%	0.0%	3946
Haro Amboo	62.4%	24.0%	12866
Haro Bjidola	77.2%	38.6%	758
Haro Burraa	34.0%	23.0%	1532309
Haro Horbate	40.5%	29.0%	14003
Haro Korobissa	83.3%	32.3%	6164
Haro Qatelaa	88.1%	32.2%	14209

Fig. 5.8 The condition of the water points is denoted by the color of the balloons (as of June 30, 2013). *Green* means *Good*; *yellow* means *Watch*; *brown* means *Alert*; and *red* means *Near-Dry*. The data are currently disseminated daily from http://watermon.tamu.edu/

and provides basic information on the condition of water resources in the changing world.

5.6.5 Dissemination

Information on the direct precipitation, evaporation losses, scaled depth, and the condition (Good, Watch, Alert, and Near-Dry) of the 41 selected water points in Ethiopia and Kenya are currently being made available through a dedicated website (http://watermon.tamu.edu). Figure 5.8 shows the online view of the water monitoring website illustrating the location, distribution, and condition of the water points as of June 30, 2013. Users can also access and visualize data since January 1998 for every water point. Figure 5.9 illustrates that the scaled water level is well above the long-term median by the end of June 2013, in the case of the Danbi Qorbaa water point located in Ethiopia. Figure 5.9 also shows online visualization and plotting options. The information is updated on the website in near-real time with a 2-day delay due to the availability of input datasets required (rainfall and ETo data).

Fig. 5.9 Current information on the scaled water levels for Danbi Qorbaa (ETH-30) as shown on http://watermon.tamu.edu. The *green* line indicates scaled depth and the dashed *orange* line indicates long-term median depth

5.6.6 Uncertainty in Modeled Scaled Water Levels

Senay et al. (2013) presented a review of uncertainties in the modeling approach used in this study. Major uncertainties in the modeling approach presented in this study can be attributed to the uncertainties in satellite rainfall, modeled water point runoff, and evaporation losses from the water point. Satellite rainfall can have uncertainties up to 50 % (Huffman 1995; Joyce et al. 2004; Crow and Ryu 2009). Similarly, modeled ETo dataset can have uncertainty up to 15–30 % (Kalma et al. 2008; Senay et al. 2008; Velpuri et al. 2013). Furthermore, even though the relationship between rainfall and runoff is not linear from individual storms, considering the homogeneous land cover and the arid nature of the catchments, the assumption of a constant rainfall–runoff coefficient can lead to uncertainty in modeled runoff. Apart from the satellite data, other sources of errors such as measurement errors (from staff gauges installed in some of the water points), substantial seepage losses from the water points, assumption of rectangular cross section of the water points, and errors due to substantial water abstraction by livestock and humans could also result in additional errors.

In spite of these sources of errors, the multisource satellite data approach presented in this study can be used to monitor relative patterns and variations in water levels as opposed to absolute depths (Senay et al. 2013). This approach provides general information on water availability in near-real time, which otherwise is limited in the remote pastoral regions. Particularly, the use of scaled depths minimizes the negative impact of bias errors from input data (errors in satellite derived precipitation or modeled ETo data) and model parameterizations are largely eliminated, making it useful for drought monitoring and early warning applications.

5.6.7 Further Research

Monitoring studies in East and West Africa demonstrate the application of the multisource satellite data integration approach for monitoring water point water levels in the remote regions of Africa. Further research includes expansion of the monitoring network across Africa. This would cover several hundred water points (small to medium sized) covering most of the sub-Saharan African countries. Some of the existing Food and Agriculture Organization (FAO)'s water point database (such as surface water body dataset (SWBD) derived from SRTM elevation or the water bodies Africa dataset generated from National Gazetteers) would be used as reference datasets to identify the water points to be modeled and monitored. Surface areas would be delineated using satellite data such as ASTER or Landsat depending on the availability of data. Modeling setup developed by Senay et al. (2013) and steps illustrated in this chapter would be implemented to generate information on the condition of water points across Africa.

Several improvements in model parameterization would be made for reducing the uncertainty in modeled scaled water levels. Some of the improvements would include (a) use of high-resolution satellite-based precipitation estimates such as 10 km resolution rainfall estimates for Africa (RFE data), (b) calibration of ETo data to account for uncertainties (negative bias) in GDAS ETo, (c) incorporation of water point bathymetry profiles to build depth–area–volume relationship, an improvement over the assumption of rectangular cross section of the water points, and (d) modeling incoming runoff contribution to the water point using hydrologic modeling approach rather than a simple rainfall–runoff coefficient.

5.6.8 Water Point Monitoring Network Support to FEWS NET

The goal of the FEWS NET program is to lower the incidence of drought- or flood-induced famine by providing to farmers and decision makers, timely and accurate information regarding potential food-insecure conditions. A water point monitoring network would help FEWS NET by providing near real-time information on the availability and condition of water point water levels in the remote regions of the world. Such information can help NGOs, governmental organizations, or communities relying heavily on changing water resources in early warning and decision making.

5.6.9 Additional Benefits of Operational Monitoring of Water Points

The Intergovernmental Panel on Climate Change (IPCC) report found that by 2020, climate change will expose an additional 75–250 million people in Africa to water shortages (IPCC 2007). Many developing countries are also located in regions around the globe that will be strongly impacted by climate change. Furthermore, these developing countries tend to lack the resources to implement adaptation measures or to build resilience by, for example, diversifying livelihoods that are heavily dependent on agriculture and water resources. Operational monitoring of water points and providing information on the condition of water resources would benefit in following ways:

Water Security Climate change is predicted to modify rainfall patterns substantially over the African continent (IPCC, 2007). While some regions may become more drought prone, others may receive more intense rainfall. These changes are likely to lead to an overall reduction in water supply. In regions where water resources are sparse and rainfall is highly variable, information on the availability of water in remote water points will become an important adaptation measure and a first step towards building resilience to climate change.

Food and Livelihood Security Knowledge of water availability will secure food and livestock production. This is especially true in pastoral regions of Africa, where nomadic pastoral communities wander from region to region in search of water and forage. Furthermore, prior knowledge of depleting water resources and availability over large areas would provide pastoralists some lead time to respond and alter their strategies such as livestock migration or diversify their livelihood to ensure food security.

Indicator of Ecosystem Performance Haas et al. (2011) indicated that surface water extent or water level in surface water bodies can act as an indicator of short-term changes in ecohydrological processes in sub-Saharan Africa. Their study in Mali and Burkina Faso suggested that vegetation cover is positively related to the amount of available surface water for those catchments that are mainly covered by annual plants. Hence, information on the condition of the water points in a region could provide useful insights on the overall indicator of ecosystem performance.

Conflict Reduction Most of the time, sparse water resources result in the congregation of several communities towards more reliable and perennial sources of water, leading to competition and conflicts Senay et al. (2013). Information on the availability of water not only would be useful for pastoralists to make decisions on livestock migration in search of forage and water, but also for NGOs and other government agencies in early warning and decision making.

5.7 Conclusions

Given humankind's dependence on freshwater, one would expect the information needed to wisely manage this important resource to be widely and readily available (Vörösmarty et al. 2005). Yet, our knowledge on the availability, trends, and patterns of the water levels in surface water resources is only limited to large rivers and lakes. Surprisingly, knowledge of surface water resource fluctuations in the rural and remote regions of Africa is very limited. Monitoring of such rural and remote surface water resources is important for the regional and national governments in planning for droughts and floods and in building resilience to adapt to climate change.

The main objective of this research was to provide useful information on the condition of water points located in the remote regions of Africa. This study demonstrated that the application of a methodology that integrates high spatial resolution satellite data (30-m ASTER and 90-m SRTM DEM) with coarse, globally available, satellite-driven datasets (25-km TRMM and 100-km GDAS ETo) for operational modeling of the condition of water points. Validation of modeled scaled depths with field-installed gauge data demonstrated the ability of the model to capture both the spatial patterns and seasonal variations. Modeled scaled estimates captured up to 60 % of the observed gauge variability with a mean RMSE of 22 %.

Up-to-date information and historical data (since 1998) on daily rainfall, evaporation, scaled depth, and condition of each water point in East Africa are currently being disseminated in near-real time via the Internet (http://watermon.tamu.edu). Information on the condition of water points and data over the entire sub-Saharan Africa will be soon made available through a dedicated FEWS NET website.

The fact that water points in the remote areas of Africa can be monitored in near-real time, at low cost, at a regional to continental scale, with reasonable accuracy makes it possible to provide useful information to the government and NGOs to build resilience to adapt to climate change. This chapter highlights potential benefits of such monitoring in building resilience to adaptation to climate change such as providing water security, and food and livelihood security, which are indicators of ecosystem and conflict resolution.

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Chapter 6
Surface Water and Groundwater Resources of Ethiopia: Potentials and Challenges of Water Resources Development

Belete Berhanu, Yilma Seleshi and Assefa M. Melesse

Abstract Ethiopia has a complex topography, diversified climate, and immense water resources. The spatiotemporal variability of the water resources is characterized by multi-weather systems rainfall of the country. Most of the river courses become full and flood their surroundings during the three main rainy months (June–August). West-flowing rivers (Abay, Baro-Akobo, Omo-Gibe, and Tekeze) receive much rainfall unlike the northeast- (Awash) and east-flowing rivers (Wabishebele and Genale-Dawa) which receive normal to low rainfall. Although it needs further detailed investigation, according to the current knowledge, the country has about 124.4 billion cubic meter (BCM) river water, 70 BCM lake water, and 30 BCM groundwater resources. It has a potential to develop 3.8 million ha of irrigation and 45,000 MW hydropower production. This chapter discusses and presents the water resources of Ethiopia and the different challenges faced by the water sector to contribute to the economic development.

Keywords Ethiopia · Surface water · Groundwater · Irrigation · Hydropower

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6.1 Introduction

Ethiopia, with a total area of approximately 1.13 million km^2, is a country that is characterized by a topography that consists of a complex blend of massive highlands, rugged terrain, and low plains. The Great Rift Valley of the eastern Africa divides the country into two plateaus and stretches from north–east to south–west with 40–60 km wide flat-lying plain in the east, south, and west borders of the country that has an elevation of around 600 m above mean sea level (amsl). It creates three major relief regions in the country: the Western Highlands, the Eastern Highlands, and the low-lying Rift Valley and Western Lowlands. The elevation also ranges between two extremes from 125 m below mean sea level at Danakil Depression to 4,620 m amsl at Ras Dejen (Dashen) peak.

Ethiopia has a diversified climate ranging from semi-arid desert type in the lowlands to humid and warm (temperate) type in the southwest (Beyene 2010). Hurni (1982), Osman (2001), and Seleshi and Demaree (1995) also described high inter- and intra-annual rainfall variability in Ethiopia. The mean annual rainfall of Ethiopia ranges from 141 mm in the arid area of eastern and northeastern borders of the country to 2,275 mm in the southwestern highlands (Berhanu et al. 2013). The complex topographical and geographical features of the country have a strong impact on these spatial variations of climate and different rainfall regimes in Ethiopia (National Meteorology Service Agency 1996; Zeleke et al. 2013).

Ethiopia is also endowed with a substantial amount of water resources. The country is divided into 12 basins; 8 of which are river basins; 1 lake basin; and remaining 3 are dry basins, with no or insignificant flow out of the drainage system. Almost all of the basins radiate from the central plateau of the country that separate into two due to the Rift Valley. Basins drained by rivers originating from the mountains west of the Rift Valley flow toward the west into the Nile River basin system, and those originating from the Eastern Highlands flow toward the east into the Republic of Somalia. Rivers draining in the Rift Valley originate from the adjoining highlands and flow north and south of the uplift in the center of the Ethiopian Rift Valley.

Since almost all river basins originate from the highlands and high rainfall areas, they have huge amount of surface water running in the river basin systems and Ethiopia is considered to be the water tower of the Horn of Africa. This potential is not fully utilized and translated into development because of many factors including limited financial resources, technical challenges, and lack of good governance in the water sector. This chapter attempts to review the potential of the surface water and groundwater resources of the country, and the opportunities and challenges of the water sector development.

6.2 Climate of Ethiopia

The climate in Ethiopia is geographically quite diverse, due to its equatorial positioning and varied topography (Block 2008). The climatic condition of the country is traditionally classified into five climatic zones based on the altitude and temperature variation. It ranges from the high cold area named as “wurch” to the highly hot

Table 6.1 Traditional climatic zones of Ethiopia and their physical characteristics. (Source: NRMRD-MoA 1998)

Zones	Altitude (m) (NRMRD-MoA 1998)	Mean annual rainfall (mm) (NRMRD-MoA 1998)	Length of growing periods (days) (NRMRD-MoA 1998)	Mean annual temperature (°C) (NRMRD-MoA 1998)	Area share (%)
Wurich (cold to moist)	> 3,200	900–2,200	211–365	Below 11.5	0.98
Dega (cool to humid)	2,300–3,200	900–1,200	121–210	11.5–17.5	9.94
Weynadega (cool sub humid)	1,500–2300	800–1,200	91–120	17.5–20.0	26.75
Kola (Warm semiarid)	500–1,500	200–800	46–90	20.0–27.5	52.94
Berha (Hot arid)	< 500	Below 200	0–45	Above 27.5	9.39

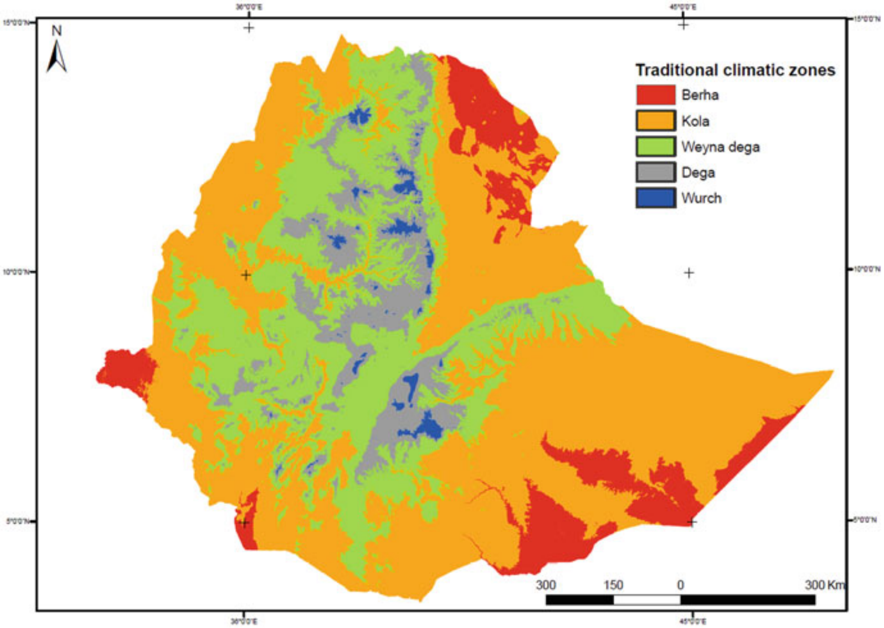

Fig. 6.1 Traditional climatic zones of Ethiopia

climatic condition area known as "Berha." Their physical characteristics and spatial distribution are presented in Table 6.1 and Fig. 6.1.

The climate of the country is described by the statistical interpretation of precipitation and temperature data recorded over a long period of time. As it is described on the

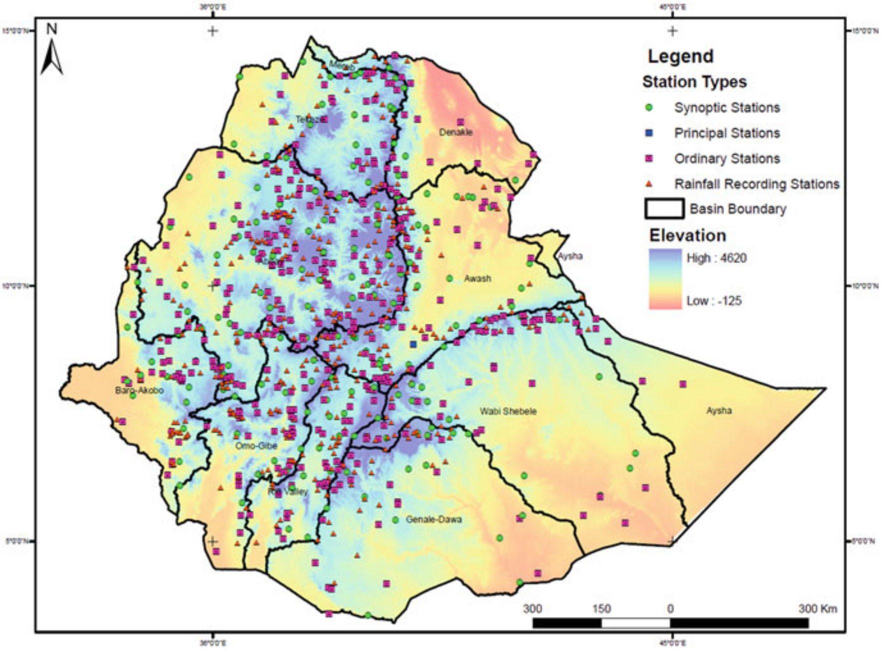

Fig. 6.2 Meteorological station distribution and types per basin and elevation variation in Ethiopia

web site of the National Meteorological Agency of Ethiopia (http://www.ethiomet.gov.et), there are a total of 919 active meteorological stations in the country (NMA 2013). These stations are classified into four classes according to the standard classification of the World Meteorological Organization (WMO). About 171 of them are synoptic and principal stations that have observations for most of the climatic elements, 363 stations are ordinary stations that have precipitation and temperature data only, and the remaining 385 stations only have rain gauge to measure the daily accumulated rainfall. Figure 6.2 shows the meteorological station distribution and types in Ethiopia.

6.3 Rainfall in Ethiopia

Rainfall in Ethiopia is the result of multi-weather systems that include Subtropical Jet (STJ), Intertropical Convergence Zone (ITCZ), Red Sea Convergence Zone (RSCZ), Tropical Easterly Jet (TEJ), and Somali Jet (NMA 1996). The intensity, position, and direction of these weather systems lead the variability of the amount and distribution of rainfall in the country. Thus, the rainfall in the country is characterized by seasonal and interannual variability (Camberlin 1997; Shanko and Camberlin 1998; Conway 2000; Seleshi and Zanke 2004). Moreover, the spatial distribution of rainfall in Ethiopia is significantly influenced by topographical variability of the country (NMA 1996; Camberlin 1997). This makes the rainfall system of the country more complex.

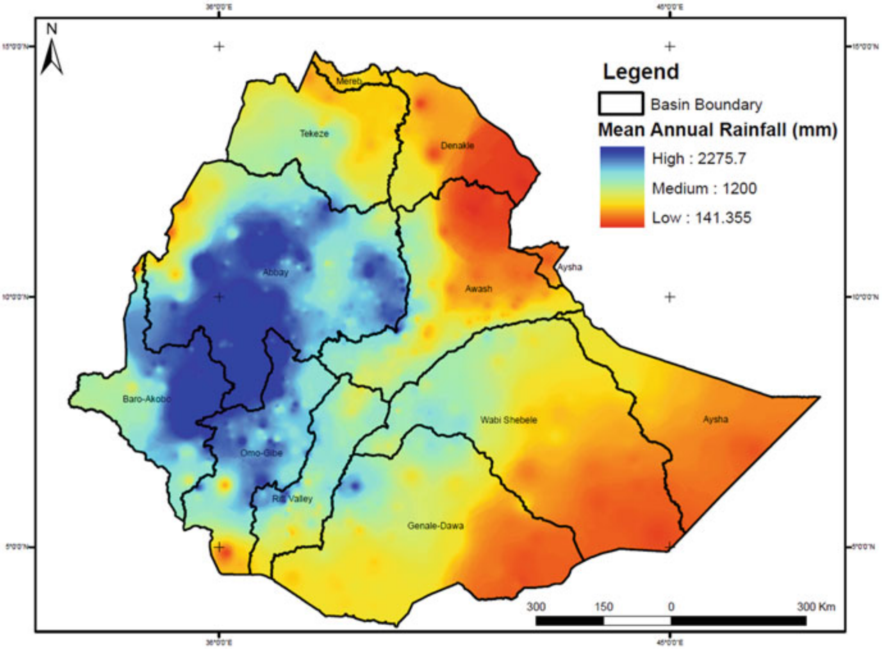

Fig. 6.3 Spatial variability of the mean annual rainfall in Ethiopia

6.3.1 *Spatial Variability of Rainfall*

The regional and global change of the weather systems and the topographic variation along with the seasonal cycles are responsible for the spatial variability of rainfall in the country. The magnitude of the mean annual rainfall in the southeast, east, and northeast borders of the country is lower by as much as less than 200 mm. The central and western highlands of the country receive an annual mean rainfall of more than 1,200 mm. Looking into the rainfall variability of the country by river basins, the eastern flowing river basins (Wabishebele and Genale-Dawa) receive low to medium rainfall, whereas those that flow to the west (Abay, Baro-Akobo, Omo-Gibe, and Tekeze) receive a mean annual rainfall in the range of medium to high (Fig. 6.3).

6.3.2 *Temporal/Seasonal Rainfall Variability*

Seasonal rainfall in Ethiopia is driven mainly by the migration of the ITCZ, tropical upper easterlies, and local convergence in the Red Sea coastal region (Conway 2000). The exact position of the ITCZ changes over the course of the year, oscillating across the equator from its northernmost position over northern Ethiopia in July and August, to its southernmost position over southern Kenya in January and February

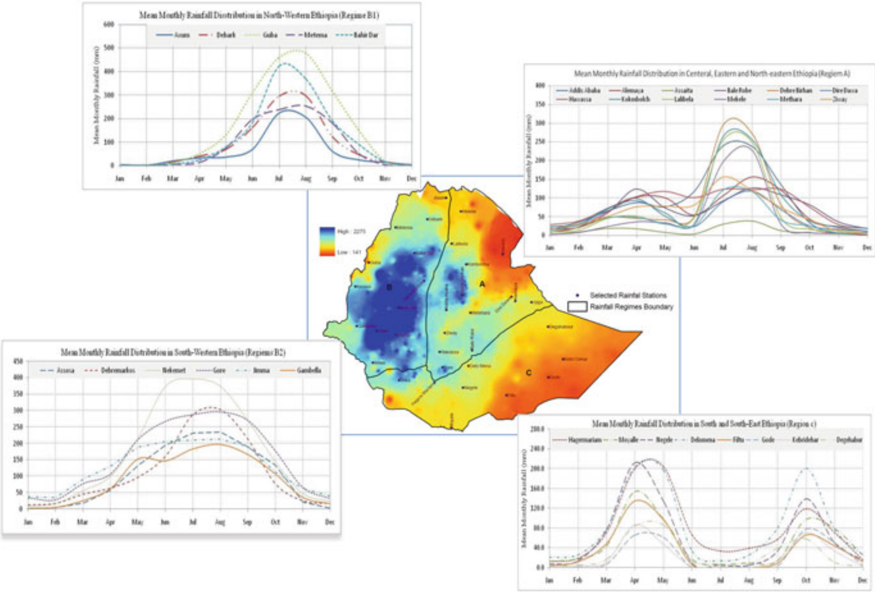

Fig. 6.4 Seasonal rainfall distribution in Ethiopia

lead the interannual variability of rainfall in the country (McSweeney et al. 2012). The complex topographical variations of the country are also responsible for this seasonal variation rainfall in the country (Abebe 2010).

Most of the area in Ethiopia receives one main wet season (called "Kiremt") from mid-June to mid-September (up to 350 mm per month in the wettest regions), when the ITCZ is at its northernmost position (McSweeney et al. 2012). Parts of northern and central Ethiopia also have a secondary wet season of erratic, and considerably lesser, rainfall from February to May (called the "Belg"). The southern regions of Ethiopia experience two distinct wet seasons, which occur as the ITCZ passes through this to its southern position. The March to May "Belg" season is the main rainfall season yielding 100–200 mm of rainfall per month, followed by a lesser rainfall season in October to December called "Bega" (around 100 mm of rainfall per month). The easternmost corner of Ethiopia receives very little rainfall at any time of the year (McSweeney et al. 2012). These unimodal and bimodal rainfall systems are the base for classifying the country into three rainfall regimes (Dawit 2010). Commonly, these rainfall regimes are named as Regime A, Regime B, and Regime C (Fig. 6.4).

Regime A It covers the central and the eastern part of the country, and follows the bimodal rainfall system classified as the long rainy season or locally called "Kiremt" (June–September) and short rains or locally called "Belg" (March–May).

Regime B It is a rainfall region in the western part of the country that covers from southwest to northwest and has a unimodal rainfall pattern (February–November). But the rainy period ranges are varied, if we go through southwest to northwest.

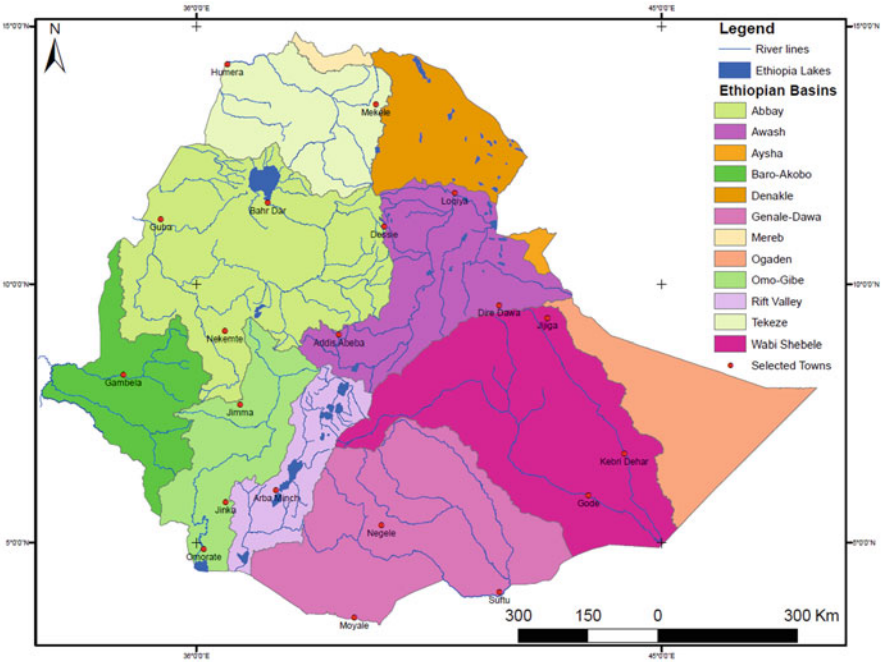

Fig. 6.5 River basin map of Ethiopia

Regime C It comprises the south and southeastern parts of the country and has two distinct wet and dry seasons. The main rainy season is from February to May, and short rains from October to November, and the dry periods are from June to September and December to February.

6.4 Surface Water Resources

Ethiopia constitutes 99.3 % of land area and the remaining 0.7 % is covered with water bodies (MOWE 2013). The country has 12 major basins, 12 large lakes, and differently sized water bodies (Fig. 6.5). However, three of the major basins are dry basins, which do not have any stream flow in these basins. Although it needs update and further detailed investigation, the country's surface water potential as identified and estimated in different integrated river basin master plans is 124.4 billion cubic meter (BCM) (Table 6.2). Since most of the rivers are transboundary, 97 % of this estimated annual stream flow of the country flows out of Ethiopia into neighboring countries and only 3 % of this amount remains within the country.

Similar to the rainfall, the surface water also shows spatiotemporal variability. Spatially, the major rivers in Ethiopia flow into two main directions based on their position from the Great Rift Valley that dissect the country into two major sections:

Table 6.2 Physical characteristics and mean annual flow of surface water at outlet of the river basins. (Source: Respective Basin Master Plan Studies compiled by the web master of Ministry of Water and Energy, MoWE (2013))

NuoO	Basin name	Type	Source	Altitude at source (masl)	Terminal	Altitude at terminal/border (masl)	Flow direction	Area (km^2)	Water Resource	
									Billion m^3	Lt/sec/km^2
1	Abbay	R	Sekela, West Gojam	2,000	Sudan border	500	West (Nile)	199,912	54.40	8.63
2	Awash	R	Ginchi	3,000	Terminal lakes	250	Northeast	110,000	4.90	1.41
3	Aysha	D	–	–	Djibouti border	400	No flow	2,223	0.00	0.00
4	Baro-Akobo	R	Illubabor	3,000	Sudan border	395	West (Nile)	75,912	23.23	9.70
5	Dinakle	D	–	–	Kobar sink	160	No flow	64,380	0.86	0.42
6	Genale-Dawa	R	Bale Mountains	4,300	Somali border	180	East	172,259	6.00	1.10
7	Mereb	R	Zalanbessa	2,500	Eritrean border	900	West (Nile)	77,120	0.72	3.87
8	Ogaden	D	–	–	Somali border	400	No Flow	79,000	0.00	0.00
9	Omo-Gibe	R	Ambo	2,800	Rudolph lake	350	South (Nile)	52,000	16.6	6.66
10	Rift valley lakes	L	Arsi Mountain	4,193	Sudanese border	550	South	5,900	5.64	3.44
11	Tekeze	R	Lasta/Gidan	3,500	Chew Bahir	300	West (Nile)	82,350	8.20	3.16
12	Wabisheble	R	Bale Mountains	4,000	Somali border	200	East	202,220	3.40	0.53

D Dry, *R* River, *L* Lake, *NF* No flow

Table 6.3 Summary of the spatial variability of surface water in Ethiopia

Flow direction	Basins included in the section	Area coverage share (%)	Surface water share (%)
West	Abbay, Baro-Akobo, Mereb, and Tekeze	38.75	69.83
East	Genale-Dawa and Wabishebele	33.34	7.58
South	Omo-Gibe, Rift Valley lake basin	5.15	17.94
Northeast	Awash	9.79	3.95
No flow	Aysha, Dinakle, and Ogaden	12.96	0.69

West and East. The rivers that originate from the western side of central highlands and western plateaus of the country are flowing to the west and joining the Nile system. These include the Abbay, Baro-Akobo, Mereb, and Tekeze basins and cover 39 % of the land mass of the country. This section of the country has the major flow of surface water in the country. It accounts for about 70 % of the estimated surface water flows in this section. The second section includes the basins that originate from the Eastern Highlands and flow toward east. It covers about 33 % of the country land mass but accommodates only 8 % of surface water of the country. The other two sections include the basins along the Great Rift Valley. And they flow to the south and north of the central part of Great Rift Valley around Meki. Awash is the only river basin that flow to the northeast direction and it covers 10 % of the country land mass and 4 % of surface flow in the country. It is the most utilized basin of the country. The south flow section includes two basins, the Rift Valley lake basin and the Omo-Gibe basin. They cover about 5 % of the land mass and 18 % of the surface flow. With regard to the Nile, Ethiopia contributes about 85 % of the Nile water, mainly during the rainy seasons from June to September (Table 6.3).

The temporal variability of the surface water of the country also follows the pattern of the rainfall. The basins that receive two rainfall seasons have two peak flows according to the seasonality of the rainfall. But those basins in the west mostly receive one rainfall season and they have one peak flow months. Although the basins in the west receive a single season rainfall, they receive the largest amount of rainfall and release it in 3–4 months. A summarized description of the seasonality of surface water in Ethiopia is presented in Fig. 6.6 with the help of mean monthly flow of selected hydrological gauging stations and some selected area basin modeling simulations.

Most of the river basin master plan studies do not take into account the surface water resources of the country in open water systems (lakes, wetlands, and flood plains). These systems store significant amount of water. For instance, the Water Audit Modeling Study of the Awash River basin shows that 5.7 BCM water is stored and exposed to evaporation in the lakes, wetlands, and flood plains of the basin (MoWE and FAO 2012). It is an indicator to change our surface water accounting system to understand the surface water potential of the country.

Accordingly, if we assess the major lakes in the country, Ethiopia has 12 major lakes. They cover about 7,300 km^2 area and store about 70 BCM of water (Table 6.4).

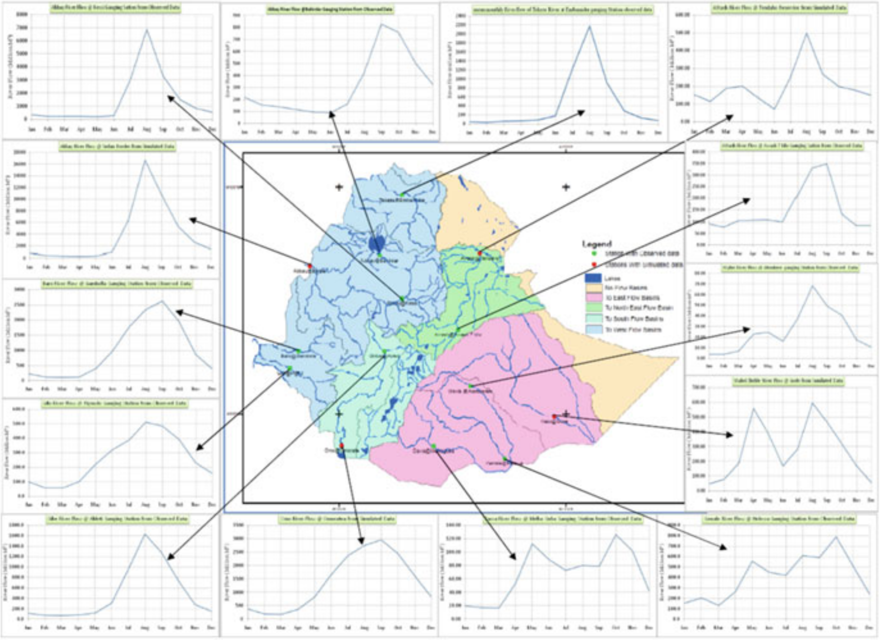

Fig. 6.6 Summarized descriptions of surface water seasonality in Ethiopia

6.5 Groundwater Resource

Always, the occurrence of groundwater is mainly influenced by the geophysical and climatic conditions of the area. The difficulty in obtaining productive aquifers is a peculiar feature of Ethiopia, which is characterized by the wide heterogeneity of geology, topography, and environmental conditions (Alemayheu 2006). Actually, the geology of the country provides usable groundwater and provides good transmission of rainfall to recharge aquifers, which produce springs and feed perennial rivers. In many parts of the country, groundwater is an important source of domestic and industrial water use especially in rural areas and towns. However, the occurrence of groundwater is not uniform because it depends on various environmental and geological factors (Alemayehu 2006). Geologically, the country can be characterized with generalized classifications, such as 18 % of the Precambrian basement, 25 % of the Paleozoic and Mesozoic sedimentary rocks, 40 % of the Tertiary sedimentary and volcanic rocks, and 17 % of the Quaternary sediments and volcanic rocks (MoWR 2009) (Fig. 6.7).

With the understanding of the nature of the distribution of these rocks and the recharge classification of the country, Alemayehu (2006) estimated the total groundwater reserve of the country as 185 BCM, which is distributed in an area of 924,140 km^2 made of Sedimentary, Volcanic, and Quaternary rocks and sediments, including the highlands and the Rift Valley. In this estimation, the mean groundwater

Table 6.4 Morphometric characteristics of lakes in Ethiopia as compiled from different sources. (Sources: Awlachew 2007; Ayenew and Robert 2007; Dinka 2012; Hughes and Hughes 1992; Mohamed et al. 2013; Kebede 2005; Bird Life International 2013)

	Maximum length (km)	Maximum width (km)	Surface area (km^2)	Average depth (m)	Maximum depth (m)	Water volume (BCM)	Surface elevation (amsl)
Lake Abaya (Awlachew (2007))	79.20	27.10	1,140.00	8.61	24.50	9.82	1,169
Lake Abijatta (Ayenew and Robert (2007))	17.00	15.00	180.00	8.00	14.00	1.00	1,578
Lake Ashenge (Bird Life International (2013))	5.00	4.00	140.00	14.00	25.50	0.25	2,409
Lake Awassa (Ayenew and Robert (2007))	16.00	9.00	129.00	11.00	22.00	1.00	1,680
Lake Basaka (Dinka (2012))	–	–	48.50	8.40	–	0.28	950
Lake Chamo (Awlachew (2007))	33.50	12.50	317.00	10.23	14.20	3.24	1,110
Lake Chew Bahir (Hughes and Hughes (1992))	64.00	24.00	1,125.00	–	7.50		570
Lake Hayq (Mohamed et al. (2013))	6.39	4.99	23.00	32.65	81.41	1.01	1,903
Lake Langano (Hughes and Hughes (1992))	23.00	16.00	230.00	20.00	46.00	3.80	1,585
Lake Shala (Ayenew and Robert (2007))	28.00	12.00	370.00	86.00	266.00	37	1,550
Lake Tana (Kebede (2005))	84.00	66.00	3,156.00	9.00	14.00	28.40	1,788
Lake Ziway (Ayenew and Robert (2007))	31.00	20.00	440.00	3.00	9.00	1.00	1,636

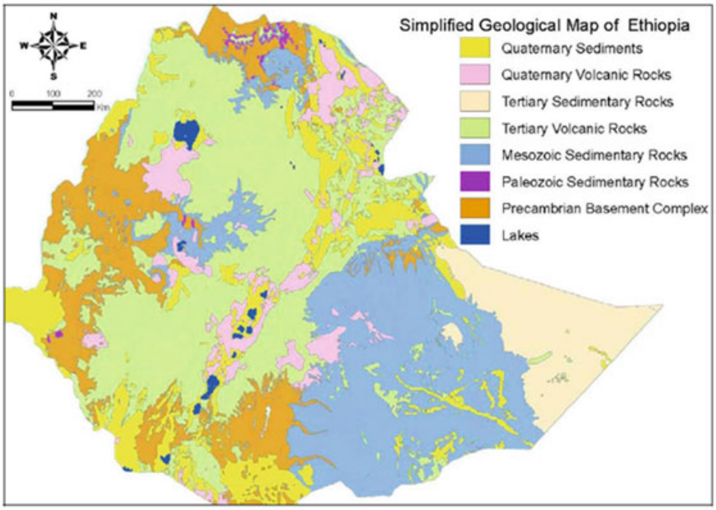

Fig. 6.7 Simplified geological map of Ethiopia. (Adopted from Water Information and Knowledge Management Project (MoWR 2009))

recharge for the entire country is assumed as 200 mm. But it should be confirmed with a detailed hydrogeological investigation to use as a reliable potential. Hydrogeological investigations refer to the study of lithological, stratigraphical, and structural aspects of a territory using basic geologic methods and will be finalized in the understanding of the factors that regulate effective infiltration, groundwater reserve, and circulation and outflow of the groundwater (Alemayehu 2006). The Ethiopia Geological Survey so far covers only 20.4 % of the Ethiopian landmass that has been mapped at 1:250,000 scale, about 36.8 % of the country is mapped at one million scale and the whole country at two million scale (MoWE 2013).

The Ethiopian National Groundwater Database (ENGDA) has been implemented since 2003 jointly by the Ministry of Water Resources, Addis Ababa University, and Geological Survey of Ethiopia. It has a close collaboration with the regional water resources development bureaus, Water Work Enterprises, NGOs, and contractors. ENGDA has large attributes and collections of about 5,000 boreholes in the country. The availability of this groundwater database is playing an important role in understanding the hydrologic cycle and discharge–recharge relation, for assessing and managing water resources within the hydrogeologic environment.

At present, detailed groundwater assessments are ongoing in several areas and these indicate that the previously estimated groundwater usage potential of 2.6 BCM was underestimated. And it needs to be revised. Best guesses in this respect range between 12 and 30 BCM, or even more if all aquifers in the lowlands are assessed (MoWR and GW-MATE 2011). Studies for irrigated agriculture in Kobo, Raya, and Adaa Bechoo suggest that regional aquifers are deep and water movement crosses surface basin boundaries. It is estimated that the groundwater reserve of the Kobo Girana Valley alone is in the order of 2.5 BCM, that of Raya is 7.2 BCM, and Adda Bechoo is 0.96 BMC (AGWATER 2012).

6.6 Water Resources-Based Development Potentials in Ethiopia

- Water resources are the central elements for the development of Ethiopia. One can easily understand that "water-centered development" is the key for growth and transformation of the country. The growth and transforming plan (GTP) also considers and targets to enhance the uses of country's water resources (MoFED 2010). It gives priority for the expansion of small-, medium-, and large-scale irrigation to the extent of possible, hydropower developments to satisfy the energy demand of the upcoming industries and then the water supply and sanitation system for the satisfaction of the inhabitants. Technologies that will enable us to use the water resources will also be used extensively. The GTP recognized to expand watershed management and to carry out effective water- and moisture-retaining works that will help to cope the challenges of climate change.
- Planning should support with information about the resources availability. Thus, to enhance the use of country water resources, we have to understand the potential with spatial and temporal variations of the resource. For the past two to three decades, the government of Ethiopia is exerting efforts to cover all the major river basins with the integrated master plan studies. All the master plan studies were devoted to assess the availability of resources and potentials of the river basins for different developments (MoWR 1996, 1997, 1998a, b; PDRE 1989).
- Some of the master plan studies need to be updated to reflect the current situation on the ground. With this regard, other resources that include the water sector development program (MoWR 2002, 2010), feasibility studies and detailed designs of different development projects (WWDSE 2005; Halcrow and MCE 2007), and other basin-level studies (MoWE and FAO 2011, 2012) are reviewed to estimate and analyze the different water resources development potentials of the country.

As a part of the water-centered development strategy in the country, it is essential to share and to own the water sector vision and principle of the country. As it is clearly described on Ethiopian Water Sector Policy, water is commonly owned economic and social goods that should be accessible to all in sufficient quantity and quality to meet basic human needs. Additionally, the principles emphasize the need for a rural-centered, decentralized, integrated, and participatory water management system as well as the attainment of social equity, economic efficiency, empowerment of water users, and sustainability. Thus, the national water sector vision is to enhance and promote all national efforts towards the efficient, equitable, and optimum utilization of the available water resources of Ethiopia for significant socioeconomic development on a sustainable basis.

6.7 Irrigation Potentials in the River Basins

Tadesse (2002) argued that food shortage can be minimized if farmers have access to irrigation water. Awulachew et al. (2007) also indicated that, as the prevalent rainfed agriculture production system together with the progressive degradation of

Table 6.5 Irrigation potential of the country by basin. (Sources: Awulachew et al. 2007; MoWE and FAO 2012; FAO 1997)

Basin	Irrigation potentials (ha) compiled from respective master plan studies			
	Small scale	Medium scale	Large scale	Total
Abbay (Awulachew et al. (2007))	45,856	130,395	639,330	815,581
Awash (MoWE and FAO (2012))	198,632	–	139,627	198,632
Ayisha	–	–	–	–
Baro-Akobo (Awulachew et al. (2007))			1,019,523	1,019,523
Denakil (Awulachew et al. (2007))	2,309	45,656	110,811	158,776
Genale-Dawa (Awulachew et al. (2007))	1,805	28,415	1,044,500	1,074,720
Mereb (FAO (1997))				5,000
Ogaden	–	–	–	–
Omo-Ghibe (Awulachew et al. (2007))	–	10,028	57,900	67,928
Rift Valley (Awulachew et al. (2007))	–	4,000	45,700	139,300
Tekeze (Awulachew et al. (2007))	–	–	83,368	83,368
Wabishebele (Awulachew et al. (2007))	10,755.00	55,950	171,200	237,905
Total				3,800,733

the natural resources base and climate variability has aggravated the incidence of poverty and food insecurity. Currently, the Ministry of Water and Energy identified more than 500 irrigation sites with a total of 3.8 million ha irrigable land. The details of this irrigation potential per Ethiopian major river basin are presented in Table 6.5.

From this irrigation potential, the GTP is being planned to develop 15.4 % of the potential at the end of 2015. It will boost the irrigable land of the country to 785,582.6 ha. Accordingly, over the past 2 years and 6 months of the GTP, the performance of the ministry indicates that the study and design have been finalized for 473,225 ha, and 148,836 ha of land has been constructed out (MoWE 2013).

Generally, up until the first 6 months of the 2012–2013 fiscal year, 276,078.6 ha of land has been at different levels of studies and design through medium- and large scale-irrigation schemes. On the other hand, several irrigation development projects are under construction, among those to mention few: Kesem-Tendaho, Koga, Rib, Gidabo, Megech-Sereba, Kobo-Girana, Raya-Azebo, and Adea-Betcho. This has increased the overall irrigation coverage growth from 2.4 to 7.34 % (MoWE 2013).

Table 6.6 Hydropower production potential of Ethiopian river basins. (Source: Solomon 1998)

River basin	Number of potential sites				Hydropower potential (GWh/year)	Percentage share of the total (%)
	Small scale < 40 MW	Medium scale 40–60 MW	Large scale < 60 MW	Total		
Abbay	74	11	44	129	78,800	48.9
Awash	33	2	–	35	4,500	2.8
Baro-Akabo	17	3	21	41	18,900	11.7
Genale–Dawa	18	4	9	31	9,300	5.8
Omo–Gibe	4	–	16	20	35,000	22.7
Rift Valley lakes	7	–	1	8	800	0.5
Tekeze–Angereb	11	1	8	20	6,000	4.2
Wabishebelle	9	4	3	16	5,400	3.4
Total	*173*	*25*	*100*	*300*	*159,300*	

6.8 Hydropower Development Potentials in the River Basin

Despite the huge amount potential of the hydropower resources of Ethiopia, the country's energy sector has been highly dependent on the biomass sources. According to Halcrow and MCE (2006), in the year 2000, 73.2 % of energy came from woody biomass, 15.5 % from non-woody biomass (8.4 % cow dung, 6.4 % crop residue, and 0.7 % biogas), 10.3 % petro fuels, and 1 % hydropower. In this period, only 360 MW has been exploited from the hydropower source (Solomon 1998).

Later, the Ethiopian government recognized the power shortage and its role in the economic development of the country (MoFED 2006) and planned on developing a number of hydropower projects. In total, generating capacity is to be increased to about 2,218 MW at the end of the Plan for Accelerated and Sustainable Development to End poverty (PASDEP) period (2009–2010). Thus, the government has highly mobilized its full capacity towards tapping water for the energy purpose. The Grand Ethiopian Renaissance Dam, which has a capacity to generate 6,000 MW electricity, and the Gibe cascading dam's hydropower projects are the parts and parcel of this motivation. All will scale up the access of electricity from 2,000 MW in 2009–2010 to 10,000 MW by the end of GTP, 2015 (MoFED 2010).

So, to have such development plan and commitment, understanding the potential sources is essential. Similar to irrigation developments, integrated master plan studies identified the potential sites for the dam's construction and hydropower developments. Solomon (1998) compiled a total of 300 different-scale hydropower sites in eight river basins of Ethiopia (Table 6.6). With these development sites, Ethiopia has 45,000 MW exploitable hydropower potential (MoFED 2010) which can generate 159,300 GWH energy annually (Table 6.7).

In the 2.5 years of GTP, electric power plants have gone operational.The constructions of Fincha-Amerti-Neshe, Gibe III hydropower, and Grand Ethiopian Renaissance Dam projects are under way and their 90, 72, and 20 %, respectively, construction of work is completed.

Table 6.7 Existing, under construction, and near-planned hydropower projects in Ethiopia

Project/site name	Basin	Installed capacity (MW)	Status
Beles	Abbay (Blue Nile)	460.0	Existing
Fincha	Abbay (Blue Nile)	134.0	Existing
TisAbbay I HPP	Abbay (Blue Nile)	11.5	Existing
TisAbbay II HPP	Abbay (Blue Nile)	67.0	Existing
Awash II HPP	Awash	32.0	Existing
Awash III HPP	Awash	32.0	Existing
Koka HPP	Awash	43.5	Existing
Gilgel Gibe I	Omo Gibe	180.0	Existing
Gilgel Gibe II	Omo-Gibe	420.0	Existing
Tekezé	Tekeze (Atbara)	300.0	Existing
MelkaWakena HPP	Wabishebele	153.0	Existing
Sub Total		*1,833*	
Fincha-Amerti-Neshe (FAN)	Abbay (Blue Nile)	100	Under construction
Great Ethiopian Renaissance Dam	Abbay (Blue Nile)	6,000	Under construction
Gilgel Gibe III	Omo Gibe	1,870	Under construction
Sub Total		*7,970*	
Beko Abo	Abbay (Blue Nile)	2,100	Planned
Chemoga-Yeda	Abbay (Blue Nile)	278	Planned
Karadobi	Abbay (Blue Nile)	1,600	Planned
Mendaia II	Abbay (Blue Nile)	2,800	Planned
Genale-Dawa	Genale-Dawa	256	Planned
Halele Worabese	Omo River	440	Planned
Gilgel Gibe IV	Omo-Gibe	2,000	Planned
Tekeze II	Tekeze (Atbara)	450	Planned
Sub Total		*9,924*	
Total project capacity		*19,727*	

Source MoWR

6.9 Water Supply and Sanitation Development Potential

1. Although an immense surface water and groundwater availability is recorded in the country, Ethiopia has one of Africa's lowest rates of accesses to freshwater supply, sanitation, and hygiene service. Based on the population censes and its growth rate provided by the Central Statistics Authority (CSA 2007), the projected demand for clean water at the end of GTP is about 2.6 BCM.
2. According to the GTP, 29,678,721 people live in rural areas and 3,613,216 people in urban areas are expected to become beneficiaries of safe drinking water by 2015 (MoWE 2013).
3. To achieve the goals set by the GTP, the Ministry of Water and Energy together with other partners has designed, and construction is being made for, different safe water facilities. The water supply development works include:

- Newly constructed water schemes

  - 26,739 hand-dug wells
  - 7,372 medium-deep water wells
  - 7,212 spring developing works
  - 880 deep-dug water wells
  - 335 water harvesting ponds
  - 545 rainwater and surface drinking water tankers
  - 1,968 rural piped water system construction

- Expansion and rehabilitation

  - 11,935 hand-dug wells
  - 2,968 hand pump medium deep water wells
  - 8,032 developed springs
  - 377 deep dug water wells
  - 785 rural piped water systems
  - 153 rain harvesting works
  - 70 old water institutions expansion works

4. Overall, 68,514 water schemes have been built. Moreover, more than 8,896 old rural water service schemes have been maintained and have become operational (MoWE 2013).

6.10 Challenges in Water Resources Developments

Despite the potential, the availability of resources and demand of the water resources and its products in Ethiopia, the water sector development is still at infancy. A number of factors that can group into four main streams as natural, technical, economical, and institutional factors hinder the water sector development. Thus, critical analysis and understanding of these challenges are required to overcome them and to arrive at appropriate mitigating strategies in the water sector.

6.10.1 Natural Challenges

The spatial and temporal variability of climate, topography, soil, and geology of the country induce high variability in the amount and distribution of water resources in Ethiopia. It hinders the water sector development. Rainfall has high seasonal and spatial variability; it also makes water availability seasonal. Since rainfall is erratic and unreliable, unless water harvesting structures (reservoirs, or ponds) are developed for off-season supply and groundwater recharge in some cases, water-based development will be challenged. The occurrence of extreme events, floods and drought is rising in intensity and extent, which hinders the development of water sector. The rugged topography also leads most riverwater flows into gorge, thereby hindering large storage and irrigation development. Also, most of the population, about 80 %, is living in the 30 % of the highlands of the country; thus, the water resource developments that can be done in the lowlands suffer with shortage of labor and focus on potential lowland areas.

6.10.2 Technical Challenges

Due to the variability in the nature of the climatic, topographic, and water resources, the country needs a wide varied knowledge and information. But there is little or no organized knowledge and information about the water resources of the country. Most information is dispersed and detailed studies at a desired scale and depth are scant. About 470 hydrological gauging stations, which cover only 40 % of the country, are operational. This is very little by any standard and lot of hydrologic information of river basins is estimated using models that may not be verified using observed data. To cover the ungauged section of the country, engineers are using rainfall–runoff methods, but there are no reliable rainfall–runoff methods that address the climatic and topographic variability of the country. Again such methods and models need highly skilled professionals. There is no dedicated national research, academic and development institute on water to assess the challenges of water resources with branch office at various climatic regions. Regional water resource bureaus are mainly charged with data gathering and project supervision instead of water resources research and outreach program. Farmers practicing irrigation have limited access to technical support. The existing system also suffers from high staff turnover.

6.10.3 Economic Challenges

The rugged topographic and the nature of the river flow again make the hydraulic structure to be expensive and need much investment. Developing countries such as Ethiopia have many priority areas (education, health, etc.), which demand huge budget and investments; thus, the water resources developments do not get sufficient budget allocation. By their nature, water resources developments are not short payable investments, securing finance for water resources projects from either lenders or private investors are challenging.

6.10.4 Hydropolitics Challenges

Most of the rivers in Ethiopia are transboundary. To date, no formal transboundary water use and management agreements exist between riparian countries. Development of projects on shared rivers, thus, leads to political discussions and sometimes it is challenging to have smooth development; often this will lead to lack of discouragement for the financing institution to lend. The terms of sharing the transboundary water resources have been a very big hindrance for transboundary water management and utilization of the Nile River equitably. This will require realizing the current setting and the needs of all basin countries and seeking for an all-winning scenario where every basin country uses the resources equitably.

6.11 Conclusion

As we see in this review work, Ethiopia has huge surface water and groundwater resources potential that can be harnessed for developments. It is clearly seen that the water centered development thinking is the footstep for the economic development of the country. It is started with self-financed development of 6,000 MW hydropower dam on the Abay River. It is time to further pull national resources to face the challenges and change the potentials to reality.

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Chapter 7
Land and Water in the Nile Basin

Wossenu Abtew

Abstract Global water stress is continuingly increasing along with the increase in water demand. Rivers are the most relatively accessible sources with better water quality. Water quantity and quality of river water issues have become a source of conflicts. The Nile basin is a model for a water-stressed transboundary basin. Water quantity and sharing are creating conflict while water quality problems are growing. Watersheds and rivers are linked and watershed management adversely or positively affects river water quantity and quality. Land grab in the Nile basin, at the current scale, is a new phenomenon that is introducing new interests in the water. Failure by the riparian countries to come into agreement of water management and sharing will increase unilateral water control projects. In this chapter, basic information on the current cause of conflict on transboundary water rights, the Grand Ethiopian Renaissance Dam, is provided.

Keywords Global water · Nile basin water demand · Nile basin water quality · Watershed management · Transboundary rivers · Land grab · Grand Ethiopian Renaissance Dam

7.1 Introduction

7.1.1 Global Water Resources Overview

Freshwater that is available and usable is limited globally. The oceans cover 70 % of the earth's surface and hold 96.5 % of the global water. The remaining 0.07 % water is in saline lakes and 0.93 % is present as saline groundwater and only 2.5 % is freshwater. Most of the freshwater is in the form of glaciers and ice caps (68.6 %), groundwater (30.1 %), and surface water (1.3 %). Rivers are 0.46 % of the surface water with a volume of 2,120 km^3 (Shiklomanov 1993). As a frame of reference, current world water demand is 7,000 km^3 per year with per capita annual demand

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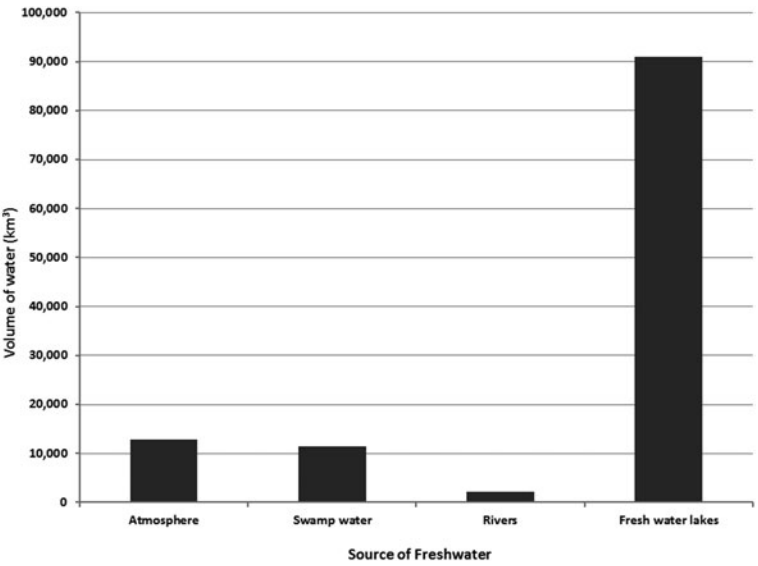

Fig. 7.1 Sources of freshwater. (Source: Shiklomanov 1993)

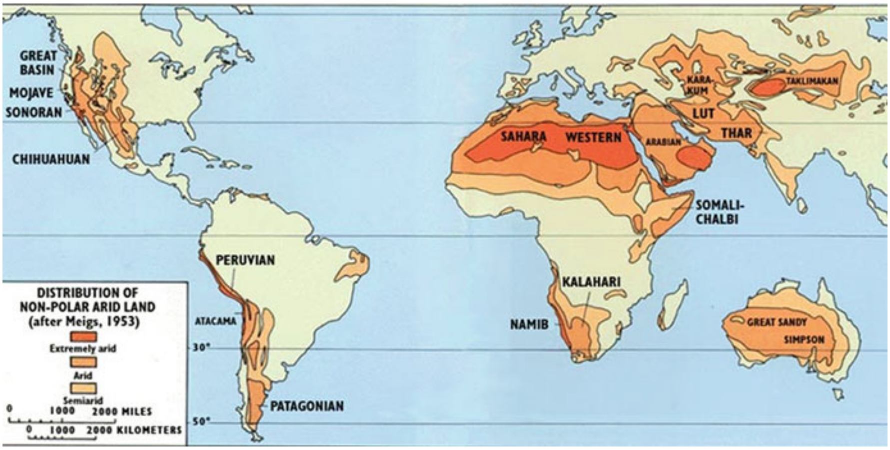

Fig. 7.2 Global nonpolar aridity map. (Source: http://pubs.usgs.gov/gip/deserts/what/world.html)

of 1,000 m^3. Figure 7.1 depicts freshwater sources and volume. Precipitation is the annual source of freshwater replenishment. Spatial and temporal variations of precipitation are a constant source of threat for regions dependent on rainfed agriculture. Precipitation variation has been moderated by storage in many regions. Shallow surface storage results in high evaporation losses. As a result, the technique of aquifer storage practice, where surface water is stored in the ground and recovered later for use, has started (Barnett et al. 2000; Shahbaz et al. 2008). Figure 7.2 depicts aridity of nonpolar regions. Most of the Nile basin is arid area. Transboundary rivers crossing arid areas have potential for water conflicts. Currently, most agriculture in the

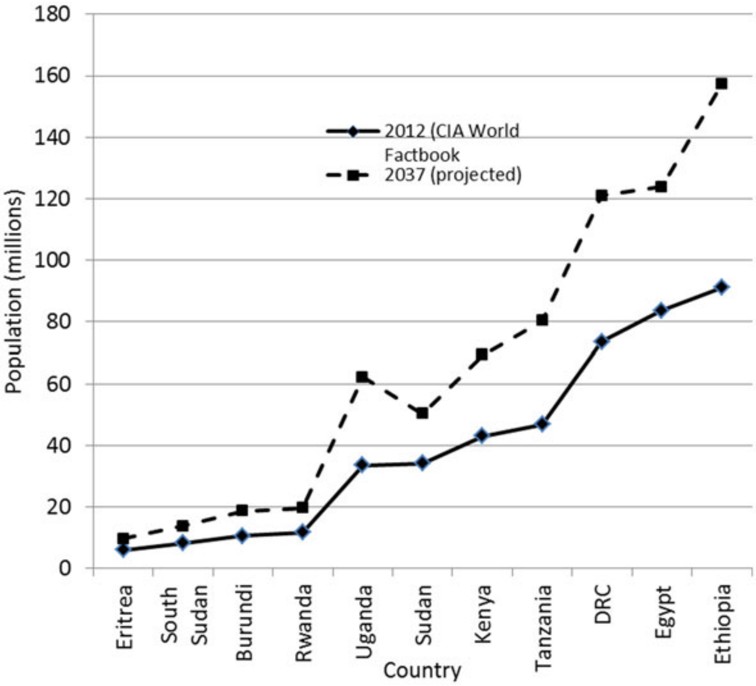

Fig. 7.3 Nile basin countries population

basin is rainfed. But, the increased demand for food, loss of soil productivity, climate change, and agricultural technology improvements will push towards irrigation.

China is a case where water shortage and projected shortage challenges are being addressed through application of available financial and technical resources. Northeastern China is water stressed. Water transfer from south to north, expanding storage through damming, and improving water use efficiency and infrastructure are being implemented as China's population is expected to be 1.6 billion by 2030.

7.1.2 *Population Growth and Water Demand in the Nile Basin*

A report by the United Nations Commission on sustainable development reported that 1.2 billion people in the world are at high risk of water stress (Rourke and Boyer 2002). Population growth rate in the Nile riparian countries, both in the Nile basin and outside the basin, is alarmingly high. The 2012 population of Nile countries is 443 million and the projected population in 25 years is expected to be 726 million (Fig. 7.3). The demand for food, water, and power is and will inevitably stress land and water resources with a significant impact on the ecology of the region. The relationship of watershed and transboundary rivers is intertwined with the right to

Table 7.1 Water availability in the Nile basin

Country	Per capita water availability (m^3/p/yr)[a]	Projected water availability in 2037 (m^3/p/yr)[b]
Burundi	2,190	1,233
Egypt	790	534
Eritrea	1,470	916
Ethiopia	1,680	974
Kenya	930	577
Rwanda	610	361
South Sudan	1,880	1,129
Sudan	1,880	1,279
Tanzania	2,420	1,413
The Democratic Republic of Congo	23,580	14,337
Uganda	2,470	1,335

[a] Source: UNESCO, The United Nations World Water Report 2

[b] Estimated based on population projection

use local water sources, territorial sovereignty, and achieving food security. When dwellers in the watershed start using local streams and river waters for sustenance, transboundary river flows will continuously decrease. If climate change affects water availability negatively, decrease in river flows will be accelerated. Dispersed water use in the transboundary watershed as a means of survival can be neither regulated nor morally objected.

A minimum of 36 m^3 per person per year is the amount of water needed for survival. When industrial, agricultural, and other uses are added, the commonly cited figure is 1,000 m^3 per person per year. By 2025, Egypt's water availability is projected to be half of that in 1990 (Cathcart 2007). Burundi, Rwanda, Uganda, and Ethiopia have far higher population growth rate which means their water demand will unavoidably be high. Table 7.1 depicts current and projected water availability for Nile countries.

Population growth, hydroecological degradation, and climate change are the current challenges facing humanity. The first crack or crash will spring in basins where population growth is not matched or preceded by technological, political, social, and economic progress to satisfy the needs of respective populations. The Nile basin and East Africa may be the first case. Increasing demand and diminishing or constant water supply sooner or later will result in water conflicts.

7.2 Watersheds and Water Management

Watershed management is closely linked to water resources management. There could not be a successful water management without watershed management. Apart from water scarcity, soil degradation is also a threat to food security. Uncontrolled soil losses by erosion result in irreversible top soil loss, sedimentation in reservoirs and waterways, water quality degradation, and increased water demand. The decline of productivity in eroded soils results in demand for increase in arable land and more deforestation. Eroded soils demand more water. On a large scale, watershed management has a link to regional climate change such as desertification.

Water management is a science and art essential for harnessing a natural resource for efficient use and managing excess. Successful water management programs require stable institutions, qualified personnel, and ample resources. Most are in limited quantity and quality in many Nile basin countries. The importance of resource monitoring is a prerequisite for resource management. Hydrometeorologic monitoring is a resource-intensive program but is the foundation for a successful watershed and water management. Detailed hydrometeorology monitoring program and application for successful water management are reported in Abtew et al. (2007). Continuous measurements of precipitation, evapotranspiration (ET), stream flows, available storage, surface water and groundwater levels, and other meteorological variables, and data storage in readily accessible database are a necessity. Where agricultural production and settlements have encroached floodplains, real-time monitoring is required for flood control decision making. Safe dam operations require real-time monitoring and decision making. Historical data analysis to see trends and forecast the future has to be part of water management. The cost of implementing a successful monitoring program is very high and the importance of the program is not well realized. Monitoring system with minimum cost and adaptable to regions can be developed. Effort has to be made to capture and use data such as satellite rainfall and ET estimates, climate and weather forecast, and other relevant analyses available from international sources with no or minimal cost.

7.3 Land Grab and Water Availability

> Multinational corporations are buying enormous tracts of land in Africa to the detriment of local communities. These land grabs puts countries on the path to increased food insecurity, environmental degradation, increased reliance on aid and marginalisation of farming and pastoralist communities. This has resulted in the sale of enormous portions of land throughout Africa. In 2009 alone, nearly 60 million hectares of land were purchased or leased throughout the continent for the production and export of food, cut flowers and agrofuel crops. (African Perspective, Sunday December 11, 2011)

There is no major change in a watershed land and water use as driving away indigenous subsistence people from their land and introducing foreign capital for industrial agriculture. The recent phenomenon of eviction of subsistence farmers and pastoralists off their lands and contracting or selling for capital will change water resources availability. In Ethiopia, it is a government policy to lease vast track of lands. It is reported that 2,500 km^2 fertile virgin lands are leased to foreign investors at a knockdown rate (The Guardian 2011). Both the water and land resources will be subjected to quick profit and inevitable degradation.

Introduction of foreign capital in the Nile basin in this form brings in new forces in the water conflict. According to UPI (2012), following the 2008 global food shortage, countries like Saudi Arabia, United Arab Emirates, China, and India have been buying vast tracks of arable land in Africa to feed their own growing population. At the same time, food is scarcer in Africa than in these countries. The Nile basin is one of the basins with land grabs with single holding of the size of some European countries. According to an article published in *Think Africa Press* (Rhode 2011), 50 million hectares of land in Africa, the size of UK, has been grabbed by foreign investors. Ten percent of South Sudan territory is grabbed by investors. Vast track of lands in Central and Western Equatoria "Green Belt" states of South Sudan is acquired by companies from various countries with leases of 30–99 years. The companies' origins are Canada, Uganda, British, Finland, Norway, North Sudan, South Africa, America, Kenya, and India (Deng 2011). The ratification of international transboundary basin water use agreements will be unlikely further with introduction of foreign interests in the basin.

A study of land grab in Kenya and Mozambique is reported by FIAN (2010). According to the report, Kenya granted 40,000 ha of fertile land at the Tana River Delta to the government of Qatar for horticulture. Land grab around Lake Victoria swamps and its human and ecological impacts are well documented. According to Friends of the Earth International, Uganda is displacing native people around Lake Victoria for large-scale palm oil production, although the constitution of the country protects land property rights (FOEI 2012). Tanzania started leasing land as early as 1979 with 156,000 ha in Monduli District leased to a foreign farmer (Nelson et al. 2012). Condor and Casey (2012) have researched and documented the threats of land grab by investors and the role of each country's land ownership laws and implementation of the laws. The report covers 7 of the 11 Nile countries except Eritrea, Egypt, South Sudan, and Sudan.

7.4 Water Quality

Water quality is the least addressed problem in the Nile basin. Water quality has to be one of the concerns in water and watershed management. In less industrialized parts of the Nile basin, salinity or high-dissolved solids is a long-term problem. Repeated application of irrigation water leaves precipitated salt in the soil when water evaporates. Runoff and leachate from the fields have high salinity. With time, leaching water demand increases to wash down the salt in the soil to maintain lower toxicity for crop growth. Other unknown threats from salinity come from deposited salt formations leaching out into streams and soils. The case of Lake Beseka in Ethiopia is such an example where a saline lake sprung from the ground (Belay 2009). Unless a solution is found, catastrophic water and soil damage will occur in the Awash valley of Ethiopia where the saline lake is overflowing. Lake Beseka in the Rift Valley sprung from geological/groundwater/spring sources and is growing uncontrollably due to non-climatic causes (Fig. 7.4). Currently, the estimated size is 45 km^2, 15 times that of 35 years ago. A growing lake in otherwise dry region with high evaporation has initiated many hypotheses for the source of water. One

Fig. 7.4 Lake Beseka, a saline lake in the Rift valley of Ethiopia

Fig. 7.5 The Sudd and the Jonglei Canal. (Source: Sudan's Higher Council of Environmental and Natural Resources)

hypothesis is tectonic modification of underground water system (Goerner et al. 2005). Initial effort of pumping and mixing with Awash River to control its expansion has failed when the pump station went under water. There is also salt formation under the Sudd in White Nile basin (Salama 1987) which has the potential as Lake Beseka to leach out into surface water and groundwater with potential adverse effect. The Jonglei Canal, proposed to drain the Sudd faster and increase the White Nile flows for the benefits of Sudan and Egypt, started in the 1980s was never completed (Fig. 7.5). Plans for canal dredging need to consider potential salt formation in the area.

Nutrients as phosphorus and nitrogen are part of fertilizers. Irrigation drainage and runoff from farms result in increased nutrient load on receiving water bodies. Lake and stream eutrophication or nutrient enrichment is a global problem that requires best management agricultural practices to control. Nutrient-enriched water bodies develop algal bloom resulting in oxygen depletion, fish kill, and toxicity. Organic compounds as pesticides, insecticide, and fungicide are potential contaminants in modern agriculture. Ethiopia had 85 flower plantations as of 2010. The chemicals added on flower farms have caused environmental contamination with a potential of 40–60 years of soil damage (Gadaa 2010). There are numerous other cases in the Nile basin where the topic requires detailed study.

Heavy metals are other contaminants associated with industrial production that pollute soil and water. Tanneries are known for chromium discharge into the environment and create numerous health impacts on the local population including related mortality. Chromium pollution in surrounding water bodies from discharges by Sheba Tannery in Ethiopia is reported by Gebrekidan et al. (2009). Heavy metal pollution from tannery effluent and contamination of vegetables in East Shoa, Ethiopia, are reported by Asefa et al. (2013). Kenya and Sudan have an experience from tannery effluent pollution and controls. Similar problems are reported in Burundi, Rwanda, Uganda, and Tanzania.

Vegetable oil, soap, tannery, and other factories on the outskirts of Lake Victoria discharge untreated waste into waterways. In Sudan, agricultural chemicals, and industrial and household waste discharges into irrigation canals cause pollution. In Egypt, the quality of water declines between the Aswan and the delta. Agricultural drainage canals are polluted with salt, wastewater, and industrial waste (Kachaka n.d.). Erosion, salinization, and pollution are causing decline of agricultural production and loss of land and coastal lagoons in the delta, while population is growing exponentially (Stanley and Warne 1993). Biological pollution from untreated sewage should be as common as similar places. The Nile basin water use has to integrate water and soil pollution control programs for long-term resource use.

7.5 Water Agreements and Conflicts

Realizing the urgency of water cooperation, in December 2010, the United Nations General Assembly declared 2013 as the United Nations International Year of Water Cooperation. Water agreements acceptable by all riparian countries need to be achieved as soon as possible to reduce water conflicts. Population growth and increase in water demand have to be accepted as a challenge that has to be addressed with improved water conservation and management, new water source exploration, food source diversification, and cooperation. Political stability, economic growth, and food security in riparian countries can create favorable environment for water agreement. Currently, war of words between Egypt and Ethiopia has started on Ethiopia's Grand Renaissance Dam on the Nile as reported by the British Broadcasting Corporation (BBC) on June 10, 2013.

Fig. 7.6 Projected feature of the Grand Ethiopian Renaissance Dam. (Source: Ethiopian Energy Ministry)

Undermining the interests of upstream countries by downstream countries through the years may have the unintended negative effect of increasing dependence on Nile water more than ever. An example is Ethiopia's loss of access to sea that undoubtedly is making it more dependent on local resources including transboundary rivers and watersheds. It is for the benefit of downstream countries to cooperate and support developments in upstream countries to make them less dependent on few resources.

7.6 The Grand Ethiopian Renaissance Dam

Ethiopia is building the Grand Ethiopian Renaissance Dam on the Blue Nile River, 40 km from the Sudan border (Fig. 7.6). Dam construction started in April 2011 and 24 % is reported complete in July 2013. Constant fund-raising and bond sales to finance the construction show that the required fund is not secured. The estimated cost of the dam is US$ 4.8 billion and some of it will be financed by the Chinese banks Bloomberg Businessweek (2013). The dam is a roller-compacted concrete (RCC) gravity dam, a practice that was developed in Italy. The difference between RCC and conventional concrete dam is that RCC requires less cement and water, and does not generate as much heat. RCC's advantage over conventional concrete is lower cost and shorter time, while conventional concrete requires more time for cooling and forming. The dam design has a height of 145 m, a length of 1,780 m, and a volume of 74 billion m^3. The dam is expected to flood 1,680 km^2 area. Supporting the dam, confining its extents, will be a 5-km-long and 50-m-high saddle dam. The dam is designed with two powerhouses with 16 Francis turbines, each generating 375 MW. In the main dam, a gated spillway with six radial gates, each with 2,450 $m^3\ s^{-1}$ maximum capacity, is part of the design. An overflow spillway is designed on the saddle dam which is to be rock filled with bituminous upstream lining. According to information from the Los Angeles Ethiopian Consulate, the dam will be operated at a normal level of 640 m with a capacity of 63 billion m^3 and a minimum level of 590 m at a capacity of 12 billion m^3 (http://ethiopianconsla.org/Documents/BONDINFORMATION.pdf. Accessed 29 June 2013). The level is assumed to be from sea level.

The main contractor is Salini Contruttori which has also worked on other dams in the country. The dam is expected to generate 6,000 MW of electricity with a plan to sell power internally and to neighboring countries. According to the Ethiopian Electric Power Corporation report of August 2012, there are 4,225 workers at the site among whom 131 are expatriates and 1,189 subcontractors with the rest 2,905 workers.

Claims and counterclaims between Ethiopia and Egypt have been going on concerning the impact of the dam on the river flows and risks associated with dam failure. A panel of ten experts, two each from Ethiopia, Sudan, and Egypt and four international experts, have evaluated the project and submitted their report on June 1, 2013. As of this time, the report is not released for the public but submitted to the parties. Each party highlighted the contents of the report that supports its respective position. Generally, contents seem to contain acknowledgment of the dam design following international standards, not enough information for some evaluations, concerns, and recommendations with encouragement to the three countries to work together. Egypt has warned that it will take necessary measures, if a drop of water is reduced from the Nile flow. Ethiopian officials have rebuffed the threat of war with Egypt.

7.7 Summary

Water is a limited resource for a growing population. Food production to feed the 7 billion plus world population is stressing water and land resources. Ecological degradation and climate change compound the problem. The Nile basin is one of the regions where population growth is overcoming institutional, social, political, and technical capabilities to feed one's population. Water shortage encourages water and land grab making water agreements harder. International conditions do not seem favorable for creating fair and equitable water agreements. Also, each transboundary river basin is unique that one for all international agreement or principle cannot satisfy every case.

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Part II
Soil Erosion and Water Quality

Chapter 8
Soil Erosion and Discharge in the Blue Nile Basin: Trends and Challenges

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Abstract Future river discharge predictions seldom take into account the degrading landscape. The objective of this study was to investigate the relationship of river discharge and sediment concentrations, and the effect of changing landscape and climate on discharge and sediment transport in the Ethiopian Blue Nile basin. This study used past precipitation records and the Parameter Efficient Distributed (PED)

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model to examine how the relationship between precipitation, discharge, and sediment concentration changed with time. All input data to the PED model were kept constant except for a conversion of permeable hillside to degraded soil in time. The results of this study show that with a gradual increase of the degraded areas from 10 % in the 1960s to 22 % in 2000s, the observed discharge pattern and sediment concentration can be simulated well. Simulated annual runoff increased by 10 % over the 40-year periods as a result of the increase in degraded soils. Sediment loads appeared to have increased many times more, but this needs to be further validated as data availability is limited. In general, the results indicate that rehabilitating the degraded and bare areas by planting permanent vegetation can be effective in decreasing the sediment concentration in the rivers. Research should be undertaken to evaluate the effectiveness of vegetation planting.

Keywords Saturation excess runoff · Variable source hydrology · Ethiopian highlands · Blue Nile basin · Soil erosion · Blue Nile river flow

8.1 Introduction

The Nile is the longest river in the world and at the same time with one of the most water-limited basins. Without the Nile, major portions of Sudan and Egypt would run out of water. Of the water entering Lake Nasser at Aswan dam, 85 % originates from the Ethiopian Highlands (Sutcliffe and Parks 1999). Consequently, there is a growing anxiety about changes in discharge and sediment load due to planned dams, climate-induced, and landscape-induced changes upstream.

Several studies have employed past rainfall and discharge as an effective method to study the effect of climate on hydrology (Conway 2000; Kim et al. 2008; Yilma and Demarce 1995). In one study by Tesemma et al. (2010), past trends of precipitation and discharge in the Blue Nile basin were investigated. The results show that there was no significant trend at 5 % probability level in the basin-wide annual, dry season, and short and long rainy season rainfall in the past 40 years. These results are in agreement with Conway (2000).

Tesemma et al. (2010) reported that despite no trend in rainfall, discharge at Bahir Dar and Kessie, representing the upper one third of the Blue Nile basin in Ethiopia and at El Diem at the border between Sudan and Ethiopia, changed significantly over a 40-year period. Specifically, the annual discharge increased by about 25 % over the 40-year period for the upper Blue Nile, while it remained the same for the whole Blue Nile basin at El Diem. The increase of discharge in the upper Blue Nile basin is unexpected since annual rainfall remained the same, and potential evaporation from year to year does not vary greatly. This study would expect, as was the case at El Diem, that the annual discharge, which is the difference between precipitation and evaporation, should stay the same for a given amount of annual rainfall. The reasons for the difference in discharge will be discussed later. In addition to the annual trends, all three stations show significant increasing discharge in the long wet season (June through September). As a percentage of the 40-year seasonal mean, these increments were 26 % at Bahir Dar, 27 % at Kessie, and 10 % at El Diem. In addition, the results show a significant increase for the short rainy season discharge (March to May) at Bahir Dar by 33 % and Kessie by 51 %. This was likely caused by the start of operation of the Chara Chara weir in 1996 at the outlet of Lake Tana that increased the flow during the dry season. No significant change was observed at El Diem over the short rainy season. During the dry season (from October to February), the discharge at both Bahir Dar and Kessie did not change significantly but there was a 10 % significant decreasing trend at El Diem.

The only long-term erosion studies for which sediment concentration data are available for an extended period of time are for the small Soil Research Conservation Practices watersheds in the upper reaches of the large basins. It is not suitable for trend analysis in the Blue Nile basin. Nyssen et al. (2004) found that, historically, erosion and sedimentation were directly related to rainfall amounts. When the climate was wet, gullies formed and the rivers incised. When the amount of rainfall declined, the gullies filled up. The findings of Professors Ahmed and Bashir indicate that these historic trends apply to recent times as well, since the Rosieres dam at the border with Sudan filled up more during low-flow years than during wet years. Concentrations at the end of the rainy season were greater for the dry years than for the wet years (Steenhuis et al. 2012).

Most studies on the future changes in hydrology employ future rainfall rates predicted with Global Circulation models (GCM). The changing landscape is not included in these hydrological considerations. To assess the trend in landscape changes on discharge and erosion in the Blue Nile basin, this study investigated how, in the past, the landscape has affected discharge and erosion rates. This study used a mathematical model and applied it to a 40-year period from 1964 to 2003. Changes in best-fit parameters in time are assumed to be indicative of changes in the landscape.

8.2 Rainfall-Runoff-Erosion Simulation

Rainfall-runoff-erosion models can show if the relationship between rainfall, discharge, and sediment concentration has changed in time, and what are the underlying landscape parameters for this change (Mishra et al. 2004). This is different from statistical tests that examine trends in rainfall and discharge which are independent of each other.

The runoff and erosion model used here is the Parameter Efficient Distributed (PED) model that was validated for the Blue Nile basin by Steenhuis et al. (2009), Tesemma et al. (2010), and Tilahun et al. (2013a, b). In the PED model, various portions of the watershed become hydrologically active when threshold moisture content is exceeded. The three regions distinguished in the model are the bottomlands that can potentially saturate degraded hillslopes and permeable hillslopes. Each of the regions is lumped average of all such areas in the watershed. In the model, the permeable hillslopes contribute rapid subsurface flow (called interflow) and baseflow. For each of the three regions, a Thornthwaite–Mather-type water balance was calculated. Surface runoff and erosion are generated when the soil is saturated and assumed to be at the outlet within the time step. Percolation is calculated as any excess rainfall above field capacity on the permeable hillside soil. Zero-order and first-order reservoirs determine the amount of water reaching the outlet. Equations are given in Steenhuis et al. (2009), Fig. 8.1 (Tilahun et al. 2013a), and in Tilahun et al. (2013b). In Fig. 8.1, P is precipitation; E_p is potential evaporation; A is area fraction for zones with subscripts 1—saturated area, 2—degraded area, and 3—infiltration areas; S_{max} is maximum water storage capacity of the three areas; BS_{max} is maximum baseflow storage of linear reservoir; $t_{½}$ $(=0.69/\alpha)$ is the time it takes in days to reduce the volume of the baseflow reservoir by a factor of two under no recharge condition; and $\tau*$ is the duration of the period after a single rainstorm until interflow ceases.

Sediment concentrations are obtained as a function of surface runoff per unit area and a coefficient that decreases linearly from the transport limit at the start of the rainy monsoon phase to the source limit after about 500 mm rainfall. Tilahun et al. (2013a, b), based on the work of Hairsine and Rose (1992) and Ciesiolka et al. (1995), expressed the sediment concentration, C_r (g L^{-1}), in runoff from runoff source areas (Eq. 8.1):

$$C_r = [a_s + H(a_t - a_s)]q_r{}^n \tag{8.1}$$

where a_t is the variable derived from stream power and relates to the sediment concentration in the water when there is equilibrium between the deposition and entrainment of sediment and a_s is related to the sediment concentration in the stream when entrainment of soil from the source area is limiting. H is defined as the fraction of the runoff-producing area with active rill formation, q_r is the runoff rate, and n is the coefficient. Assuming that the interflow and baseflow are sediment free, the sediment load per unit watershed area, Y (g m^{-2} day^{-1}), from both the saturated and degraded runoff source areas can be obtained as flux per unit area, Eq. 8.2:

$$Y = A_1 q_{r_1}[a_{s_1} + H(a_{t_1} - a_{s_1})]q_{r_1}{}^n + A_2 q_{r_2}[a_{s_2} + H(a_{t_2} - a_{s_2})]q_{r_2}{}^n \tag{8.2}$$

where q_{r1} and q_{r2} are the runoff rates expressed in depth units for contributing area A_1 (fractional saturated area) and A_2 (fractional degraded area), respectively. Theoretically, for both turbulent flow and a wide field, n is equal to 0.4 (Ciesiolka et al. 1995; Tilahun et al 2013a, b; Yu et al. 1997). Then, the concentration of sediment in the stream can be obtained by dividing the sediment load Y (Eq. 8.2) by the total watershed discharge as shown in Eq.8.3:

$$C = \frac{(A_1 q_{r_1}{}^{1.4}[a_{s_1} + H(a_{t_1} - a_{s_1})] + A_2 q_{r_2}{}^{1.4}[a_{s_2} + H(a_{t_2} - a_{s_2})])}{A_1 q_{r_1} + A_2 q_{r_2} + A_3(q_b + q_i)} \tag{8.3}$$

where q_b (mm day^{-1}) is the baseflow, q_i (mm day^{-1}) is the interflow per unit area of the non-degraded hillside, and A_3 is the area water that is being recharged to the subsurface reservoir (baseflow).

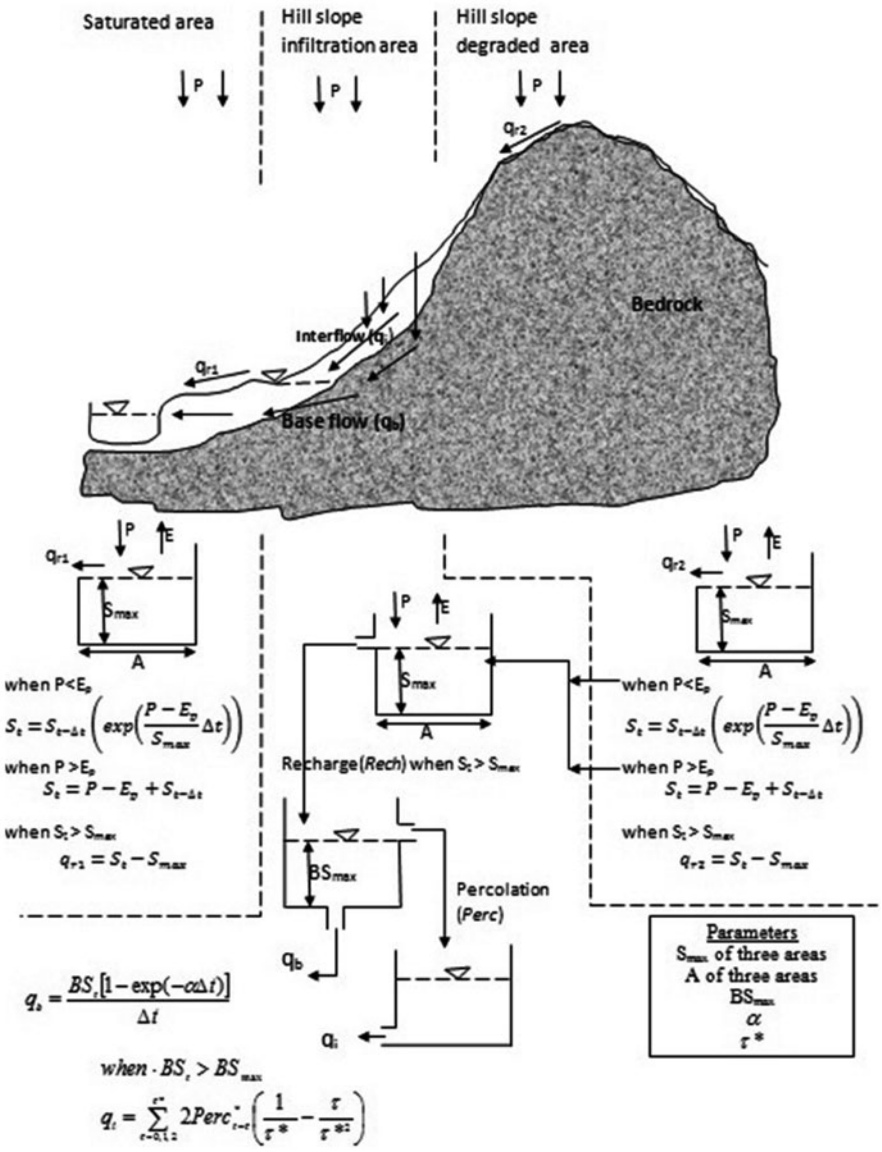

Fig. 8.1 Schematic of the hydrology model. (Tilahun 2013a)

8.2.1 Input Data

Two types of input data needed for the PED model are climate and landscape. Climate input data were derived from 10-day rainfall amounts of ten selected rainfall-gauging stations using the Thiessen polygon method (Kim et al. 2008). Potential evaporation was based on long-term average potential evaporation data over the basin and was equal to 3.5 mm day^{-1}for the long rainy season (from June to September) and 5 mm day^{-1} for the dry season (from October to May) (Steenhuis et al. 2009). Landscape input parameters of both the relative areas and the maximum amount of water available for evaporation for the saturated, degraded, and recharge areas in the basin were estimated. In addition to the six "surface parameters," the three baseflow parameters are the first-order baseflow reservoir constant, a zero-order interflow rate constant that indicates the duration of the linearly decreasing interflow, and the maximum water content of the baseflow reservoir. The landscape parameter values cannot be determined a priori and need to be obtained by calibration. The sediment input parameters, the sources and the H function, were calibrated similar to those of Tilahun et al. (2013a), with the exception that it was assumed that during the latter part of the rainy monsoon phase, some sediment in the streams would be picked up from the banks.

Since this study's interest was in the overall trend in the Nile basin, a relationship was established between precipitation and discharge, and between sediment concentrations and predicted surface runoff and discharge at El Diem at the Ethiopian and Sudan border. Available data at El Diem for this study were 10-day precipitation for the period from 1964 to1969; 1993; and from 1998 to 2003. Ten-day discharge measurements were available for 1964–1969, 1993, and 2003. Monthly discharge was available for the period 1998–2003. Erosion measurements were available only for 2 years, 1993 and 2003.

8.3 Results

Calibration of the model parameters (Tables 8.1 and 8.2) was based on the assumption that the subsurface flow parameters (interflow and baseflow) remained the same over time, as well as the storage of the landscape components. This study assumed that over the 40-year time span, only parameters that were affected by erosion would change. Since erosion makes the soil shallower, the fraction of the degraded soils that produce surface runoff was increased from the 1960s to the 2000s. For estimating sediment concentration, this study assumed that the erosivity (both transport and source limit) remained the same with time. Thus, the variations in concentrations were contributed by an increase in degraded areas over the simulation period.

The calibrated parameter values that are fixed throughout the rainy phase for the model are shown in Table 8.1. In accordance with earlier findings for small watersheds (Engda et al. 2011; Steenhuis et al. 2009; Tilahun et al. 2013a, b), this study assumed that a total of 15 % of the Blue Nile basin produced surface runoff when the area became saturated around the middle to end of July. Since the Blue Nile basin intercepts interflow that is missing in the water balance from the smaller basins, the interflow lasts approximately 5 months (Table 8.1) and is much longer than from the smaller basins. Half-life of the aquifer was 40 days and is in the range that is

Table 8.1 Model input parameters fixed in time for surface flow components, baseflow and interflow

Parameters		Input values	Units
A_s	Fractional area, saturated bottomlands	0.15	
$S_{max,\ s}$	Maximum water content saturated lands	200	mm
$S_{max,\ d}$	Maximum water content, degraded soils	10	mm
$S_{max,\ h}$	Maximum water content, permeable hillsides	250	mm
t^*	Duration of interflow after rain event	200	days
$t_{½}$	Half-life baseflow aquifer	40	days
BS_{max}	Maximum water content aquifer	80	mm
$a_{t,\ s}$	Transport limit erosion saturated lands	3	$(\text{g L}^{-1})(\text{mm d}^{-1})^{-0.4}$
$a_{t,\ d}$	Transport limit erosion degraded area	6.5	$(\text{g L}^{-1})(\text{mm d}^{-1})^{-0.4}$
a_s	Source limit erosion	3	$(\text{g L}^{-1})(\text{mm d}^{-1})^{-0.4}$

Table 8.2 Model input parameters variable in time for fractional areas of degraded hillsides and permeable hillsides

Period	Fractional areas of hill sides	
	Degraded	Permeable
1964–1969	0.10	0.75
1993	0.18	0.67
2003	0.22	0.63

found for the smaller basins. The calibrated transport-limiting and source-limiting coefficients are in the range found earlier as well.

As noted earlier, only the fraction of the degraded hillsides was adjusted so that the predicted discharge fit better to the observed 10-day discharge values for the periods 1964–1969,1993, and 2003. Since the three fractions should add up to one, an increase in degraded land resulted in a decrease in permeable hillsides (Table 8.2).

8.3.1 Discharge

In the 1964–1969 period, the observed and predicted discharge values corresponded most closely when the hillside (recharging the interflow and groundwater) made up 75 % of the landscape with a soil water storage of 250 mm (between wilting point and field capacity). Surface runoff was produced from the exposed surface or bedrock making up 10 % of the landscape and saturated areas comprising 15 % of the area (Tables 8.1 and 8.2, Fig. 8.2, solid line). After the dry season, the exposed bedrock needed to fill up to a storage of 10 mm before it became hydrologically active, whereas the saturated areas required 200 mm (Table 8.1) which were invariant in time. The Nash–Sutcliffe efficiency was an acceptable 0.88 for discharge over a 10-day period (Table 8.3). In Table 8.3, the last three rows indicate the goodness of fit when the degraded areas in the second row are used in the PED model for the years specified in the first column.

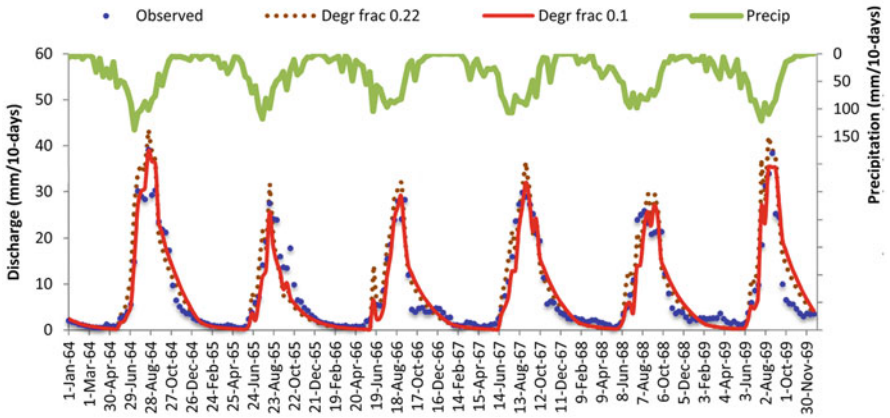

Fig. 8.2 Observed (*closed spheres*) and predicted (*solid line*, with 10 % of the watershed consist of degraded hillslopes) discharge for the Blue Nile at El Diem at the Ethiopian Sudan border for the period of 1963–1969. The *dotted line* is the discharge assuming that the degraded areas constitute 22 % of the landscape

Table 8.3 NS (Nash–Sutcliffe) values and RM (root-mean-square error) in mm day^{-1} for discharge at El Diem (*bolded numbers* are the best fit)

	1964–1969		1993		2003	
Fraction degraded area	0.12		0.18		0.22	
Period	NS	RM	NS	RM	NS	RM
1964–1969	**0.87**	**3.3**	0.87	3.4	0.84	3.7
1993	0.92	2.7	**0.94**	**2.4**	0.92	2.7
2003	0.95	3.1	0.97	1.7	**0.98**	**1.2**

In 1993, it was assumed that the fraction of degraded area in the basin increased to 18 % (Table 8.2) with otherwise the same input parameters. The predicted discharge fitted the observed 10-day values with a Nash–Sutcliffe efficiency of 0.94. Note that the average precipitation for 1993 came from a different source than Tesemma, and this study used a constant potential evaporation of 4 mm day^{-1} to obtain a mass balance. The best fit was obtained for 2003 by increasing exposed bedrock coverage to 22 % (from the 10 % in the 1964–1967 period) and decreasing the hillslopes by 12–63 % (Table 8.2), while all other parameters were kept the same (Table 8.1, Fig. 8.3b) when compared to 1993 (Fig. 8.3 a). The Nash–Sutcliffe model efficiency of 0.98 was again remarkably high for the PED model with nine input variables (Table 8.3). Similarly, small root mean square errors were obtained (Table 8.3). The high runoff Nash–Sutcliffe efficiencies are an indication that, although the model had only a few parameters, it effectively captured the hydrological processes in which various portions of the watershed became hydrologically active after the dry season.

To further confirm that the model parameters predicting discharge actually changed between the mid-1960s to the 2000s, the calibrated model parameters

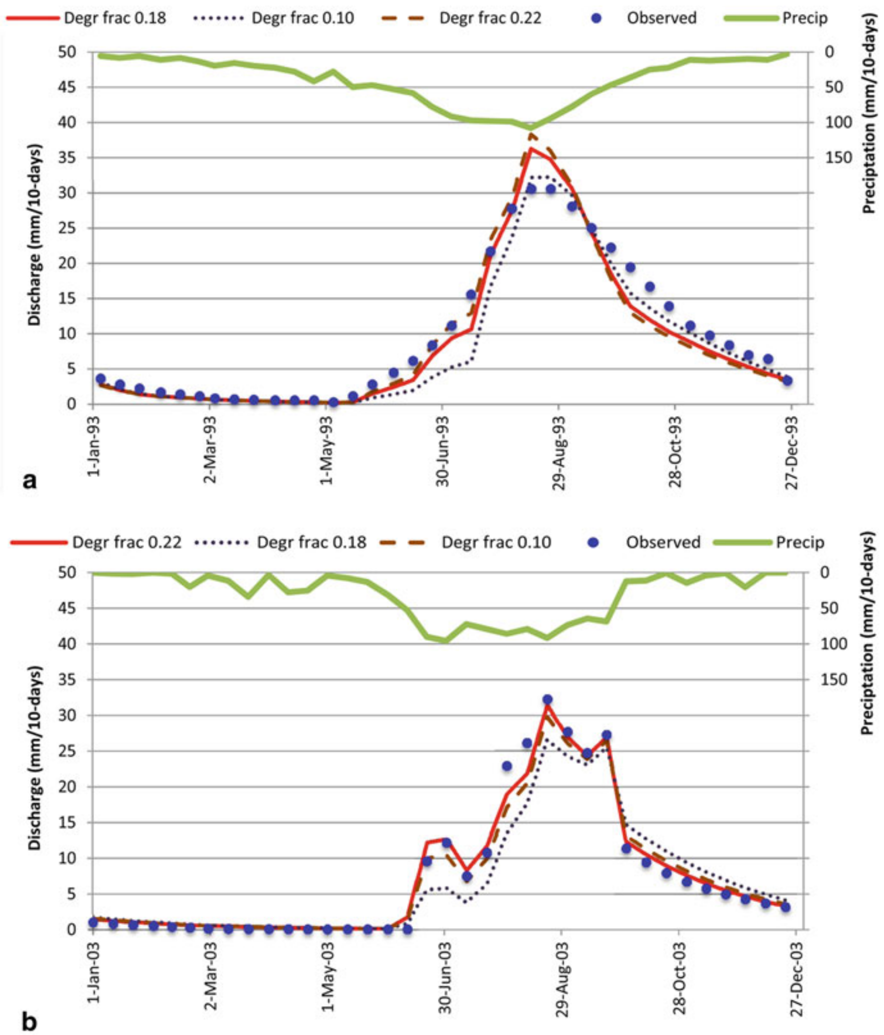

Fig. 8.3 **a** Observed (*closed spheres*) and predicted discharge (*solid line*) for the Blue Nile at El Diem at the Ethiopian Sudan border for three fractions of degraded hillsides for 1993, 10 % (*dotted line*), 18 % (*solid line*), and 22 % (*dashed line*). **b** Observed (*closed spheres*) and predicted discharge (*solid line*) for the Blue Nile at El Diem at the Ethiopian Sudan border for three fractions of degraded hillsides for 2003, 10 % (*dashed line*), 18 % (*dotted line*), and 22 % (*solid line*)

between the three periods were interchanged. The results (Table 8.3) show that the accuracy of simulation decreased when the degraded areas were inputted for the other periods. This was most distinct for the discharge simulations for 2003. The 10 % degraded area resulted in a Nash–Sutcliffe efficiency of 0.92 and a root mean square error of 3.1 mm/10-day (Table 8.3). This improved to 0.97 and 1.7 mm/10-day, respectively, for the 18 % degraded fractional area, and for the optimum 22 % degraded area the Nash–Sutcliffe was 0.98 and the root mean square error was 1.2 mm/10-day (Table 8.3 bottom row). Moreover, by comparing observed versus predicted discharge in Fig. 8.2, it became obvious that the peaks are overpredicted by using the 22 % degraded area (instead of the optimum 10 %) and the peak is underpredicted in Fig. 8.4b for the 10 % degraded area instead of the 22 %. The increased runoff with increasing degraded areas is also confirmed by calculating the average discharge for the years 1963–1969, 1993, and 1997–2003 which is 290 mm/year for a 10 % degraded area and 317 mm/year for 22 % degraded area. Thus, runoff increased by almost 10 %. The results in Fig. 8.3a are not as conclusive for the peak flows but show that initial amounts of runoff increased when the degraded areas increased, which is better simulated by the optimum solution. Finally, the simulations (Figs. 8.2 and 8.3a, b) show that the baseflow and interflow are decreased when the degraded areas are increased, because there is a smaller fraction of area in the watershed that fills up the reservoirs.

Although this model is based on a conceptual framework, it can be seen as a mathematical relationship that relates the spatially averaged 10-day rainfall to the 10-day watershed discharge. This relationship between rainfall and watershed discharge clearly changes over the 40-year period (Figs. 8.2 and 8.3a, b), indicating that the runoff mechanisms are shifting due to landscape characteristics since the precipitation variation is accounted for in the mathematical relationship.

The discharge model results explain soil erosion during the period from the early 1960s to 2000. The hillsides that were eroded in this period no longer stored rainfall as much and produced more runoff in 2003 that otherwise was a source of interflow in 1963. This in turn caused a greater portion of the watershed to become hydrologically active at an earlier stage, releasing more of the rainfall sooner and resulting in earlier flows and greater peak flow.

These simulation results are in line with the statistical result at the El Diem site, which shows increasing trends of runoff during long or short rainy seasons but decreasing dry season runoff, while annual flow has no significant change at El Diem. This is likely due to the large forest tracks in the south, but a significant increase in wet season flow in the upper Blue Nile was found by Tesemma et al. (2010) in a statistical analysis.

8.3.2 Sediment Concentrations

Sediment concentrations were simulated using Eqs 8.1–8.3. Input data consisted of surface runoff and baseflow and interflow calculated with the hydrology model (Fig. 8.1), with H function (Tilahun 2013a) and the transport and source limit (Table 8.1). Consequently, any erosion- related parameters were not changed for 1993 and 2003. In this case, the best-fit predicted line to the observed sediment concentrations was obtained for 1993. For estimating sediment concentrations in the Blue Nile River at El Diem for 2003, the same parameters were used with increased

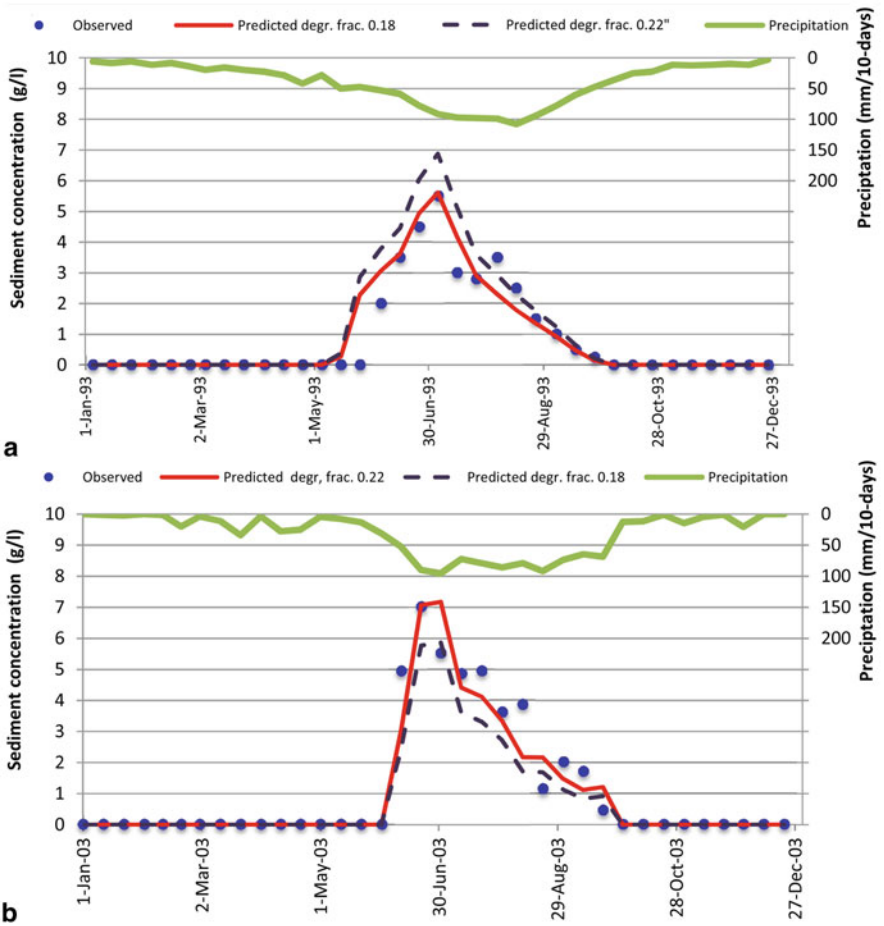

Fig. 8.4 **a** Observed (*closed spheres*) and predicted sediment concentrations (*solid line*) for the Blue Nile at El Diem at the Ethiopian Sudan border for two fractions of degraded hillsides for 1993,18 % (*solid line*) and 22 % (*dashed line*). **b** Observed (*closed spheres*) and predicted sediment concentrations (*solid line*) for the Blue Nile at El Diem at the Ethiopian Sudan border for two fractions of degraded hillsides for 2003, 18 % (*dashed line*) and 22 % (*solid line*)

surface runoff due to increased degraded hillsides, obtained from the hydrology model.

The simulation results are shown in Fig. 8.4a, b and the statistics in Table 8.4. The Nash–Sutcliffe efficiencies are very close to one for the averaged 10-day concentrations. For both years, interchanging the hydrology output of the PED model resulted in a poorer fit. For example, using the degraded area of 18 % for simulating 2003 the sediment concentration had a Nash–Sutcliffe efficiency of 0.90 while using the correct 22 % degraded area increased the Nash–Sutcliffe efficiency to 0.94 (last line Table 8.4). The root mean errors were also significantly improved.

Table 8.4 NS (Nash–Sutcliffe) values and RM (root-mean-square error) values for sediment concentration in g L^{-1} during the rainy monsoon phase at El Diem (*bolded numbers* are the best fit)

Period	1993		2003	
Fraction degraded area	0.18		0.22	
Year	NS	RM	NS	RM
1993	**0.97**	**0.9**	0.94	1.4
2003	0.90	1.3	**0.94**	**1.0**

While the total discharges were only minimally affected for the years 1993 and 2003, as can be seen in Fig. 8.4a, b, where the dashed line can hardly be distinguished from the solid lines, the sediment concentrations were significantly more affected. The peak concentration in 1993 of 5 g L^{-1} in Fig. 8.4a was well simulated by 18 % degraded area (solid line) but by using the 22 % degraded area in the PED model overpredicted the peak concentration to almost 7 g L^{-1}, an overestimate of 2 g L^{-1}. In Fig. 8.4b, the peak concentration of 7 g L^{-1} was well simulated by using predicted surface runoff and subsurface flows for the 22 % degraded area. The 18 % degraded area underpredicted the peak by more than1 g L^{-1}. In Table 8.4, the last two rows indicate the goodness of fit when the degraded areas in the second row are used in the PED model for the years specified in the first column.

8.4 Discussion

Since the PED model simulated the discharge and sediment concentrations well, the model parameters could be optimized so that the effect of increasingly degrading landscape could be detected in the output signal of both discharge and sediment concentration of the Blue Nile basin in Ethiopia. It is obvious from these results that landscape is becoming increasingly more degraded and has a significant effect on the discharge and more significantly on the concentration of sediment. To understand better what the effect of the increased degradation was on the discharge of the Blue Nile, the PED model was run over the period from 1964 to1969 and from1993 to 2003 with the fraction of degraded areas in 1964 (0.10), 1993 (0.18), and 2003 (0.22), Fig. 8.4a. Thus, doubling of degraded areas from 10 to 22 % increased the annual discharge at El Diem approximately from 30 to 33 cm per year. This 10 % increase in discharge (similar to the study by Gebremicael 2013) between the 10 % degraded area in 1964 and the 22 % degraded area in 2003 is highly important for Egypt. For instance, it is widely alleged that the current Nile flow is more than 85 billion m^3 (BCM) that was originally allocated in the 1929 treaty dividing the Nile flow between Egypt and Sudan. Although pure speculation, it might be very well that the original estimate of 85 BCM in 1929 might have been accurate and that the current alleged increase in Nile flow is caused by the degrading landscape in Ethiopia. If this scenario can be shown to be a reality, Ethiopia could argue for the use of the additional Nile flow due to the degradation for its planned irrigation works even though Ethiopia was not part of the 1929 treaty and is not abiding by it.

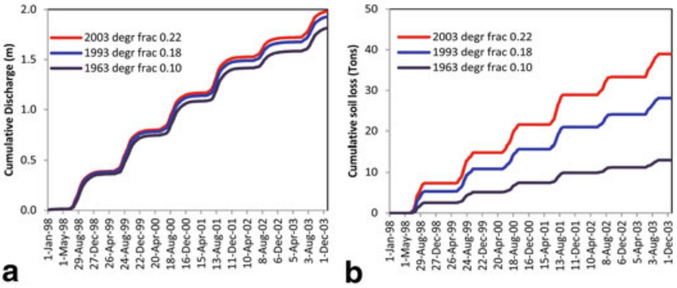

Fig. 8.5 **a** Cumulative runoff for the Blue Nile at the border with Sudan for the period 1998–1993 assuming an increasing fraction of the landscape becoming degraded. **b** Sediment losses for the Blue Nile at the border with Sudan for the period 1998–1993 assuming an increasing fraction of the landscape becoming degraded

To show that increasingly degrading landscape has significant effect on sediment concentration, again cumulative flows from 1998 to 2003 were used (Fig. 8.5a). Cumulative sediment load was calculated for the period assuming that land has not degraded since the 1960s when degraded area was 10 %, intermediate degrading in 1993 (18 %), and severe degrading in 2003 (22 %) of the land. It was assumed that erosion per unit land surface of the three land conditions was not affected which is realistic. An unlikely assumption was that conservation measures that significantly change land degradation was not carried out through this period. Thus, the threefold increase (Fig. 8.5b) from approximately 2 t ha^{-1} year^{-1} for the 10 % degraded area to 6 t ha^{-1} year^{-1} for the 22 % degraded area was the maximum that can be expected. The 5–6 t is equal to what is the same as the reported sediment loss at El Diem (Steenhuis et al. 2012), but the 2 t ha^{-1} year^{-1} in the 1960's at El Diem (assuming the same rainfall as in the 1990) is unlikely. Many soil and water conservation practices have been installed during the past 50 years and that would have lowered the present-day erosivity. This implies that the erosivity in the 1960s would have been greater resulting in more soil loss at that time than indicated in Fig. 8.5b.

Moreover, unlike the conclusion on discharge, the findings on the sediment concentrations are clearly limited by the restricted access to the sediment data at El Diem. In this case, there were only two good years of sediment data available and those were 10 years apart. The 2 years' sediment data indicated a significant increase in the sediment concentrations over a 10-year period, which was well simulated by assuming that the degraded areas increased. However, extrapolating this over a longer period of time, as was done in Fig. 8.5b, introduces uncertainty. Thus, more research needs to be done before our sediment load results representing the 1960s can be accepted.

8.5 Concluding Remarks and Challenges

The Blue Nile in Ethiopia that drops more than1,000 m from Lake Tana (1,786 m.a.s.l.) to the Ethiopian Sudan border in approximately 800 km distance has more than enough stream power to carry all the sediment delivered from the agricultural lands. Although there may be sediment deposition before the runoff reaches the stream, it was hypothesized that once the sediment is in the stream, it is carried downstream across the Ethiopian border. At the border with Sudan, sediment concentration as high as 12.3 g L^{-1} has been reported (Seleshi et al. 2011). This has positive and negative implications. When sediment delivery from the agricultural land is decreased, the concentration in the river is decreased as well and less sediment will deposit in the reservoirs. However, if more sediment is delivered when the landscape degrades more or if forests are being converted to agricultural lands, this additional sediment will be delivered downstream as well and will fill up the planned reservoirs at a more rapid rate once constructed.

Thus, the challenge is to decrease the landscape erosion. Currently, many soil and water conservation practices are being installed by farmers to decrease erosion. The farmers volunteer their labor on behalf of the government. This effort could be made more effective if the effect of these practices is monitored, and then install those that are most effective. In this regard, the study by Tilahun et al. (2013b) that show (gully) erosion from the bottomlands, especially at the end of the rainy season, is greater than from the upland is important. In addition, the model indicates that the degraded areas contribute greatly to the sediment load. Therefore, concentrating efforts in decreasing gully formation in bottomlands by planting permanent vegetation in the degraded areas will benefit most. In addition, there is some evidence in the experimental observations of Tilahun (2012) that tillage greatly accelerates soil loss and that no-till might be an effective soil and water conservation practice, provided that weeds and diseases associated with this practice can be suppressed (McHugh et al. 2006).

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Chapter 9
Spatial and Temporal Patterns of Soil Erosion in the Semi-humid Ethiopian Highlands: A Case Study of Debre Mawi Watershed

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Abstract The effectiveness of water management interventions is hampered by the lack of knowledge about the spatial distribution of runoff and associated soil loss. A study was conducted in the 95-ha Debre Mawi watershed in the Upper Blue Nile basin to understand where and when runoff and erosion takes place on the landscape. During the rainy phase of the 2010 and 2011 monsoons, storm runoff and sediment concentrations were measured from five sub-watersheds. In addition, perched groundwater tables, infiltration rates, and rill erosion from agricultural fields were measured. The results show that saturation excess runoff was the main runoff mechanism because the median infiltration rate was only exceeded 3 % of the time. Early during the rainy period, runoff produced from upslope shallow soils infiltrated

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downslope and did not reach the outlet. At the end of July, the bottomlands became saturated, and the runoff coefficient at the outlet became greater than upslope areas. Sediment concentrations were greater in the beginning of the rainy monsoon phase when the rill network had developed on the plowed land and it becomes lowest at the end of rainy phase when rill formation stopped. At all times, the sediment concentration at the outlet was greater than upslope because both runoff losses were greater in the saturated bottomlands and loose unstructured soil was available from newly forming gullies. This research indicates that watershed management interventions to control erosion should be implemented in areas which produce the most runoff such as those shallow upland soils and bottomlands near the river that become saturated by the end of the rainy phase. In addition, for proper planning and management, runoff and erosion models should capture these dynamics.

Keywords Erosion · Sedimentation · Ethiopian highlands · Nile basin

9.1 Introduction

African mountains and highlands are important resource areas for the African population (Messerli et al. 1988). The East African highlands and mountains above 1.5 km, being the center of major agricultural and economic activities, comprise up to 43 % of Ethiopia's land mass and constitute more than half of all the highland areas of Africa (Hurni 1988). However, soil erosion has been the cause of topsoil loss and declining agricultural production for a long time. The highlands have experienced erosion since the early Oligocene Epoch (29 Ma) with high, long-term incision rates that have increased exponentially from 0.05 to 0.32 mm year^{-1} (Gani et al. 2007). Currently, this rate has reached approximately 0.5 mm year^{-1} when averaged uniformly over the whole basin (Garazanti et al. 2006).

The economy and development of Ethiopia are directly affected by the locally high erosion rates (Hurni 1993; Sutcliffe 1993; Taddesse 2001). Erosion-induced decreases in land productivity can lead to greater food shortages (Bewket and Sterk 2003) by removing soil nutrients (Mitiku et al. 2006), decreasing water-holding capacity, and increasing overland flow from shallow eroded soils (Tesemma et al. 2010). In addition, it is becoming the main threat to planned reservoirs such as the Grand Ethiopian Renaissance Dam under construction in the Blue Nile basin, which is projected to generate up to 6,000 MW of energy.

In order to prevent siltation of the dams planned on the major rivers and to assist in agricultural development efforts, a large number of soil and water conservation (SWC) practices have been installed to reduce soil loss (Hurni 1988; Herweg and Ludi 1999; Nyssen et al. 2008). However, sediment concentrations, a measure often used to observe changes in erosion processes, have been increasing. This is likely due to a poor understanding of the spatial and temporal pattern of soil erosion on the highland undermining the design of these structures. One of the obstacles to effective soil conservation is that steep slopes are targeted for implementation while in reality most runoff and erosion processes are produced on the parts of the hillslope with shallow soil and lower slopes near the rivers through gullies (Steenhuis et al. 2009; Tebebu et al. 2010; Zegeye et al. 2010; Tilahun et al. 2013). Moreover, sediment concentration in the Ethiopian rivers uniquely decreases at the time when stream flow peaks during the first week of August (Awulachew et al. 2008). This dynamic is not well explained in the models currently used for the planning of SWC practices (Steenhuis et al. 2009; Tilahun et al. 2013).

Thus, in order to better estimate sediment concentration changes in the Ethiopian highlands influenced by a monsoonal climate, a better understanding is needed of soil erosion and sediment transport at various landscape units. In this chapter, we will use recently collected field experiment information in the Debre Mawi watershed (Tilahun 2012) to understand how soil erosion occurs spatially and temporally.

9.2 Watershed Description

The Debre Mawi watershed research site, named after the Kebele Debre Mawi in Yilmana-Densa Woreda (district), covers a total area of 523 ha. It is situated 30 km south of Bahir Dar adjacent to the Bahir Dar-Adet road at 37°22′ East and 11°18′ North in the western plateau of the Ethiopian highlands at the northern source region of the Blue Nile River (Fig. 9.1). The study area is a sub-watershed of approximately 95 ha, located in the upstream portion of the whole watershed. Its slope ranges from 1 to 30 % and topography ranges from 2,212 m above sea level (m.a.s.l.) near the outlet to 2,306 m.a.s.l. in the southeast.

The watershed is underlain by shallow highly weathered and fractured basalt overlain by dark-brown compacted clay, then by light-brown wet and sticky clay soil, and then finally by black clay and organic-rich soil sequences (Abiy 2009). The fractures are highly interconnected with limited clay infillings. Lava intrusion dikes block the fractures at several locations in the watershed. The dominant soil types in the watershed are Nitisols, Vertisols, and Vertic Nitisols. Nitisols (locally referred to as *Dewel*) are found in the upper part of the watershed. This is a very deep, volcanic-derived, and well-drained red clay loam soil and is considered the most productive and permeable soil. The Vertisols (locally referred to as *Walka*) are black and cover the lower slope positions. This soil forms deep, wide cracks during the dry period and it swells and develops an adhesive texture during the rainy period. Vertic Nitisols (locally known as *Silehana*) are located mid-slope between the Vertisols and Nitisols. It is reddish-brown in color and has properties of draining water when it is in excess and holding water when it is low in soil moisture. When it is dry, it has similar cracking properties as Vertisols. It is especially suitable for tef production.

Seventy percent of the watershed is cropland with the remaining areas as grassland, bush, or fallow that is either too dry or too wet for crop production (Mekonnen and Melesse 2011). Most of the upper (slope of 0–6 %) and middle area (slope of 6–27 %) of the sub-watershed is used for cultivation. The lower part of the watershed with

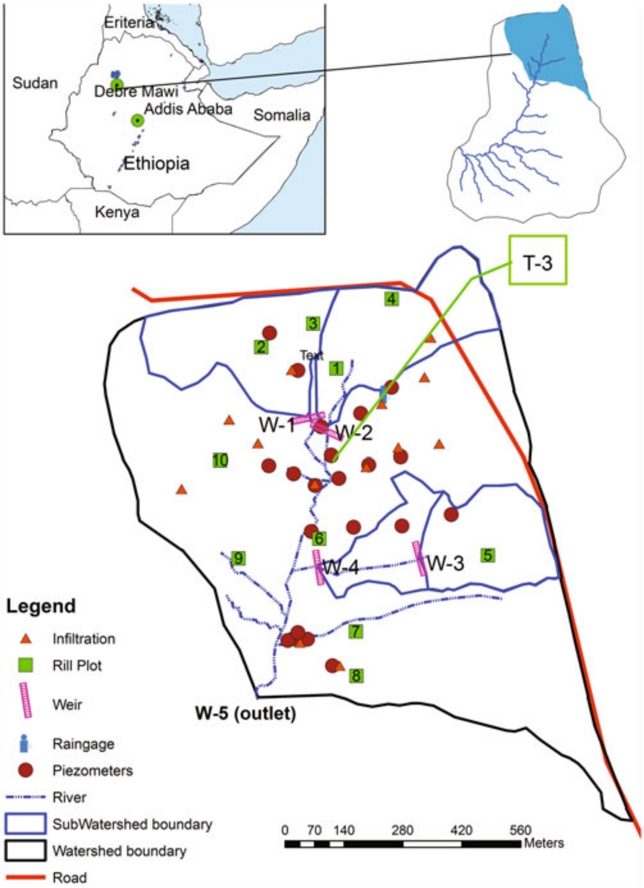


Fig. 9.1 Location, boundary, and drainage map of Debre Mawi with runoff and sediment concentration-monitoring sites (*W*), perched water table sampling (*dark red circles*) and infiltration test sites (*red triangles*), and agricultural field plots (*numbers inside the green square boxes*)

slopes of 0–6 % is usually saturated during the rainy season and covered with grass and gullies. These areas of the watershed serve as grazing land. Sparse shrubs are located at the middle, which are relatively steeper and difficult to plow.

Stone bunds existed at the mid-slope, perpendicular to the surface flow direction and form a conservation structure allowing soil deposition. Fields at the upper and middle are continuously cropped. Cereal-plow cultivation is the dominant cultivation system in the area, and most of the cultivated fields are planted with tef, wheat, maize, and barley. Finger millet, lupine (particularly, *Lupinus albus*), and grass pea are also common crops grown in the area.

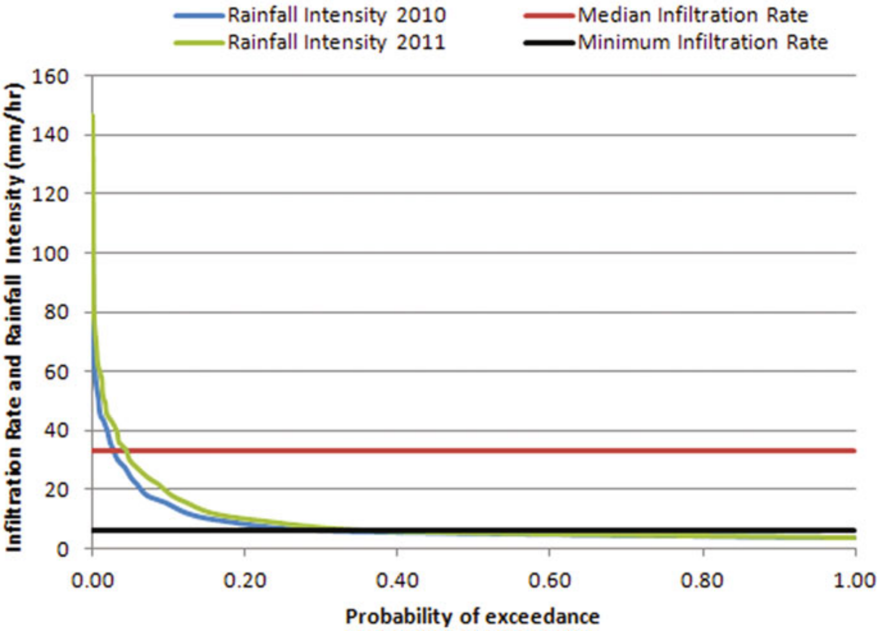


Fig. 9.2 The exceedance probability of the average intensities of 2,523 storm events and median infiltration rate for the Debra Mawi watershed in 2010 and 2011

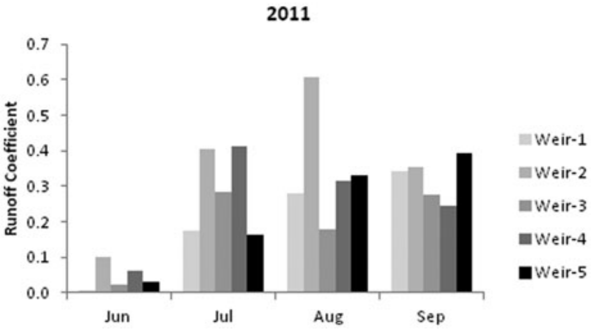
9.3 Runoff Mechanism in the Debre Mawi Watershed

9.3.1 Infiltration and Rainfall Intensity Measurements

Erosion and sediment transport are governed by the rainfall and runoff characteristics that define runoff mechanism. Field experiments were carried out during the summer of 2010 and 2011 in the Debre Mawi watershed to identify whether the dominant runoff mechanism was based on infiltration-excess or saturation-excess processes (Tilahun 2012). Rainfall intensity was calculated from automated rainfall measured using a tipping bucket rain gauge at 5-min intervals during the two summers. This rainfall intensity is compared with the spatially averaged infiltration capacity obtained from infiltration tests conducted at 14 locations in the watershed in August 2010.

The steady-state infiltration rates ranged from 6 to 360 mm h^{-1} in the Debre Mawi watershed. In general, infiltration rates were negligible on saturated areas close to the river, lowest in the downslope areas on Vertisols, and greatest in the midslope position of the landscape on Vertic Nitisol soils (Tilahun 2012). The average infiltration rate from all 14 measurements was 70 mm h^{-1} and the median 33 mm h^{-1}. The median infiltration rate is the most meaningful rate for comparison with rainfall intensity (Bayabil et al. 2010; Engda et al. 2011). The exceedance plot of rainfall intensities (Fig. 9.2) shows that the median infiltration is only exceeded with

Fig. 9.3 Runoff coefficients for 4 months at each weir for summer 2011



a probability of 1.5 % in 2010 and 4.4 % in 2011 suggesting the dominant runoff mechanism is saturation excess. However, the minimum rate was exceeded 30 % of the time indicating that surface runoff due to infiltration excess also occurs in the watershed. As shown later, this infiltration excess runoff tends to infiltrate further downslope in the more permeable soil when not saturated.

9.3.2 Rainfall and Runoff Characteristics

In order to understand the rainfall–runoff relationship, discharge was monitored at five gauging stations (one at the outlet (weir-5) and four at sub-watersheds (weirs1–4)) as shown in Fig. 9.1 during the 2010 and 2011 period. Furthermore, perched groundwater levels were monitored in 2010 using piezometers to map saturated areas and timing of saturation during the rainy period.

In order to easily compare runoff among the sub-watersheds and watershed outlets, a runoff coefficient (defined as the quotient of runoff and rainfall volume) was calculated for each storm and averaged for each month during which data were available (Fig. 9.3). An increase in runoff coefficient at each outlet occurred when the watershed became more and more saturated during the whole rainy phase of 2010 and 2011. The increase was more rapid in 2010 than in 2011, since there was more rain in June 2010 (Tilahun 2012). June 2011 (Fig. 9.3) has the lowest runoff coefficient indicating that most rainwater infiltrated. After June, the runoff coefficient for weir-5 at the outlet increased consistently over the two periods of observation indicating that the area of saturation increased during this time in the bottom part of the watershed. This has an effect on erosion as discussed later in the next section. In June and July, runoff from upslope areas are relatively greater than at the outlet indicating that it infiltrates downslope before it reaches the outlet. After increasing in saturation, which is corroborated by the perched groundwater level measurements as shown in Fig. 9.4, the runoff coefficient becomes higher at the main outlet than at sub-watersheds, with the exception at weir-2 where it is influenced by road drainage. Piezometer no. 7 (P7), as shown in Fig. 9.4, is located on the steep mid-slope part of the watershed where no perched water was observed because the water drained quickly as subsurface flow due to the high slope gradient. The water tables near P8

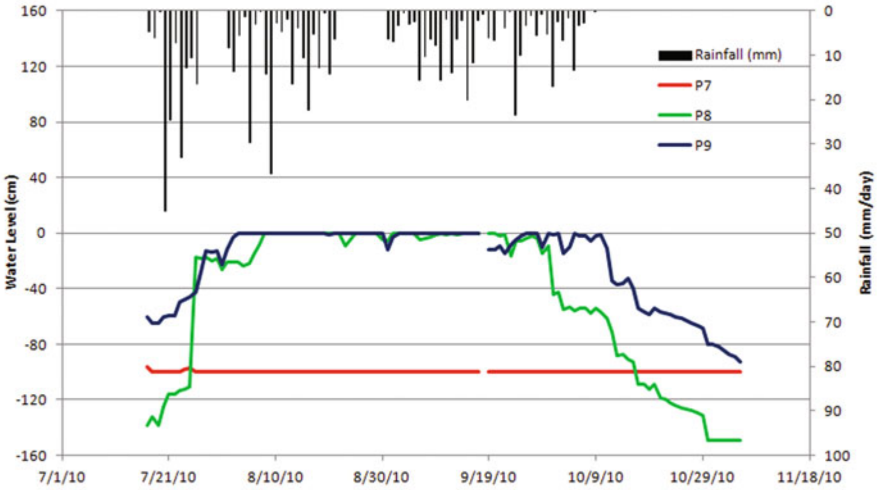


Fig. 9.4 Transect 3 (in Fig. 9.1) in the Debre Mawi watershed where the water level was measured twice a day and averaged during the 2010 main rainy season using the ground surface as a reference. Rainfall data shown at the top with bar graph were daily

and P9 in the grasslands on the lower gentle slopes of the watershed reached the surface in the first week of August and became saturated. Water drained from the steep upslope could not be carried off by the smaller slope gradient at these locations. The storm runoff (without including June and early-July runoff) correlated well with the cumulative effective rainfall (Fig. 9.5) with coefficient of determination (R^2) in the range of 0.58–0.82. This correlation is statistically significant at 1 % significance level with a P-value of less than 0.01 at all weirs (number of data, $n = 17$). The correlation became poor (0.38–0.56) when the June and early-July data were included implying that early rains in the rainy monsoon phase infiltrate and fill up the soil storage (Liu et al. 2008).

In general, infiltration capacities were greater than rainfall intensity on the soil except in some local degraded areas where the subsoil was close to the surface. In addition, since total storm rainfall and total discharge were correlated after the watershed was wetted up, we concluded that saturation excess runoff was the dominant runoff mechanism in the Debre Mawi watershed. Based on these findings, we will discuss the erosion processes in the watershed in the next section.

9.4 Soil Erosion and Sediment Concentrations in Debre Mawi

9.4.1 Upland Erosion

Ten representative fields were selected from the Debre Mawi watershed and the erosion rates from rills formed in these fields were determined after nine storm events in the periods from July 14, 2011, to September 15, 2011. The total area of

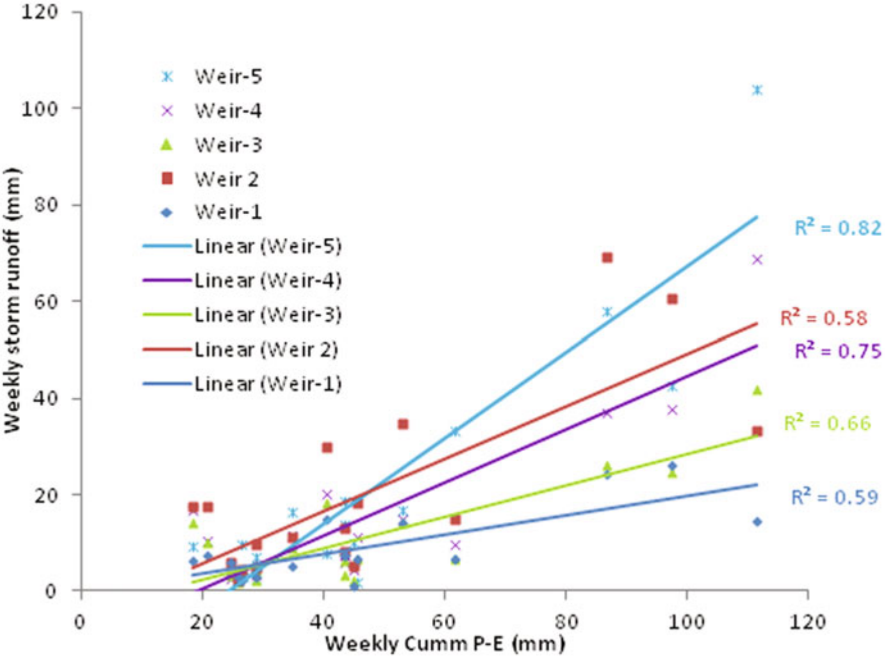


Fig. 9.5 Weekly summed effective daily rainfall and storm runoff relationships for Debre Mawi watershed excluding June and early-July data

the ten fields was 2.6 ha (almost 3 % of the watershed area, Table 9.1). These fields were selected at different slope positions in the watershed: upslope, mid-slope, and downslope fields (Fig. 9.1). Fields 1 and 6 were in maize; field 5 in fava bean; fields 7 and 10 in finger millet, and in the remainder of the fields (2, 3, 4, 8, and 9) tef was grown.

Spatially averaged cumulative soil losses (as indicated by the volume in the rills) and the rill density from ten agricultural fields (Fig. 9.1) increased from July 14, 2011 to the first week of August (Fig. 9.6). There was an apparent decrease in cumulative soil loss and number of rills after August 6, 2011 until the end of September when the rain stopped, and the rills were filled up by soil from the inter-rill areas. Therefore, the rate of soil loss from rills corresponds with the amount of soil lost on August 6. On average, the cumulative soil loss rate from rills in the watershed was approximately 60 t ha^{-1} (Fig. 9.6). But this rate varies in the landscape. Fields 3, 8, and 9 did not have any soil loss for days at the beginning of the observation period because the fields were not plowed (Table 9.1). Fields such as 1, 6, and 9 which are close to the valley bottom had an average cumulative soil loss of 200 t ha^{-1} while the upslope fields such as 2, 3, 4, and 5 had losses of 17t ha^{-1}. This difference between upslope and downslope was statistically significant at 1 % significance level using the F-test (Tilahun 2012). Increase of soil loss from agricultural fields varied with landscape position (Table 9.1) in Debre Mawi watershed and soil loss is related to wetness rather

Table 9.1 Cumulative soil loss rate from agricultural fields monitored in 2011

Field ID	Field size (ha)	Type of crop	Cumulative soil loss (t ha^{-1})								
			Jul 14	Jul 18	Jul 24	Aug 6	Aug 8	Aug 11	Aug 21	Aug 27	Sep 15
1	0.34	Maize	144.3	221.2	174.4	171.1	62.1	110.9	23.1	58.5	53.4
2	0.098	Tef	14.9	31.8	44.7	24.9	10.9	12.5	7.6	8.80	0.63
3	0.481	Tef	0.00	0.00	10.1	17.1	20.9	17.2	10.4	5.7	4.1
4	0.27	Tef	16.5	37.9	42.1	22.4	5.3	5.1	1.5	0.53	0.10
5	0.27	Fava bean	0.78	3.1	4.3	5.1	2.3	1.9	0.00	0.00	0.00
6	0.16	Maize	77.6	231.2	105.4	277.3	91.5	87.4	51.6	48.5	29.7
7	0.336	Finger millet	10.9	12.4	3.5	7.9	7.0	2.3	2.8	1.9	0.43
8	0.17	Tef	0.00	0.00	35.9	77.8	88.70	95.5	41.1	64.5	21.8
9	0.356	Tef	0.00	153.0	201.1	153.0	190.2	180.2	149.7	214.8	113.2
10	0.148	Finger millet	15.6	10.00	5.4	6.9	1.2	1.4	0.85	1.1	0.46

than run-on flux from upstream fields because farmers drain the water from these areas through field drainage furrows. The overland runoff rate is greater downhill than uphill because the soil is wetter, and less water is able to infiltrate generating more runoff that erodes more soil. This spatial variation on soil loss determines the sediment concentration variation within the watershed as explained in the next section.

9.4.2 Sediment Concentrations in the Rivers

In order to understand the spatial distribution of sediment transport and its temporal variation within the watershed, water samples (1 L volume) were taken at 10-min intervals for sediment concentration analysis in 2010 and 2011 at the five monitoring sites shown in Fig. 9.1 (weirs 1–5).

The sediment concentration and sediment load vary spatially along the landscape as shown in Fig. 9.7a, b. When the sediment concentrations from the different weirs are compared to each other (Fig. 9.7a, b), the sediment concentration and load at the outlet of weir-5 and weir-4 were always greater than the concentrations and loads at the outlets located upstream (weir-1 and weir-3). Sediment concentrations at the outlet in June and July were more than three times greater than that of the sub-watersheds. This indicates that there are hotspot sediment source areas close to the river channel and at the outlet in contrast to the findings of Mekonnen and Melesse (2011) that reported the most erosion from the upslope areas in the same watershed using the Universal Soil Loss Equation.

The spatial variation in soil loss is directly related to the runoff from agricultural fields. Runoff is generally greater downslope than upslope (Fig. 9.3). At times, the runoff is greater in the upslope area than downslope, the stone bunds located upslope trap some sediment. Agricultural fields 1, 6, and 9 with soil losses in the order of 200 t ha^{-1} are delivering sediment to the watershed outlet at weir-5 in which concentrations are consistently greater than upslope weirs (Fig. 9.7a, b). Upslope

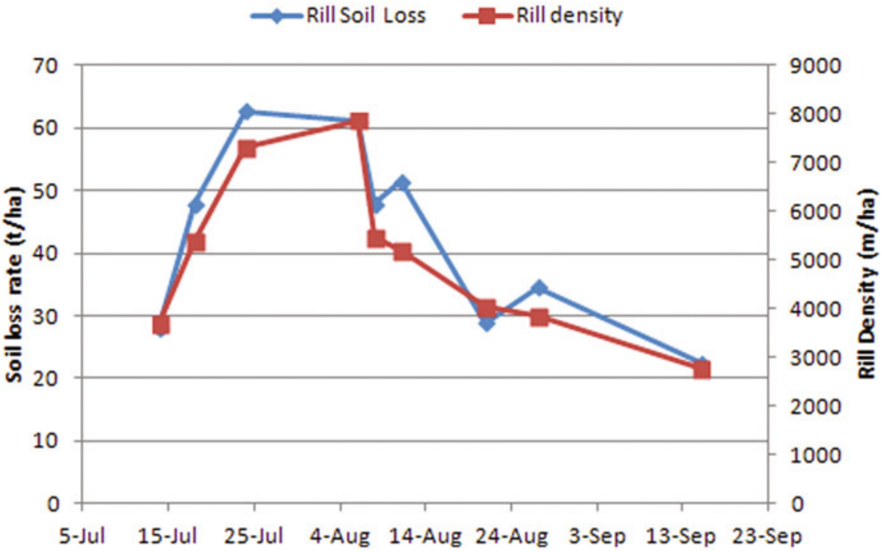


Fig. 9.6 Average cumulative soil loss and rill density for the agricultural fields measured in the summer of 2011 (x-axis shows date with format of day/month)

weirs (weirs-1 and 3) that were supplied by agricultural plots of 2, 3, and 5 had soil losses in the order of only 20 t ha^{-1} (Table 9.1).

The two plots in Fig. 9.7a, b show the monthly averaged sediment concentrations for two cases: Fig. 9.7a includes the high-intensity events of rainfall amounts in excess of 130 mm h^{-1} of June 12, 2011 and July 17, 2011 and Fig. 9.7b does not include these two storms in the monthly averages. Figure 9.7a, b show that the load, not the concentrations, is affected by the large storms. The July storm did not increase the concentration at all while the June storm resulted in a concentration increase from 3 to 4 % when the high-intensity storm was included. This confirms that the increasing trend of runoff (Fig. 9.3) and decreasing trend of concentration (Fig. 9.7a, b) balance each other in determining the magnitude of the sediment load.

Looking at the temporal variation within the watershed, sediment concentrations were up to 3 % by weight in June and July and then decreased in August and September to values of less than 0.1 % (Figs. 9.7a, b and 9.8). The decreasing trend in the sediment concentration (Figs. 9.7a, b and 9.8) is opposite of increasing runoff coefficient shown in Fig. 9.3. This is likely due to storms in June and early July having a low runoff coefficient as explained in Fig. 9.3. The lateral flow concentrated in rills and all runoff events carries as much soil as the transport capacity allows. This is confirmed reasonably well by the soil losses of upland erosion shown in Fig. 9.6 with sediment concentrations in the rivers (Figs. 9.7a, b and 9.8). Before July 24, 2011, the rills were actively being formed and sediment concentration increased. After that date, rill formation nearly stopped and the measured concentration decreased as well.

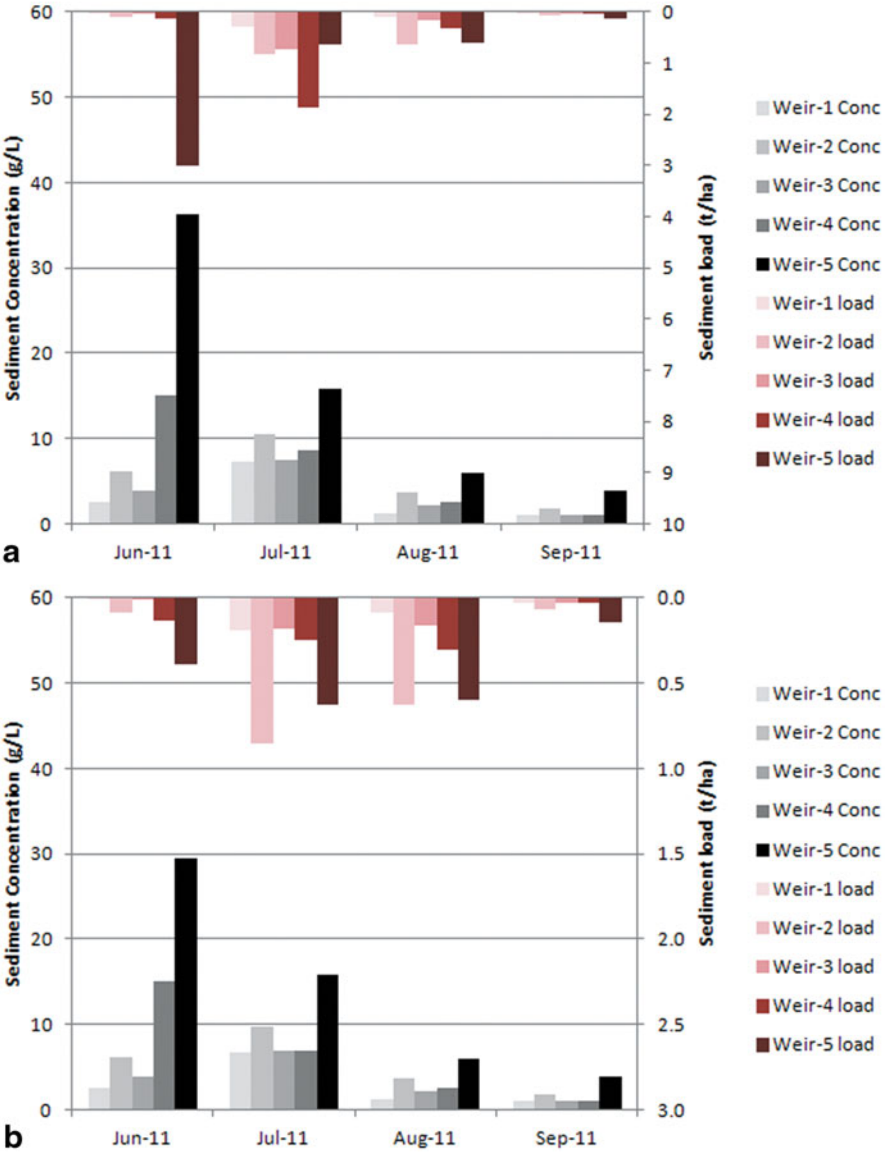


Fig. 9.7 Monthly average sediment concentrations and the corresponding sediment load at each sub-watershed for the rainy phase of the monsoon in 2011 for the Debra Mawi watershed **a** using all data and **b** excluding dates with rainfall intensities in excess of 130 mm h^{-1}

This timing also coincided with the timing of saturation of the watershed as shown in Fig. 9.4. This is likely one reason that concentration decreases as the rainy period progresses. As soil moisture approaches field capacity and saturation, the

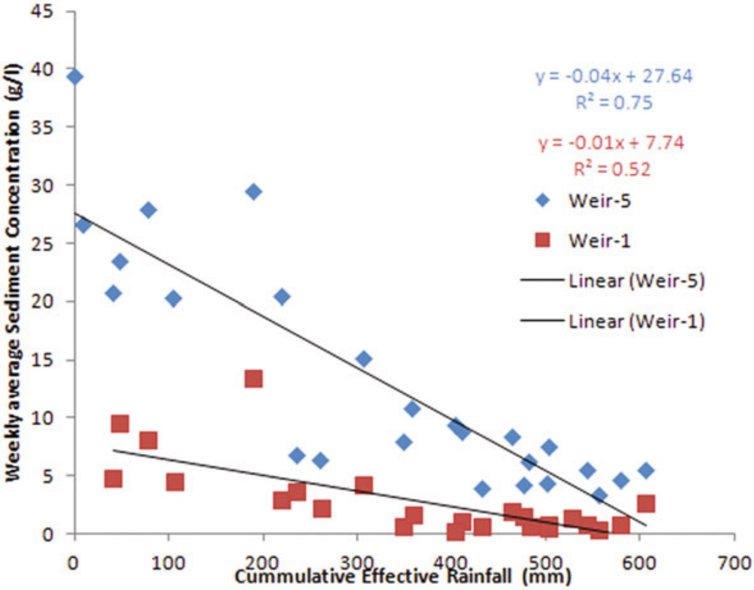


Fig. 9.8 Scatter plot of cumulative effective rainfall (P–E) and weekly average sediment concentration at the sub-watershed at weir-1 and at the watershed outlets at weir-5

cohesiveness of the soil increases for clay-dominated watersheds (Fredlund et al. 1996). Before saturation, it was mainly associated with the loose erodible sediment on the plowed land at the beginning of the rainy period. Since rill erosion theoretically occurs when the shear stress of the overland flow is greater than the critical sheer stress of the soil (Hofer et al. 2012), it was around the end of July that the relative magnitude of sheer stress of the runoff and critical shear stress reversed. Other researchers have, however, argued that the underlying reason for the decrease in erosion with time is due to sediment depletion and plant cover development (Descheemaeker et al. 2006; Awulachew et al. 2008; Vanmaercke et al. 2010) while others indicated the possibility of the dilution of sediment by an increase of subsurface flow after July (Tilahun et al. 2013).

Furthermore, the concentration decreased linearly for the sub-watershed at weir-1 in both years until the cumulative effective rainfall reached about 400 mm after which it remained at equilibrium (Fig. 9.8). However, the contributing watershed to weir-5 has linearly decreasing concentrations after 400 mm of cumulative effective rainfall. The watershed flowing to the outlet (weir-5) has additional losses of sediments from seasonally saturated active gully incisions that are easily transported when the runoff becomes higher. Weir-3 has similar behavior as weir-1, while weir-4 and weir-2 had intermediate behavior (Tilahun 2012). Physically, the sub-watersheds at weir-1 and weir-3 have no gullies and their sediment sources are only from upland erosion. The other sub-watersheds, however, have gullies with different levels of progression leaving loose soil in the channel that can be picked up by runoff water in the stream when discharge and steam power increase.

In general, the investigation of sediment concentrations and sediment load at five nested spatially different locations in Debre Mawi watershed showed that concentration varies along the landscape due to higher soil loss through rill erosion from agricultural fields located at downslope positions than from those located upslope. In addition, sediment sources from active gullying from downslope saturated areas are the causes. This indicates that best management practices should include downslope areas in addition to degraded hillslope areas.

One similarity among the landscape is that the concentration at the watershed outlet and sub-watershed outlet decreased with a similar trend after the end of July. The most likely reason for this is soil in the watersheds reach field capacity and saturation leading to the increase in cohesiveness that reduces entrainment of sediment by the flowing water after the month of July. The decrease of rill density and erosion from observations of ten agricultural fields after the heavy storm at the end of July led to the formation of maximum rill density and then any storm after this event produced lower runoff that decreased the shear stress of the flow and ability to entrain sediment and transport it to the outlet of the sub-watersheds. Erosion modeling practices should therefore consider these temporal and spatial dynamics in order to properly predict erosion patterns.

9.5 Conclusions

In this study, an experiment was conducted to identify the dominant storm runoff mechanisms and the process of erosion in the 95-ha Debre Mawi watershed by measuring infiltration rates, rainfall intensities, rainfall amounts, perched water tables, discharge, rill erosion, and sediment concentrations for the main watershed and four nested sub-watersheds. In general, rainfall intensities were greater than infiltration capacity of the soil except in some local degraded areas where the subsoil was close to the surface. In addition, since total storm rainfall and total discharge were correlated after the watershed was wetted up, it is concluded that saturation excess runoff was the dominant mechanism in the watershed. Sediment concentration from all five nested areas was higher at the beginning of the rainy period when erosion rate from rill was higher. It decreased in all areas after end of July when the watershed saturated and the rill density stopped developing further. However, sediment concentration at downslope areas was all the time greater than upslope areas due to higher runoff from saturated downslope areas. This supports the consideration of best management practices at downslope areas in addition to the shallow soil degraded hillslopes areas. In addition, modeling needs to consider local saturation and erosion dynamics for future planning of these practices.

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Chapter 10
Modeling Sediment Dynamics: Effect of Land Use, Topography, and Land Management in the Wami-Ruvu Basin, Tanzania

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Abstract Soil erosion and soil conservation have been major issues in Tanzania as it has been the case of many other tropical countries. Policy makers have identified soil erosion as a critical problem since the 1920s. However, it has been difficult to obtain reliable data on the type, extent, and current rates of soil erosion and sedimentation. The limitation of such information has delayed the current and future interventions for soil and water conservation in critical areas throughout Tanzania. The main objective of this study was to test the sediment prediction capability of the Water Erosion Prediction Project (WEPP) model on tropical watersheds and also identify erosion hotspot areas. Simulation of this initial study in Tanzania focused on secondary data. There was insufficient information about on-site soil properties, daily rainfall and temperature records, and initial condition of land use/cover data to define crop/plant growth and tillage practices. Runoff also varied with soil type in all four watersheds. The highest and lowest total average annual soil loss rate was estimated in Mfizigo Juu, 45.09 kg/m^2 and Kibungo chini, 0.45 kg/m^2, respectively. The cultivated land contributed to more than 81 % of soil loss and 86 % of sediment yield in all four scenarios. The overall spatial result maps indicated WEPP model can help water resources managers to implement necessary precaution measures to prevent sediment yield and soil erosion.

Keywords Erosion · Sedimentation · WEPP model · Runoff-discharge · Land management · Soil Erosion

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10.1 Introduction

Water resources management in recent years is facing many challenges including pressure on water demand. A number of studies have insisted the engagement of multisectoral natural resources management as cross-cutting agenda. Most of these studies focused on assessing quality and quantity of water available without linking to effects of land use, topography, and land management. Land degradation leads to the reduction or loss of biological or economic productivity of land caused by deterioration of physical, chemical, and biological or economic properties of soil. According to Hillel (1991), large-scale degradation of land resources has been reported from many parts of the world in different figures depending on the variation of causing factors. The economic impact of land degradation is extremely severe in densely populated areas of South Asia and sub-Saharan Africa that account for 70 % of the total degraded land of the world (Dregne and Chou 1994). It has been observed that about 75 % of soils in hilly areas are the most susceptible due to sheet, rill, and gully erosions (Hasan and Alam 2006). In addition, human alterations of land use have caused erosion rates to increase in many areas of the world, resulting in significant land and environmental degradation. However, in East African highlands, soil loss rate is reported to exceed the tolerable recommended limit (10–12 t/ha/year) by 50 t/ha/year (Kimaro et al. 2008). Since in Tanzania information and resources are limited, education to raise awareness on soil conservation seems to be more important to start with (Rapp et al. 1973). In addition, policy makers have been asking for quantification of erosion rates at local, regional, and global levels in order to develop environmental and land use management plans which will consider both on-site and off-site impacts of erosion (de Vente et al. 2008). However, because of limited resources, the Tanzanian government decided to concentrate only on land use management rather than implementing extensive projects for soil erosion prevention and conservation (Rapp et al. 1973).

Tanzanian water resources are managed at the basin level by implementing the concept of integrated water resources management (IWRM). IWRM practices vision ensures that water resources in a basin are sustainably managed for socioeconomic and environmental needs. The Wami-Ruvu basin is one of the nine basins in the country. Currently, water quality management at the Wami-Ruvu basin is facing challenges related to land use and human activities as a result of rapid population increase. The Morogoro District Council that occupies the Upper Ruvu catchment had a population of about 304,019 in 2011 with an average population density of 25 people/km^2 in 2000 at the Upper Ruvu catchment (Mt. Uluguru). The catchment accommodated 60% of the total population with a population density of 250–300 people/km^2 (URT 2011). Ruvu River catchment has been affected by agricultural activities toward Uluguru Mountains as a result of population increase.

Wetlands available in lower Ruvu plains have been affected by increase of sediments (Ngoye and Machiwa 2004). In addition, observed increase of turbidity from 130 NTU in 1992 to 185 NTU in 2002 in the Ruvu River subbasin was a result of the increase in agricultural activities (Yanda and Munishi 2007). Deforestation on the other hand is another major problem facing Uluguru, Ukagulu, Nguru, and Mgeta mountain forests in Ruvu subbasins derived from demand for timber cutting, collection of firewood, and land clearing for agricultural purposes and timber production. However, the forests and woodland cover in the Uluguru Mountains has decreased by 12.7 and 59.0 % in 1995 and 2000, respectively (Yanda and Munishi 2007).

Different studies have been conducted to explain the processes of erosion, identify the major factors influencing the processes, and also develop models suitable to quantify the processes. Most of these models have been "on-site impact oriented" by identifying loss of soil from a field. The breakdown of soil structure, and the decline of organic matter and nutrients, results in a decline in soil fertility and a reduced food security and vegetation cover. Furthermore, "the off-site effects" of erosion include sedimentation problems in river channels, increased flood risk, and reduced lifetime of reservoirs (de Vente et al. 2008). Most available studies and modeling have limitations in the applicability and adaptability to tropical larger watersheds (Ndomba 2007, 2010). The challenge to slopes and topography is reported to affect sediment loading as compared to total watershed sediment yield. Although several soil erosion modeling studies have been adapted in larger tropical watersheds, validation with field measurements gave unreliable estimates (Ndomba 2010). Therefore, this study aims at contributing to the development of a sediment assessment model/framework using Water Erosion Prediction Project (WEPP) in Upper Ruvu subbasin. This study gives insight into the water quality problems related to sediment loading in streams to Kibungo catchment. It specifically aims to estimate the quantity of sediment yield delivered from the upland areas and identify areas that will benefit most from soil conservation practices. Quantification of sediment yield and upland/hillslopes and catchment runoff using the WEPP model will unfold information required for the ongoing effort to enhance river water quality management as an integrated component of water resources management of the Wami-Ruvu basin.

10.2 Study Area

Wami-Ruvu Basin covers approximately 66,820 km^2 with three subbasins which are the Wami River subbasin 43,946 km^2, Ruvu catchment 18,078 km^2, and coastal rivers 4,796 km^2 (Fig. 10.1). This study focused on the Upper Ruvu River subbasin where there is an ongoing implementation of the Kidunda dam for Dar es Salaam city and coast region water supply. The subbasin is located between latitudes 6°05′S and 7°45′S and longitudes 37°15′E and 39°00′E. The rivers that flow in this subbasin are Mvuha, Mfizigo, Ruvu, and Mgeta whose headwaters are in the Uluguru and Mgeta mountains 2,634 m above sea (WRBO 2010). Ruvu is the main river fed by its tributaries Mgeta, Mfizigo, Mvuha, and other small streams. The regime of the Ruvu River reflects the trend of the wet and dry seasons. According to the basin office and Ministry of Water report, the river flows at the Kidunda and Mikula stations decrease from about 60 m^3/s in May to around 25 m^3/s in October or September. After this month, it rises slowly reaching 70 m^3/s in December. In January and February, the flows arrive at 60 and 50 m^3/s, respectively. The highest monthly

Fig. 10.1 Location of the study area

average flow is reached in April at around 160 m^3/s. The lowest value of about 5 m^3/s has been reached in October. The mean annual flow is approximately 66 m^3/s (SP Studio Pietrangel Consulting Engineers 2010). To fulfill the objectives, this study focused on the Kibungo catchment. For a detailed study, as required by WEPP model, the subbasin was delineated further to get four catchments which are Mgeta, Kibungo, Ngerengere, and Ruvu. The catchments were selected considering the type of regulation (natural or modified) and the region geographical importance.

10.3 WEPP Model Overview

The WEPP is aimed at developing process-based prediction technology to replace the universal soil loss equation (USLE). The WEPP model operates on a continuous daily basis by using mainly physically based equations (Baigorria and Romero 2007). It describes hydrologic and sediment generation and transport processes at the hillslope and in-stream scales (Baigorria and Romero 2007). The basic WEPP hillslope model components are weather generation (climate), surface hydrology, hydraulics of overland flow, hillslope erosion, water balance, plant growth, residue management and decomposition, soil disturbance by tillage, and irrigation (Foster and Lane 1987). With limitations in availability of data to this study, main input components are weather generation, surface hydrology, hydraulics of overland flow, hillslope erosion, residue management and decomposition, and soil disturbances. A unique aspect of the WEPP technology is the separation of the erosion processes into rill detachment (as a function of excess flow shear stress) and interrill detachment. Additionally, the model simulates sediment transport and deposition, and off-site sediment particle size distribution. These items allow better assessment of soil erosion at a site, and subsequent sediment transport to channels and impoundments in catchments (Foster and Lane 1987).

WEPP has been tested and applied in different geographic locations across the world out of the USA. In Peru (Baigorria and Romero 2007), the model was validated using three different-sized runoff plots, at four locations under natural rainfall events. According to Baigorria and Romero (2007), all climatic characteristics, soil physical parameters, and topographical and management characteristics were determined in the field and laboratory. The measured runoff and erosion from agricultural fields were low compared to predicted levels. A poor relationship between runoff and sediment yield as well as rainfall and runoff was observed, and this poor relationship was observed because of the dynamic change in soil properties during rainfall events due to sealing (Baigorria and Romero 2007).

In Africa, with little modifications, WEPP has been used in mountainous catchments. For instance, WEPP has been tested in the Anjani catchment, Ethiopian highlands (Zeleke 2001). The emphasis was on the new standalone program to create a climate input file for WEPP using standard weather data sets called breakpoint climate data generator (BPCDG). However, the final results overpredicted runoff and underestimated soil loss. In addition to that, validation of the model was done in Kenya at Amala and Nyangore upstream watersheds of Mara River basin (Defersha and Melesse 2012; Defersha et al. 2012). Simulated runoff was reasonably compared to observed results. However, sediment yields and erosion were fairly simulated for different land use areas as expected (Deferesha and Melesse 2012; Defersha et al. 2012). In North Africa, the analysis of model performance on sediment yield and runoff predication was conducted on Mediterranean cultivated Kamach catchment, Tunisia. In the Minnesota River basin, WEPP was applied to estimate sediment load as well as evaluate the effect of subsurface drainage using tiles on runoff and sediment transport (Maalim and Melesse 2013; Mallim et al. 2013).

10.3.1 Predicting Runoff (Interflow and Base Flow)

Hydrology within the watershed reflects on the effects of water balance, channel hydrology, and soil effects. WEPP mathematical calculations of channel hydrology and water balance are the result of infiltration, evapotranspiration, soil water percolation, canopy rainfall interception, and surface depressional storage. The model uses the Green-Ampt Mein–Larson approach to simulate the temporal changes in infiltration rate during the rainstorm (Ascough et al. 1997). Runoff which is rainfall excess occurs when rainfall rate exceeds infiltration rate. This is assumed to start after the depression storage is filled. The differential form of mathematical equation for soil matrix of infinite depth is

$$i = k_e + \left(1 + \frac{(\phi - \theta_{\circ})\varphi_c}{l}\right) \tag{10.1}$$

where

i	Actual infiltration rate (m s^{-1})
k_e	Effective hydraulic conductivity of the wetted zone (m s^{-1})
$\theta_{\circ}$	Initial saturation (m^3 m^{-3})
ϕ	Effective porosity (m^3 m^{-3})
φ_c	Effective capillary tension or wetting front suction potential (m)
l	Cumulative infiltration (m)

Water balance is based on a component of the simulator for water resources in rural basins (SWRRB) model with some modifications for improving estimation of percolation and soil evaporation parameters (Ascough et al. 1997). The distribution of water through soil layers is based on evapotranspiration percolation models and storage routing techniques. If the potential surface storage depression is completely satisfied, the positive difference between the net rainfall intensity at the ground surface and the infiltration rate becomes the input to the overland flow calculation (Defersha et al. 2012). The basic equations which describe the movement of water are based on the laws of mass and momentum conservation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = r(t) - i(t) = q(x, t) \tag{10.2}$$

and

$$Q = \propto PR^{m-1} \tag{10.3}$$

with

$$\propto = \mathrm{C}\sqrt{\mathrm{s}} \tag{10.4}$$

where

A	Cross-sectional area (m^2)
t	Time (s)
Q	Discharge (m^3/s)
x	Down slope distance (m)
r	Rainfall intensity (m s^{-1})
i	Local infiltration rate (m s^{-1})
q	Lateral inflow rate (m s^{-1})
R	Hydraulic radius (m)
P	Wetted perimeter (m)
m	Depth-discharge exponent Chezy: $m = 3/2$, Manning: $m = 5/3$
α	Depth-discharge coefficient ($m^{1/2}$ s^{-1})
s	Average slope (mm^{-1})

In WEPP, the overland flow is conceptualized as plane runoff which means that A is substituted by the average flow depth h (expressed in m). Equations 10.5 and 10.6 are solved analytically by the methods of characteristics which require the rewriting of these equations as differential equations on characteristics curve on the x–t plane:

$$\frac{dh}{dt} = v(t) \tag{10.5}$$

and

$$\frac{dx}{dt} = \alpha m h(t)^{m-1} \tag{10.6}$$

where

h Flow depth (m)
v Runoff or rainfall excess (m s^{-1})

These equations are solved together with the infiltration calculations by using a Rungge–Kutta iteration scheme with as spatial resolution of one hundredth of the total hill slope length and a time step of 1 min.

10.3.2 Predicting Sediment Concentration

Hillslope Erosion (Rill and Interrill) The WEPP model divides erosion into two types: rill and interrill erosion. The movement of the sediment along the hillslope is described on the basis of the steady-state sediment continuity equation which is applied flow conditions (Elliot et al. 1995; Flanagan et al. 2007; Nearing et al. 1989):

$$\frac{dG}{dx} = D_i = D_r \tag{10.7}$$

where

G Sediment load (kg sec^{-1} m^{-1})
x Distance down slope (m)
D_r Rill erosion rate (kg sec^{-1} m^{-1})
D_i Interrill erosion rate (kg sec^{-1} m^{-1})

The interrill erosion is estimated from the equation

$$D_i = K_i I^2 S_f f(C) \tag{10.8}$$

where

D_i	Detachment rate (kg $\sec^{-1}$ m^{-2})
K_i	Interrill soil erodibility parameter (kg $\sec^{-1}$ m^{-4})
I	Effective rainfall intensity (m $\sec^{-1}$)
S_f	Slope factor (m $\sec^{-1}$)
$f(c)$	Function of canopy and residue

The erosion rate in rill erosion is a function of hydraulic shear and amount of sediment already in the flow (Elliot et al. 1995; Nearing et al. 1989). Rill is estimated in WEPP model by:

$$D_r = K_r(t - t_c)\left(1 - \frac{G}{T_c}\right) \tag{10.9}$$

where

D_r	Rill erosion rate (kg $\sec^{-1}$ m^{-2})
K_r	Rill soil erodibility parameter (sec m^{-1})
t	Hydraulic shear of water flowing in the rill (Pa)
t_c	Critical shear below which no erosion occurs (Pa)
G	Sediment transport rate (kg $\sec^{-1}$ m^{-1})
T_c	Rill sediment transport capacity (kg $\sec^{-1}$ m^{-1})

WEPP model is based on modern hydrological and erosion science. It calculates runoff and erosion on daily basis (Baigorria and Romero 2007). Its simulations can be enhanced by using digital sources of information through the linkage with geographic information systems (GIS). The GeoWEPP model is a geo-spatial erosion prediction model developed to incorporate advanced GIS features (ArcGIS software and its Spatial Analyst extension) to extract essential model input parameters from digital data sources.

GeoWEPP is designed to integrate four different data for accuracy of WEPP process-based model. The main inputs include topography, soil, land use, and climate information while the basic maps required should be in American Standard Code for Information Interchange (ASCII) formats exported by ArcGIS. The scales and resolution of the spatial inputs can vary according to the variable.

10.4 WEPP Application

In this study, data requirements were in accordance to GeoWEPP for ArcGIS 9.x Full Version Manual for GeoWEPP Version 2.2008. The GeoWEPP package includes two tools that further expand its utility. These are the topographic parameterization (TOPAZ) tool and Topwepp software products developed by the US Department of Agriculture/Agricultural Research Service (USDA-ARS). The TOPAZ generates hillslope profiles by parameterizing topographic data using a given digital elevation model (DEM). This process provided the needed input data for the subsequent

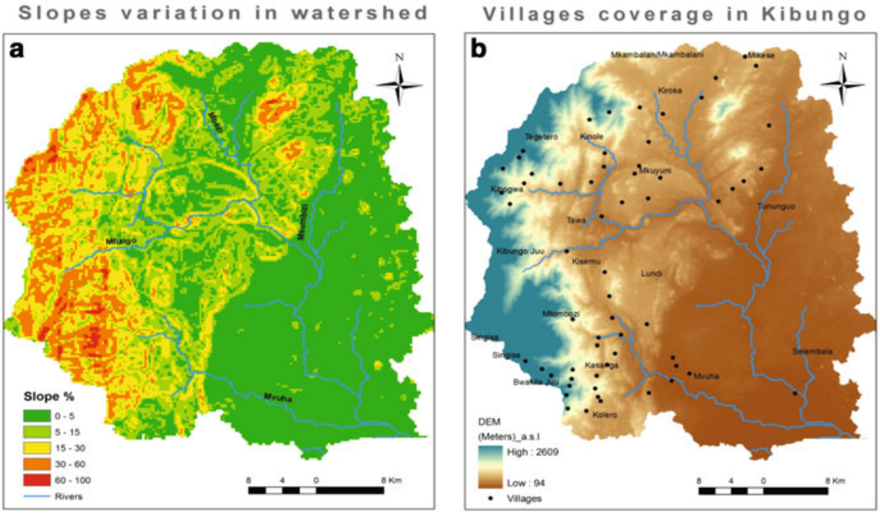


Fig. 10.2 **(a)** Slope map and **(b)** population increase toward high elevation in Kibungo subwatershed

delineation of a watershed, subcatchments, flow direction determination, and channel network generation. Topwepp uses grid-based information stored in the raster layers of the land cover; soil and land use management to execute the model runs and produces the output maps.

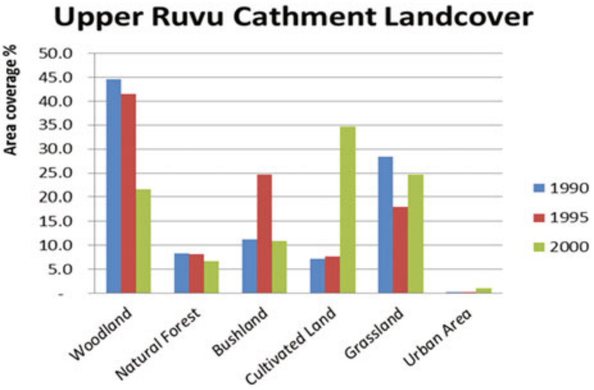
10.4.1 Topography

The DEM of 30 m resolution (Fig. 10.2b) was downloaded from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM (ASTER GDEM) website. The ASTER GDEM provides topographic information of the global terrain. A polygon representing study area was used to extract study area DEM from the original data set using the Spatial Analysts tool. The advantage of using this high resolution of 30 m is its applicability for GeoWEPP modeling. Figure 10.2a shows the slope values of the study area in percent and existing rivers used to delineate catchments in GeoWEPP The projected DEM was changed to raster format and then converted to ASCII format using the ASCII conversion tool in ArcToolbox of ArcGIS.

10.4.2 Soil Data

The geology of the catchment is influenced by the Precambian Usagarian system that has suffered different plutonic histories and Neogene. The area contains Jurrassic, Karoo, Neogene, and Quaternary strata in some parts of the catchment. There are

Fig. 10.3 Land use changes in the Upper Ruvu catchment



different types of soils in the upper river basin that vary in texture from sand to clay. Soil map of the study area was downloaded from the Harmonized World Soil Database (HWSD) from the Food and Agriculture Organization (FAO) with a scale of 1:2,000,000. The data were in tagged image file format (TIFF) converted to grid and reprojected in similar cell size and resolution of DEM and then converted to shape file. The different soil types in the upper river basin were classified as per the Soil Terrain Database of East Africa (SOTER) classification. The main soil orders are Fluvisols, Cambisols, Leptosols, Acrisols, Ferralsols, and Vertisols. Three essential soil files required in the model (an ASCII and two text files) were generated. The shape file was converted to raster format then converted to ASCII format. The soil data, the soilmap.txt, and soilmapdb.txt were created with the map unit key and the map unit symbol corresponding to the raster value and description, respectively.

10.4.3 Land Cover Data

The land cover in the study area is characterized by various types of natural vegetation. Cultivation is the main land use activity in the catchment. Human settlements in the most steep area range from small towns to villages (Ngoye and Machiwa 2004). A high percentage change of land cover from 1990–2000 caused by agriculture and settlement was observed (Fig. 10.3). The 1990 land use/land cover used in simulation considered as presettlement period to give snapshot erosion effects at that period. The shape files converted to raster format making sure the projection and cell size are similar with DEM and then exporting the attribute table values to text file. The raster also was converted to ASCII format to be used in modeling.

10.4.4 Climate Data

Monthly climate data for the study area were obtained from Tanzania Meteorological Agency (TMA) and Morogoro Weather stations as recorded by Wami Ruvu Basin

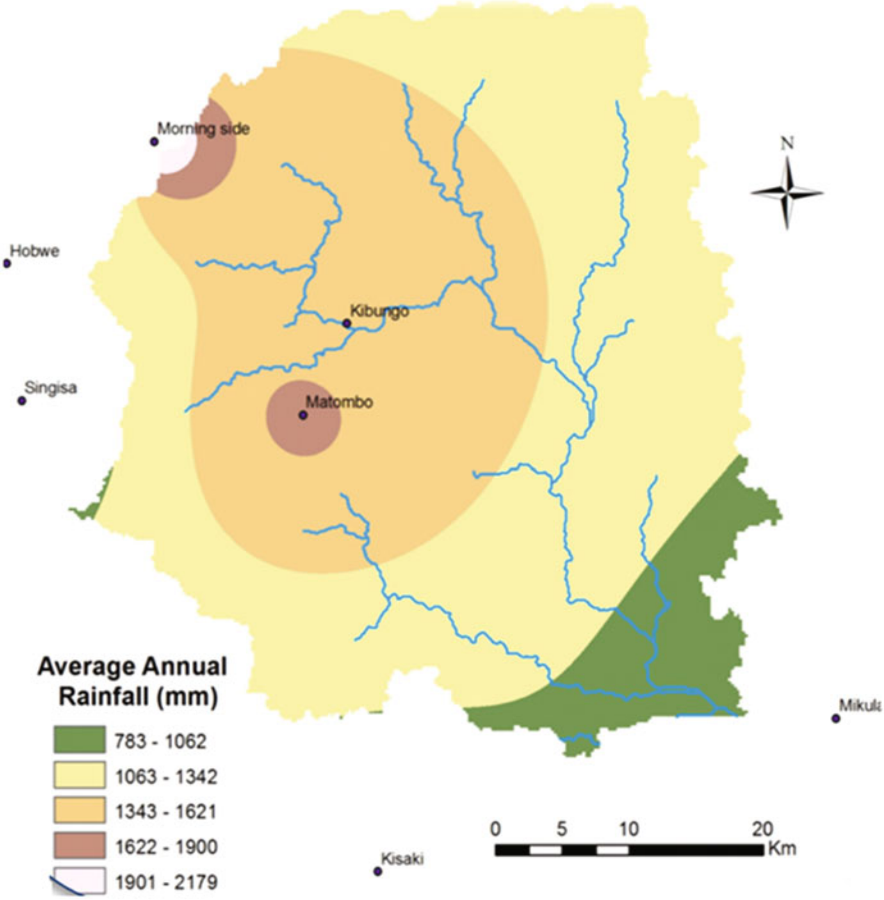
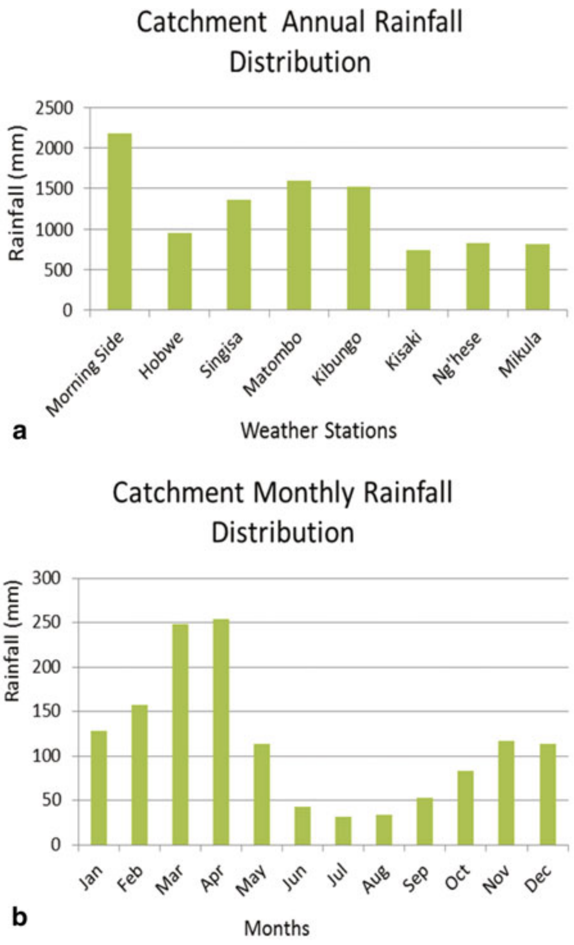


Fig. 10.4 Rainfall variation with elevation: upstream and downstream of the Kibungo subwatershed

Water Office (WRBWO). For this study, a total of ten available meteorological/weather stations were selected, namely, Matombo Primary School, Hobwe, Morning side, Mikula, Kisaki, Ng'ese Utari, Duthumi Singisa, Mtamba, and Ruvu at Kibungo (Fig. 10.4). Stations selected were those within or near the study area and with 30 or more years (between 1950 and 2005) of monthly and some with daily data acquired for further processing (Fig. 10.5). Based on information from these gauges, the mean annual rainfall varies from 900 to 1,300 mm and daily temperature ranges between 22 and 33 °C.

Maximum and minimum daily temperatures and precipitation depths are required as model inputs. The data were analyzed by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) tool which allows modification of an existing WEPP climate parameter file—the files WEPP uses to generate the climate events for a simulation. PRISM allows this modification to the WEPP climate

Fig. 10.5 Rainfall variation in the Upper Ruvu catchment as recorded in eight weather stations (1950–2005) average: **a** annual, **b** monthly



parameter files so that it can more closely match the climate found in area of interest (Minkowski and Reschler 2008). The information in PRISM files are monthly temperature, precipitation, and wet days. Also, there is climate station name, elevation, and its location (latitude and longitude). For the purpose of this study, average monthly rainfall measurements from all stations were converted to inches to allow comparable modification process.

10.5 Experimental Procedures

Field measurements for water quality are important to determine whether significant changes occurred with time. The quality of data depends on sampling protocols including methods, time interval, documentation, and purpose of field measurements.

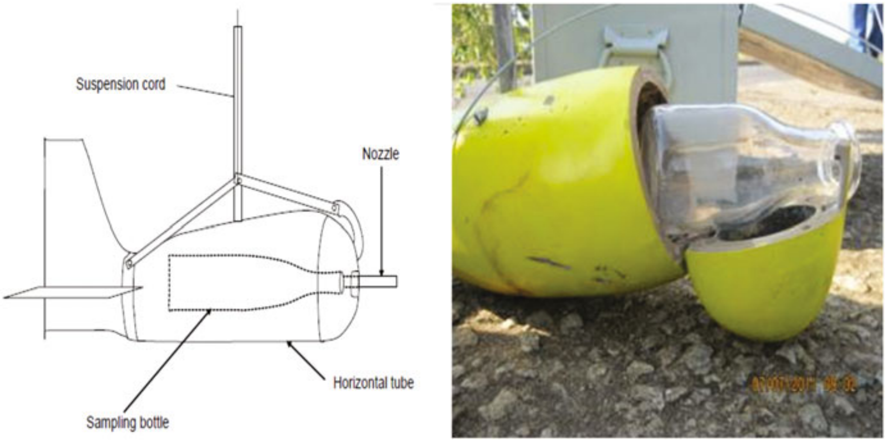


Fig. 10.6 D-48 and D-74 sediment sampler used during field research

The accurate measurement and calculation of suspended transport depend on the time and sampling procedures used. In the Wami-Ruvu basin, there is limited continuous sediment data of its catchments. The data available are event based and most were taken during rainy season. In the case of this study, the field measurement was done for the purpose of getting a snapshot of total suspended solids (TSS) in dry season in the area where secondary streams converges in most hill slopes. Although the results are on a weekly basis, the data will assist in proposing sediment sampling locations for monitoring.

10.5.1 Hydrological Data

Sediment sampling locations were set up in order to obtain insight into the spatial variability of suspended solids concentration (SSC) in the river systems. Continuous/throughout the year accessibility to sampling locations was considered in line with assessment of the spatial variation in sediment response. The sampling points were selected as much as possible on bridges along the roads that cover the study area allowing easy access to collect river water samples (with suspended sediment) and to carry out streamflow velocity measurements. Seven sampling sites of Ruvu at Kibungo, Mgeta at Duthumi, Mgeta at Mgeta, Mfizigo at Lanzi, Mfizigo at Kibangile, Mvuha at Tulo, and Mvuha at Ngangama were selected along the Upper Ruvu River and its major tributaries.

At each station, flow velocity measurements were done by the Acoustic Digital Current (ADC) meter (wading method) and the Q-liner instrument as shown in Figs. 10.6 and 10.7. Flow velocity measurements were normally taken at 60 % of the water depth (0.6D) at regular intervals along the cross section in order to establish a stage discharge rating curve. For suspended sediment loading analysis, water

Fig. 10.7 Field sampling photos and source of the diagram

sampling at each station of the river was demarcated into 3–5 sections in which 3–5 samples for analysis of suspended solids were taken by using a D-48 sediment sampler and D-74 integrating suspended handline sampler into a labeled container for laboratory analysis.

10.5.2 Suspended Sediment Load

Analysis of suspended sediment load in water samples was carried out at the Soil Laboratory of Sokoine University of Agriculture in Tanzania. Filtration of water samples for suspended solids was done by using vacuum pressure pump fitted with glass fiber of 0.45-µm-diameter membrane filters. The membrane filters were initially dried in the oven at 70 °C for 24 h and weighed (in grams) using a sensitive balance. The water samples were filtered, and then the wet filters were dried in an oven at 103–105 °C for 1 h. The weights in grams of the filters with dried residue were noted. After the laboratory analysis, the amount of suspended solids in each sample was calculated using the formula

$$T = \frac{(A - B)^{*}1{,}000}{C} \qquad (10.10)$$

where

T Total suspended solids (mg/l)
A Weight of filter with dry residue in (mg)
B Dry weight of filter in (mg)
C Sample volume (ml)

The total suspended load (milligram per second) was calculated by multiplying by river flow at crossing area in cubic meter per second and then changed to kilogram per second by multiplying by 1,000.

10.6 Results and Discussion

10.6.1 Simulation Outputs

The model was simulated in four subwatersheds delineated by the model. Subwatershed delineation was done to select a channel cell as an outlet point. The number of hillslopes and streams were calculated and checked before simulation to compare with model requirements. The names of subwatersheds were given to relate to the rivers/streams drained in a particular subwatershed. A total number of four subwatersheds, namely Mfizigo, Msumbizi, Mvuha, and Kibungo, were generated. GeoWEPP results of runoff, soil loss, sediment deposition from hillslopes, and channels are displayed as text files and sediment yield is visualized as a map showing hotspot areas by subwatersheds that are very vulnerable to soil erosion. The discussion is based on the effects of land cover change, topography, and land use management.

10.6.1.1 Average Annual Runoff

Effect of Topography and Land Use/Land Cover: Average annual runoff volume on cropland, open woodland, and grassland is shown to be greatest in most of all subwatersheds as shown in Fig. 10.8. In these areas, the surface has been paved or soil is no longer retaining water which leads to rainfall to be converted to runoff. The low runoff indicated in land use/cover is characterized by shrubs/bushland and natural forest. The model simulated high amount of runoff in Mfizigo Juu (11,247 m^3/ha/year) and Mvuha (9,293 m^3/ha/year) as it is caused by higher elevation and substantial land use/land cover contributing factors (Fig. 10.8). Mfizigo Juu is characterized by 41 % of woodland at Tegetero, Kibogwa, and Kinole wards which makes runoff to be high as related to land use/land cover. Although there are patches of natural forest that can be found in Kibungo Juu and Mkuyuni wards, still high rainfall caused high runoff volume. Most of Mvuha subwatershed has been converted into agriculture and grassland in larger areas of the Kasanga, Kolero, and Mvuha wards. However, being in lower elevation makes the area to be a flooding area of runoff volume from the highland. Figure 10.8 shows Msumbizi and Kibungo chini subwatersheds with low average annual runoff volume. Msumbizi area, which covers Tununguo and Kiroka wards, is more characterized by woodland (58 %) and natural forest (16 %), while Kibungo chini area is characterized by open woodland with cultivation (94 %). The average annual runoff volumes at Msumbizi and Kibungo chini are 5,689 m^3/year and 4,578 m^3/year, respectively. Moreover, runoff depth was estimated under four

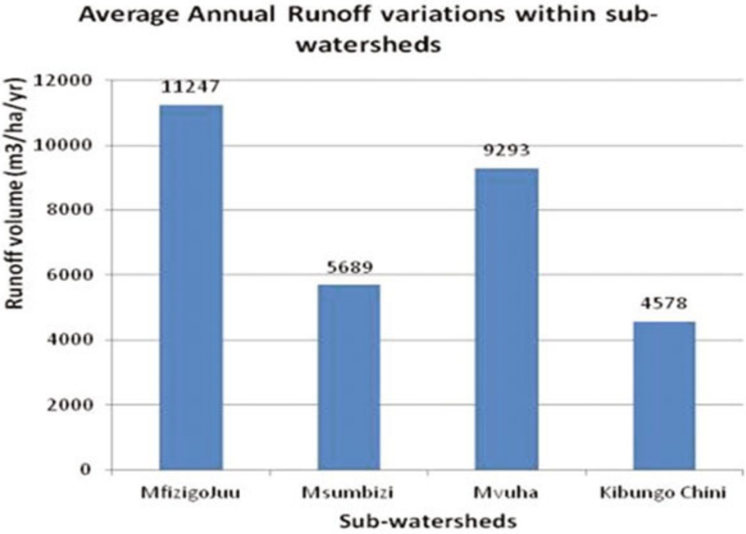


Fig. 10.8 Average annual runoff variations within the subwatersheds as estimated by the model

scenarios categorized considering two levels of topography steep slopes and lowland areas. These four scenarios considering soil types of the high coverage percentage in the area such as Ferralic Cambisols and Humic Acrisols are the major soil types in the highland areas (Mfizigo Juu) while Rhodic Ferralsols and Eutric Leptosols are found in lowland areas (Kibungochini). Simulation results showed some variations with land use/land cover both in highland steep slope and lowland slope areas. Results showed that cultivated land to have the maximum average annual runoff depth of 1,135 mm. The minimum average runoff depth was 51 mm represented by bushland and natural forest areas. A summary of results of the average annual runoff depths for all scenarios as related to land use/land cover are shown in Figs. 10.9–10.12.

The average annual runoff volume as estimated by the model showed good correlation with subwatershed characteristics. It is indicated that the amount of runoff in Mfizigo and Mvuha is high caused by upland high slopes with open woodland land cover and some patches of agricultural land (Table 10.1). Runoff of Msumbizi was low, although the subwatershed is located at high slope but characterized by the natural forest land cover. Discharge at the outlet of watershed depends on drainage area, inflow, or outflow of groundwater to or from the surface area.

10.6.1.2 Soil Loss

Effect of Land Use/Land Cover: Soil loss seems to be affected by land use/land cover, runoff, and topography in all subwatersheds. The areas with high slopes tend to increase soil loss in different land use/land cover. WEPP model watershed simulation predicated minimum average soil loss rate in grassland and natural forest areas. The

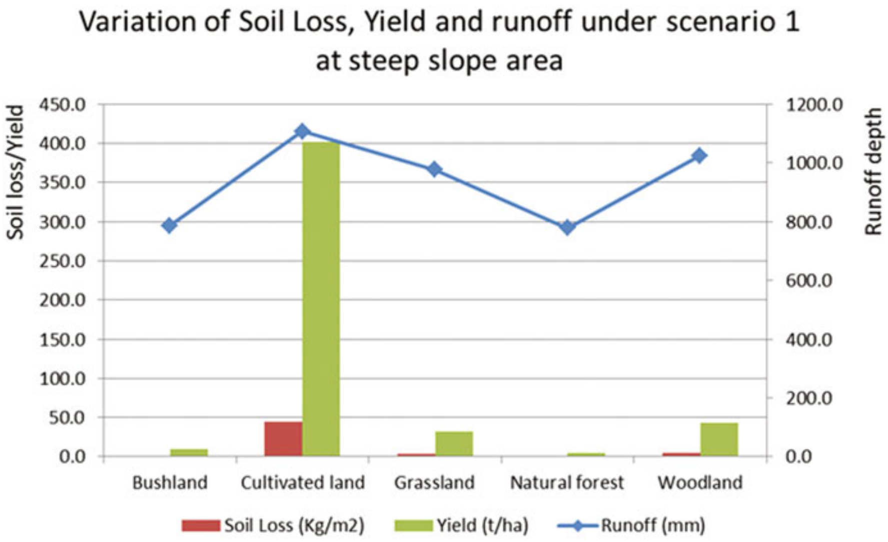


Fig. 10.9 Variation of soil loss, sediment yield, and runoff with land use/land cover under scenario 1 in steep slope area as estimated by the model

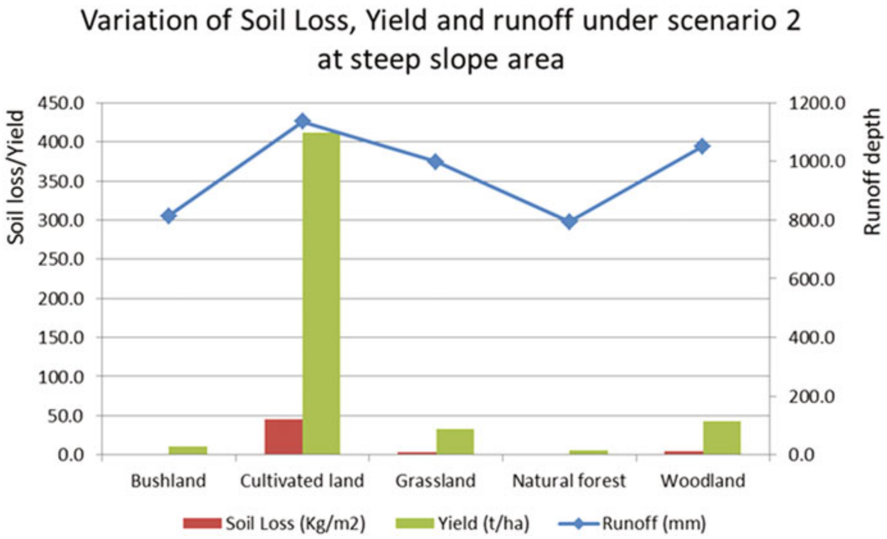


Fig. 10.10 Variation of soil loss, sediment yield, and runoff with land use/land cover under scenario 2 in steep slope area as estimated by the model

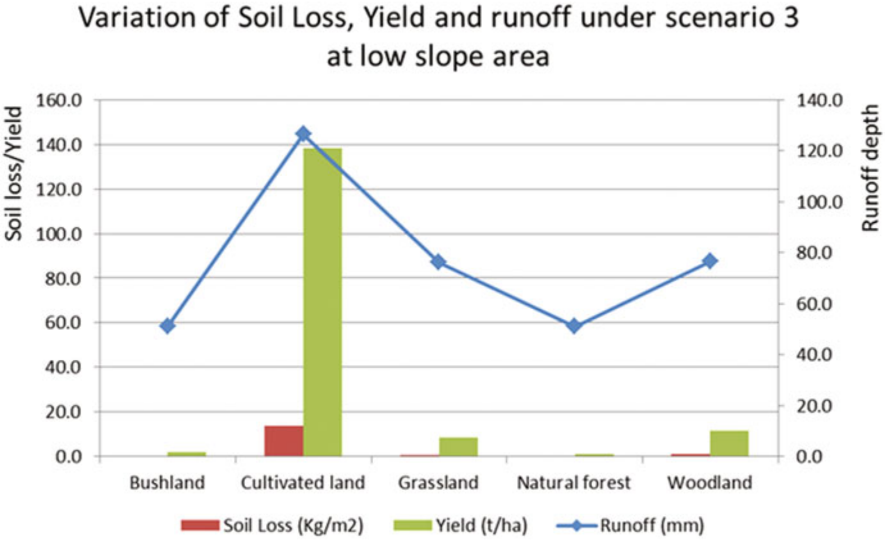


Fig. 10.11 Variation of soil loss, sediment yield, and runoff with land use/land cover under scenario 3 in low slope area as estimated by the model

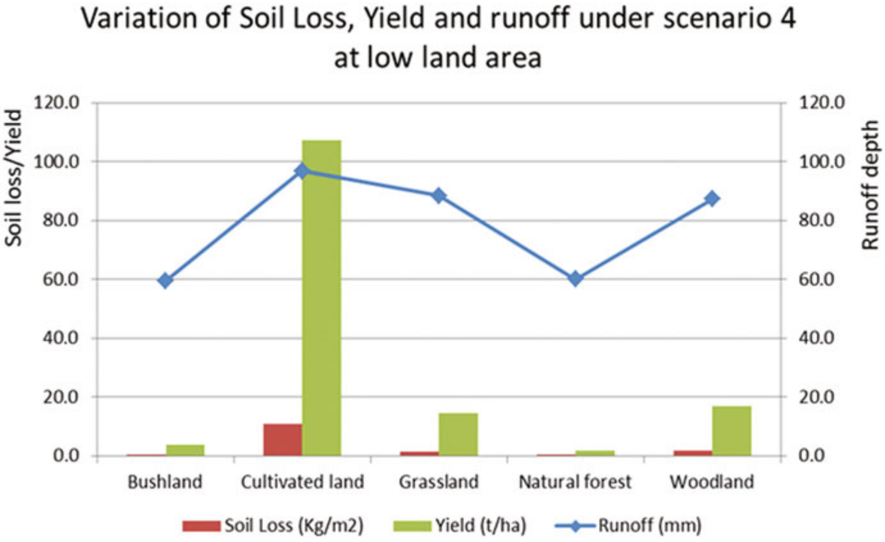


Fig. 10.12 Variation of soil loss, sediment yield, and runoff with land use/land cover under scenario 4 in lowland area as estimated by model

Table 10.1 Summary of variation in soil annual loss and sediment yield with land use/land cover under different scenarios

Land use	Scenarios							
	Steep slopes/ Ferralic Cambisols		Steep slopes/ Humic Leptosols		Lowland/ Rhodic Ferralsols		Lowland/ Euric Leptosols	
	Soil loss (kg/m^2)	Yield (t/ha)	Soil loss (kg/m^2)	Yield (t/ha)	Soil loss (kg/m^2)	Yield (t/ha)	Soil loss (kg/m^2)	Yield (t/ha)
Bushland	1.1	10.3	1.1	10.7	0.2	1.9	0.4	3.7
Cultivated land	44.3	402.1	45.5	412.2	13.8	138.5	10.7	107.4
Grassland	3.5	32.5	3.6	33.4	0.8	8.3	1.5	14.5
Natural forest	0.5	5.3	0.6	5.5	0.1	1.0	0.2	2.0
Woodland	4.8	43.5	4.8	43.3	1.1	11.4	1.7	16.9

minimum annual soil loss ranged from 0.33 to 9.14 kg/m^2. The reason for these estimates was the coverage area in watershed for the cultivated land use/land cover to be small compared to woodland and natural forest. The maximum average annual soil loss was in woodland and cultivated land as compared to natural forest/bushland with minimum average soil loss 0.5 kg/m^2 in steep slope and 0.1 kg/m^2 in lowland areas (Table 10.1). However, although soil in woodland is covered, the area is classified as disturbed land cover with severe fire every year, leaving bare land and reducing its erosivity and increasing erodibility by water.

Moreover, soil loss seems to be high in areas with high slopes (scenarios 1 and 2) and low in low slope areas (scenarios 3 and 4). The reason for this much difference is the effect of a runoff volume. Reduction of runoff depth from 1,135 mm (1.135 m) in scenarios 1 and 2–51 mm (0.051 m) in scenarios 3 and 4 resulted in a decrease of soil loss from 45.5 to 10.7 kg/m^2 under cultivated land (Table 10.1). Even though there are variations of soil loss, yield, and runoff in all four scenarios, land use/land cover showed sensitivity in all factors considered in modeling.

10.6.1.3 Sediment Yield

GeoWEPP model generated sediment yield map which indicates the area with tolerable yield (i.e., from light to dark green) and not tolerable yield (i.e., from light to dark red). Results given from the model simulation are in a tolerable maximum value (T-Value) of 1 t/ha/year. Results were converted to 12 t/ha/year, the East African highlands soil loss rate-tolerable limit as reported from previous studies (Kimaro et al. 2008), in order to get clear visualization of maps. Sediment yield was categorized in eight groups; four displayed in green color are below the tolerable soil losses. The other four categories are displayed in red color and are above the tolerable value which indicates areas with high level of yield as shown in (Figs. 10.13–10.16). Since sediment yield is a function of contributing factors including topography, land use/land cover, runoff, and land management practices, and the simulated results in four subwatersheds prove good relation with regard to these factors.

The simulated average annual sediment yield at the Mfizigo Juu watershed outlet was 113,009,137.60 t/year and sediment delivery ratio for the watershed was 0.30. The contributing area was 81,113.82 ha which includes 1,023 hillslopes and

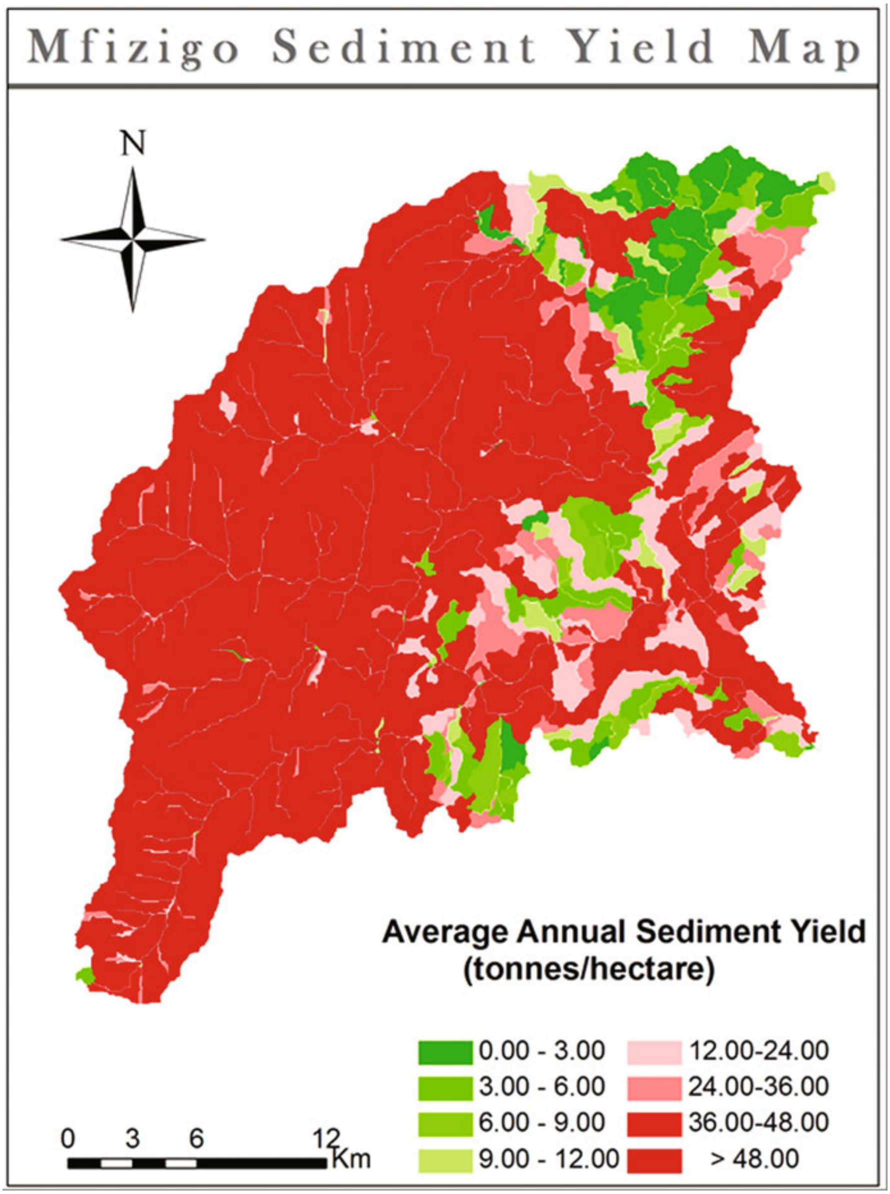


Fig. 10.13 Map of average annual sediment yield for Mfizigo subwatershed

411 channels. Average annual sediment yield from Msimbizi subwatershed was 183,430.00 t/year and the predicted sediment delivery ratio for the watershed was 0.2. Simulation created 272 hillslopes and 109 channels in 21,217.66 ha of contributing area. Mvuha and Kibungo chini are subwatersheds at the downstream of Kibungo watershed. These areas showed 418,459,188 t/year and 270,658.9 t/year, respectively. Results showed that 461 hillslopes and 185 channels in Mvuha, and also 78

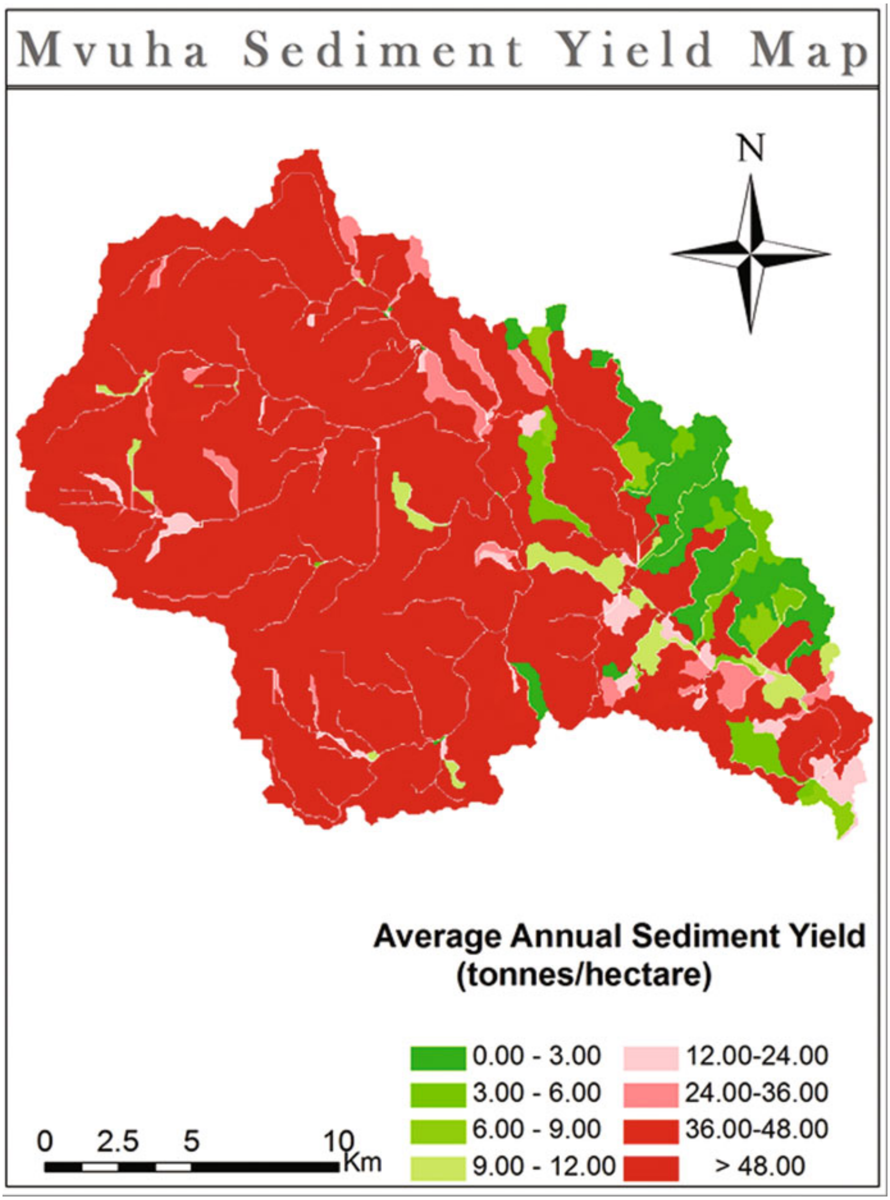


Fig. 10.14 Map of average annual sediment yield for Mvuha subwatershed

hillslopes and 31 channels in Kibungo Chini. Sediment delivery ratio in Mvuha was 0.66 from 36,871.54 ha contributing area while computed delivery ratio in Kibungo chini was 0.87 with a contributing area of 5,478 ha. As shown in Figs. 10.13–10.16, higher values of soil losses from high rainfall and high elevation are expected in the zones with red color, whereby the minimum losses are in the zone with green color.

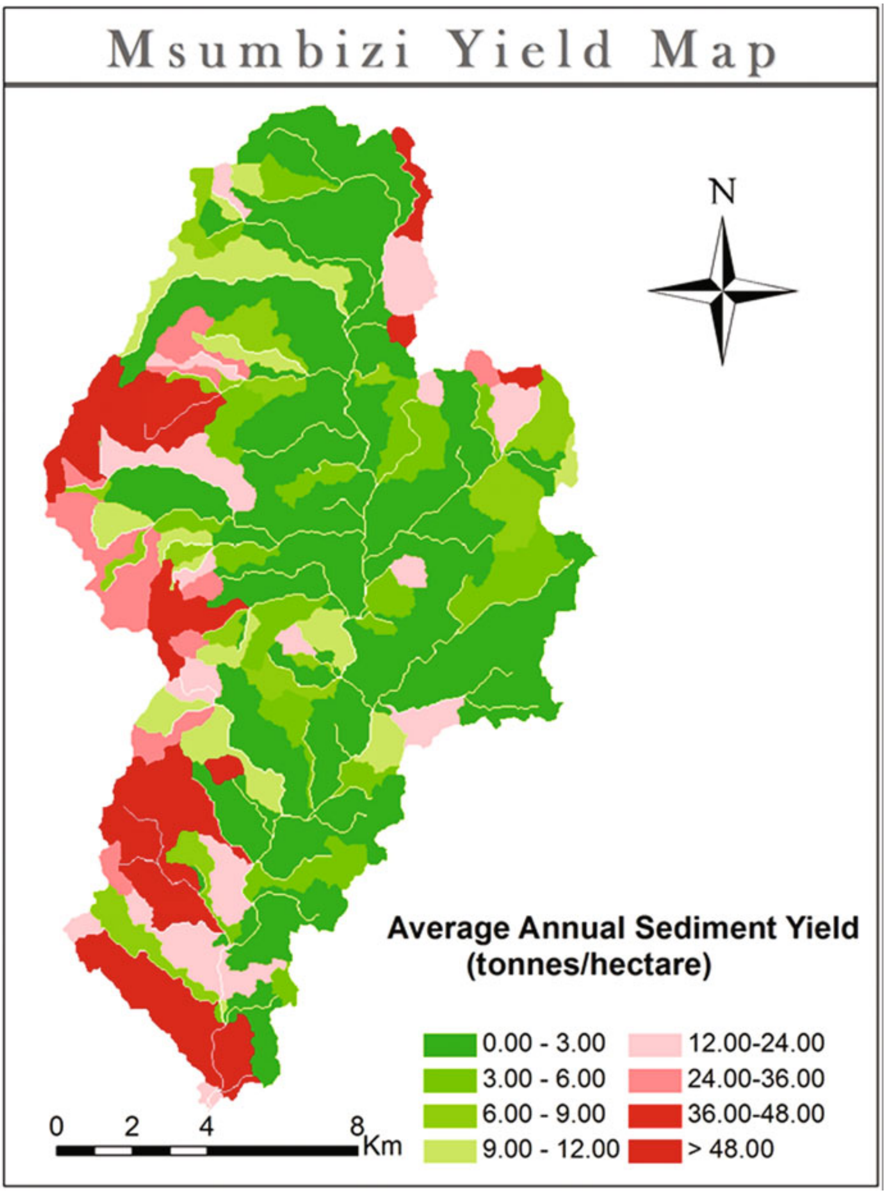


Fig. 10.15 Map of average annual sediment yield for Msumbizi subwatershed

10.6.2 Field Results

Total Suspended Solids and Average Annual runoff: During the field data collection campaign, the sediment load was observed to be higher at Mgeta at Duthumi (MD), Mvuha at Ngangama (MN), and Mvuha at Tulo (MT) as indicated in Fig. 10.17. The

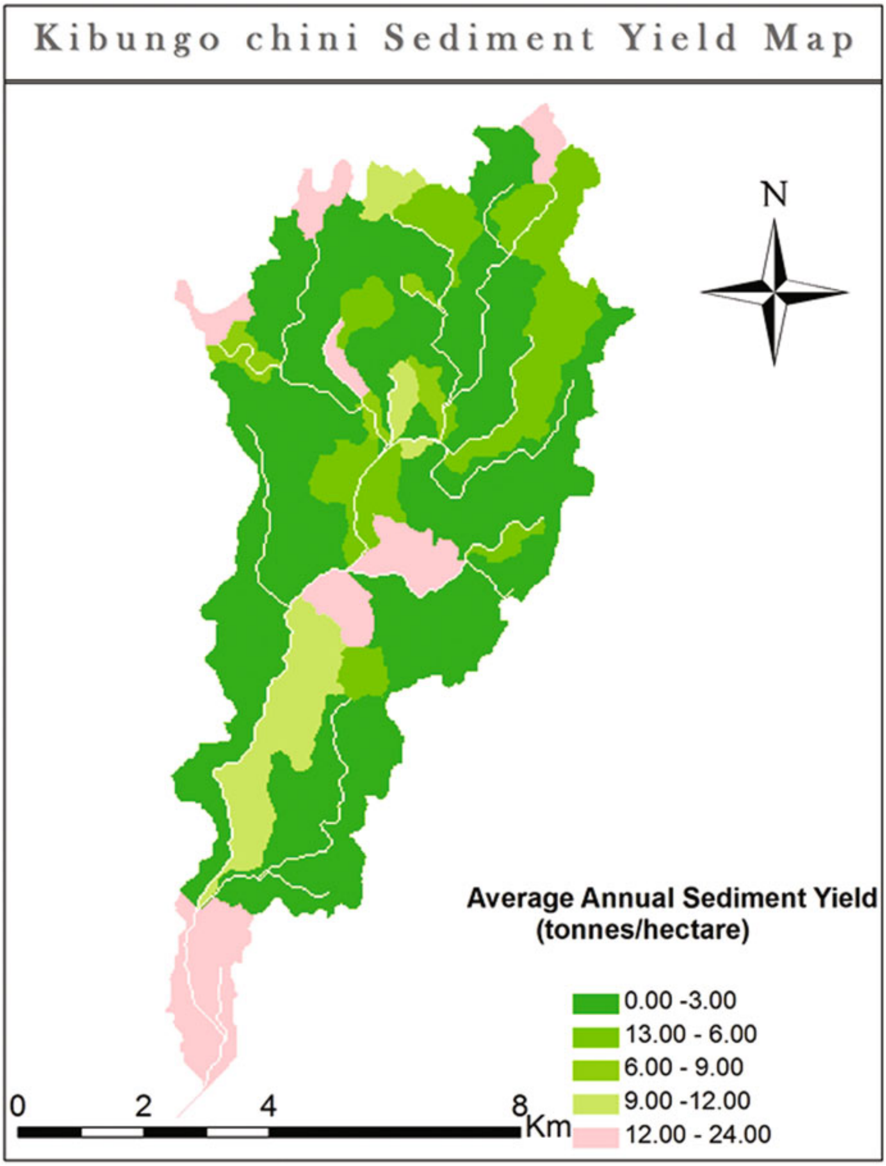


Fig. 10.16 Map of average annual sediment yield for Kibungo Chini subwatershed

levels observed at MD, MN, and MT were 298.7, 243.0, and 351.8 kg/s, respectively. All these sampling locations are downstream of cultivated lands. MD in Mgeta River is located downstream of Mgeta, Singisa, Bwakila Juu, Bwakila Chini, Kolero, and Kisaki wards. MN is located downstream of hillslope cultivated lands of Mtombozi, Kisemu, Kasnga, and Mvuha wards. The MT is the location further downstream

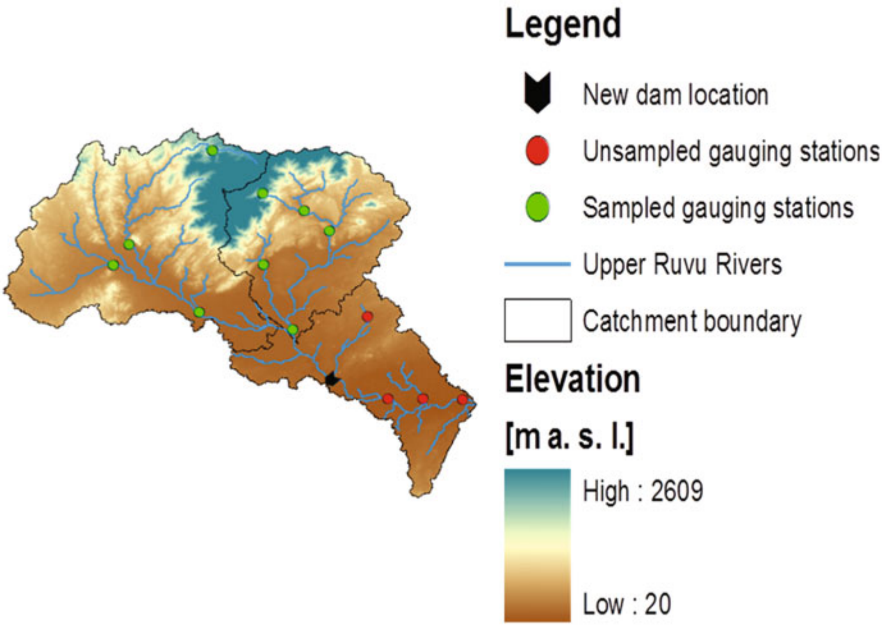


Fig. 10.17 Selected spatial sediment sampling locations at Upper Ruvu catchment

of MN at the same Mvuha River. MM is the starting location of Mgeta River at the mountain, which is not much degraded. Water can be clearly seen with less sediment.

ML, MK, and RK are downstream of Kibungo, Tawa, Kibogwa, Mfizigo, and Ruvu Rivers. These rivers pass through the forest reserve area while the cultivated upland is managed by agricultural management practices. Management practices in Kibungo subwatershed include contour farming, strip cropping, and mixed farming. Although the sampling interval was weekly in 4 weeks, the trends show differences in results. The first week sampling shows a high level of sediments in rivers because of some of final rains of the rainy season in June and early July. The second through fourth sample was taken during July and early August which is within the dry season of the area. With no incoming runoff, streams have resulted in unchanged levels of sediment as shown in Fig. 10.18.

It was also found that there is a very good correlation between stream flow and sediment load as shown in Fig. 10.19.

10.7 Conclusions

This study should not be seen as validation of the WEPP model in the Upper Ruvu catchment environment. The main objective of this study was to test the prediction capability of WEPP on tropical watersheds located in hillslope areas. The overall

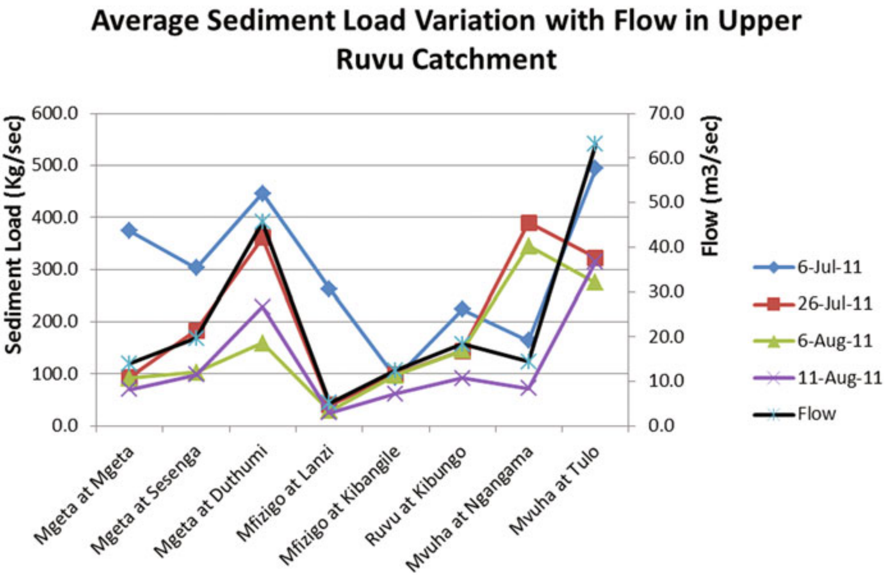


Fig. 10.18 Sediments load and flows in the Upper Ruvu catchment rivers

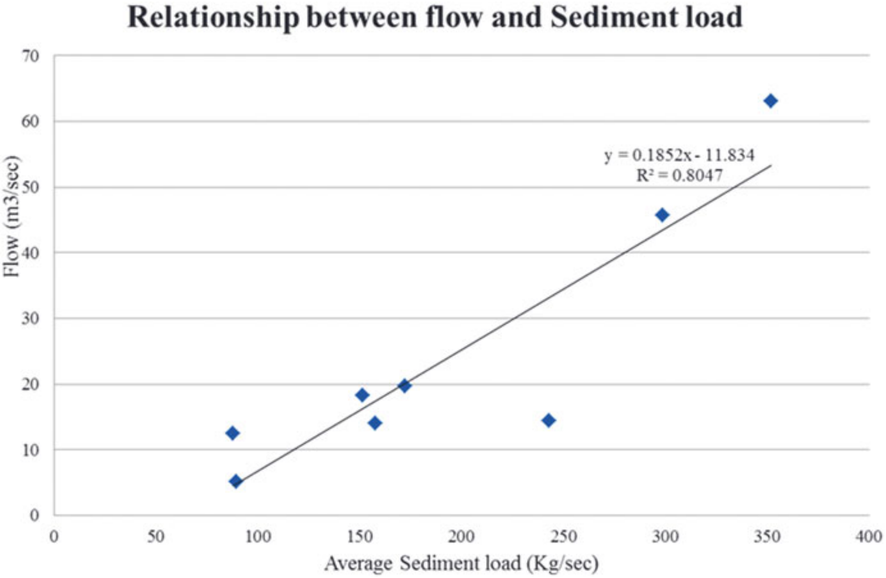


Fig. 10.19 Relationship of average measured sediment load variation with flow in Ruvu catchment

results indicated that the WEPP model can assist watershed-related management institutions to quickly generate conservation zones by accepting predictions of sediment yield runoff outputs in spatially distributed format. Further study on testing the model with different assumptions is needed. The results showed that hydrological outputs were quite well predicted. Average annual runoff depths predicted in all four subwatersheds during the research period at different rainfall events varied from 460 mm in lowlands within a high forest area (Kibungo chini) to 1,120 mm in hill-slope area, within open woodland and cultivated areas (Mfizigo Juu) subwatershed. Establishment of four scenarios at different conditions also predicted maximum average annual runoff depth to be 1,135 mm at scenarios 1 and 2, while minimum average annual runoff depth was 51 mm in areas with the same conditions of soil types.

The maps locate only potential hotspots erosion areas with high sediments delivery which can help watershed and basin managers to implement necessary precautionary measures to minimize or prevent soil erosion. High hazard soil erosion spots appeared in high elevation areas of Tegetero, Kibogwa, Kibungo Juu, Tawa, Kinole, and Mkuyuni wards in Mfizigo subwatershed. Similarly, Mtombozi, Singisa, Kasanga, and Kolero wards in Mvuha subwatershed showed high vulnerability to soil loss. The watershed soil loss and sediment yield were correlated with runoff. The highest and lowest total average annual soil loss rates were estimated to be 45.09 kg/m^2 at Mfizigo Juu watershed and at 0.45 kg/m^2 Kibungo chini watersheds, respectively. Although average total soil loss varied with runoff changes, the simulation showed some effect of soil type and slope in different land use/land covers within subwatersheds. Model results show cultivated land contributes 81 % of soil loss and 86 % sediment yield in all four scenarios.

A detailed accurate prediction of sediment yield and runoff in Wami-Ruvu basin is crucial for planning and development of watershed-based projects. According to Walling (1994), sediment load represents a small percentage of the total land area eroded and converted to sediments but still is a good source of information for management of soil erosion and sedimentation within the basin. More complete experimental data sets such as plot scale information than this used in the study will enhance the applicability of the WEPP model. The limited measured data used in simulation was certainly not ideal for the model validation. However, the study leads the way to better understanding of model assumptions and data input needs.

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Chapter 11
Assessment of Soil Erosion in the Blue Nile Basin

Gizaw Desta Gessesse

Abstract Water erosion in the form of sheet and rill erosion and lack of good land management practices lead to accelerated land degradation. Rill erosion is a major contributor to sediment detachment and transport from agricultural fields leading to both on-site and off-site effects of erosion. Farm-runoff drainage ditches have also contributed to the same effects. This chapter, thus, presents assessment results of rill erosion and farm ditches in the Lake Tana subbasin of the Blue Nile basin in order to understand their contribution to the overall soil loss. Monitoring the spatial and temporal rill erosion development on agricultural lands of 6, 15, and 300–500 m slope lengths has revealed the greater role of tillage-induced surface roughness, soil texture, slope shape and length, and barriers along the topo-sequence of the catchment. Similarly, quantitative assessment of the farm-runoff drainage ditches has made a clear picture that ditches serve as both a source of erosion and a sediment transport channel for the soil eroded from the inter-ditch areas. The changes in depth and width of ditches constructed on moderate to steep slopes vary between 8 and 20 mm, and 20 and 30 mm during two months rainfall period, respectively. Eroded sediment from inter-ditch areas is transported at a rate between 0.5 cm^2 and 4.0 cm^2 per meter of single ditch. This study indicated the role of rills and ditches for total soil loss and the importance of protecting and controlling both rill and ditch erosion without compromising the need to drain excess water.

Keywords Rill erosion · Catchment · Tillage roughness · Ditch erosion · Blue Nile basin

11.1 Introduction

11.1.1 Features of Ethiopian Highlands

Soil erosion, nutrient depletion, and deforestation are common environmental problems in the Ethiopian Highlands in general and in the Blue Nile basin in particular

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(Hagos et al. 1999). In the Blue Nile basin, topography follows a gradient from flat lowlands in the west to mountainous areas in the east (Pfeifer et al. 2012). The same report indicated that most of the western Ethiopian Highlands are dominated by Nitisols, while the eastern part and highland plateau of the Blue Nile basin are dominated by Leptosols and Vertisols, respectively.

The agricultural system in the central, northwestern, and northern Ethiopian Highlands has been described as "grain-plough complex." Tillage was made using Ethiopian ard or *maresha* in Amharic language, a wooden plough pulled by two oxen (Nyssen et al. 2000). Land preparation using *maresha* requires several ploughs or passes in order to prepare adequate seedbed for different crop types. The number of tillage operations per year ranges from one for most leguminous crops to four to five for teff. The main crops are barley (*Hordeumvulgare* L.), wheat (*Triticum* sp.), faba bean (*Vicia faba*), and teff (*Eragrostis tef*) an endemic cereal crop.

The dominant areas in the Blue Nile basin are characterized by steep cultivated slopes and high rainfall intensity causing severe soil erosion hazards. Moreover, in association with the topography and high intensity rainfall, poor land management practices and lack of effective soil and water conservation (SWC) strategies are prevalent. For instance, in the Ethiopian Highlands, a very high percentage of the land area is drained by some form of indigenous artificial drainage networks in addition to the natural streams and channels. These indigenous drainage practices are of different forms, such as broad bed and furrows (BBFs) and ridge and furrows (RFs) in the Vertisols and simple open ditches in the moderate to flat slope lands. The primary aim of the drainage is to reduce the level of excess soil water and to dispose excess runoff. However, under heavy rain storms and combined with excessive ditch gradients, they serve as hot spots for accelerated erosion in the form of rills and gullies. The problem of soil erosion is, thus, severe in the highland areas.

11.1.2 Soil Erosion in the Ethiopian Highlands

A major environmental hazard associated with agricultural production in the Ethiopian Highlands is mainly water erosion, in the form of sheet and rill erosion, in terms of both its economic costs and the areas affected (Berry 2003). The degradation is more aggravated due to rapid population growth and economic needs that push farmers to cultivate steeper and more fragile lands, resulting in an annual loss of 1 billion tones of top soil per year (Constable 1985; Hurni 1993). A number of factors of both physical and socioeconomic natures contribute to the accelerated erosion on agricultural lands. With steady growth of population, continuous clearing of forests to meet increased demand of fuel and construction, conversion of marginal lands to cultivation without sustainable land management practices, methods of crop production, and lack of consideration of land user participation in the development of remedial measures are mainly the conducive factors for increased soil erosion by water.

Consequently, soil erosion is considered to be a major agricultural problem in the highlands (above 1,500 m a.s.l.). Nearly three decades ago, the Ethiopian Highland Reclamation Study (EHRS) estimated that about half of arable lands in the highlands have been eroded from a moderate to a serious level (Constable 1985). The Soil

Conservation Research Projects (SCRP) had estimated at 130–170 t ha^{-1} $year^{-1}$ for cropland reaching up to a maximum of 300–400 t ha^{-1} $year^{-1}$ in highly erodible and intensively cereal cultivated fields in the highlands of Ethiopia (Hurni 1993; Herweg and Stillhardt 1999; EPA 2003). As a consequence, annual farm productivity is reduced to 1–3 % (Mitiku et al. 2006) and lead to economic decline and social stress. For instance, a direct cost of loss of soil was estimated about 3 % (US$ 106 million) of agricultural gross domestic product (GDP) in 1994 (Berry 2003).

Erosion in the form of sheet wash and rills was the dominant form of erosion where it is prevalent almost on every farm land (Aklilu and de Graaf 2006). Apart from estimates of erosion from scientific results, linear erosion is directly visible on moderate and steep slopes of agricultural lands in various forms. Among these erosion forms, rills are the predominant form of erosion. Comparison of rill erosion with sheet erosion in Ethiopia has shown that linear erosion can greatly exceed sheet erosion (Herweg 1996). In a case study at Chemoga watershed with the average annual rainfall of 1,300 mm, seasonal average soil loss by rills was estimated about 13–60 t ha^{-1} from agricultural fields with a range of rill density from 328 to 864 m ha^{-1} (Weldeamlak and Sterk 2003). Moreover, the rill data collected in one of the former SCRP research sites indicated that the range of rill erosion is estimated from 50 to 250 m^3 ha^{-1} and rill density of 400–1,050 m ha^{-1} (SCRP AnditTid database, unpublished). These rates imply that rill erosion constitutes one of the mechanisms of soil loss by water on agricultural lands and more generally can be considered as an indicator of land degradation. It is the most important erosion form, because in addition to being an erosion feature in itself, rills serve the purpose of transporting materials supplied by the inter-rill (splash) erosion (Weldeamlak and Sterk 2003) and being an indicator of where to start soil conservation. Thus, without the implementation of specific SWC measures, the development of rill erosion into gullies and to severe degradation is commonly observed in many farm plots.

Farmers' decisions to conserve the soil are largely determined by their knowledge of the problems and perceived benefits of soil conservation. However, farmer perceptions of erosion problems and effectiveness and efficiency of runoff drainage ditches have received little analysis. High density of ditches is commonly observed on Teff fields planted on gentle and flat slopes. It has most frequently been ploughed down the main line of the slope with varying gradients. Properly constructed drainage ditches can prevent erosion and gullying of land on slopes by catching surface water before it reaches the critical stage. However, under heavy rain storms combined with excessive ditch gradients, they serve as hot spots for accelerated erosion. Unless there is proper construction, it provides high risk of erosion downstream in the form of rills and gullies and leads to conflicts among adjacent land owners. The negative impacts of this practice are apparently observed in the field by forming gullies along adjacent farm boundaries, thereby damaging the terrace structures and serving as a sediment-transporting channel. Consequently, many land users who are practicing open farm ditches do not notice the risk of traditional open ditches to properly address erosion problems since they are constantly struggling only against the control of highly recognized and visible forms of erosion (Aklilu and de Graaf 2006). For sustainable and effective erosion control, therefore, there is a need for an understanding of specific practices and their negative effects on their relative erosion contributions.

This chapter presents the formation and development of rill erosion at different spatial scales and the erosion contribution of open runoff drainage ditches on agricultural lands in the highlands of Ethiopia.

11.1.3 Rill Erosion

11.1.3.1 Formation of Rill Erosion

On agricultural lands, the erosion processes most commonly encountered are rill and inter-rill erosion. According to Loch (1996), inter-rill erosion is dominated by rain flow, which refers to the entrainment and transport of sediment by shallow and non-incised overland flow hit by rainfall. With increasing slope lengths, inter-rill erosion rates could be expected to reach a maximum and then decline as water depths increase down slope. Inter-rill erosion is conceptualized as a process of sediment delivery to concentrated flow or rills (USDA 1995). Rills are generally defined as flow channels that can be obliterated by tillage. Rill erosion is the detachment and transport of soil particles by concentrated flow (Romero et al. 2007). The process of rill erosion occurs when the flow increases its depth and starts to organize itself following lines of slopes. During severe rainfall, overland flow concentrates and after crossing a threshold value causes rill development resulting in high erosion rates (Rejman and Brodowski 2005).

Rill incision is controlled by topographic factors like slope steepness and contributing upslope area (Rieke-Zapp and Nearing 2005) and soil tillage surface pattern (Desmet and Govers 1997) that often indicated to control the initiation and development of rills. The starting points for individual rills were not well predicted as they did not take into account the influence of minute surface irregularities resulted from tillage (Desmet and Govers 1997; Favis-Mortlock 1998; Rieke-Zapp and Nearing 2005). According to Favis-Mortlock et al. (2000) micro-topography plays a role for the temporal dynamism of rill development upon modifications of the surface by subsequent runoff. The combined effect of topography and soil surface roughness parameters on rill incision is not clear where successive rainfall storms modify the soil surfaces (Favis-Mortlock et al. 2000). Understanding the processes of rill formation and its development is, therefore, crucial if overall soil loss is to be predicted and controlled effectively. These processes of erosion would enable one to identify the critical locations of erosion along the slope profile (Herweg 1996).

11.2 Study Areas in Lake Tana Sub-basin

The study area, Angereb watershed, is found in the Lake Tana Subbasin in the upper part of Blue Nile basin (Fig. 11.1). The watershed is located between 37° 25′–37° 31′ E and 12° 00′–12° 34′ N north of Lake Tana, near Gondar city. The altitude ranges from 2,100 to 2,870 m a.s.l. The watershed covers a total surface area of 76 km^2. The annual rainfall varies from 712 to 1,822 mm with a mean annual of 1,160 mm.

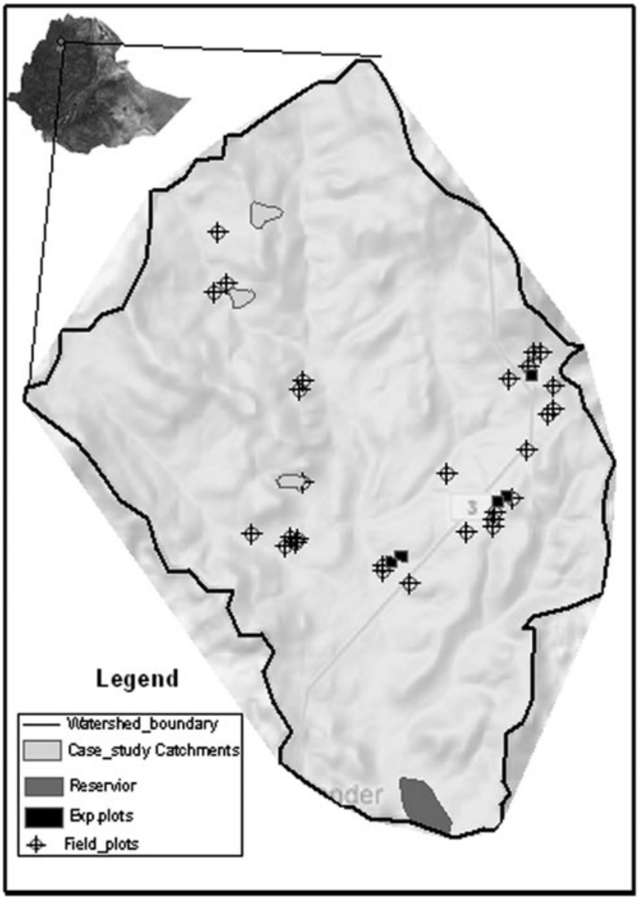

Fig. 11.1 Angereb in the Blue Nile basin

Three small case study catchments, namely *ChiraGodguadit, ChiraKiltimsebari*, and *Embestig* (Fig. 11.1), with slope lengths between 300 and 500 m, were selected. A total of 23 individual farm plots were selected to measure rill dimensions along the toposequence. The geomorphology of the three catchments is differentiated based on the shape, slope, and barrier structures along the toposequence. On 27 agricultural fields of farmers, 5-m-wide and 6-m-long plots, in the open area between terrace structures, were selected to survey rill erosion on individual fields. For the application of the close range photogrammetric method, two fields of farmers were selected representing different soil texture classes and conventional tillage practices with a slope of 19 % and 21 %, respectively. The textures are clay and sandy clay loam soil textures with bulk density of 1.22 and 1.31 g cm^{-3} and organic carbon (OC) of 2.81 and 2.12 %, respectively.

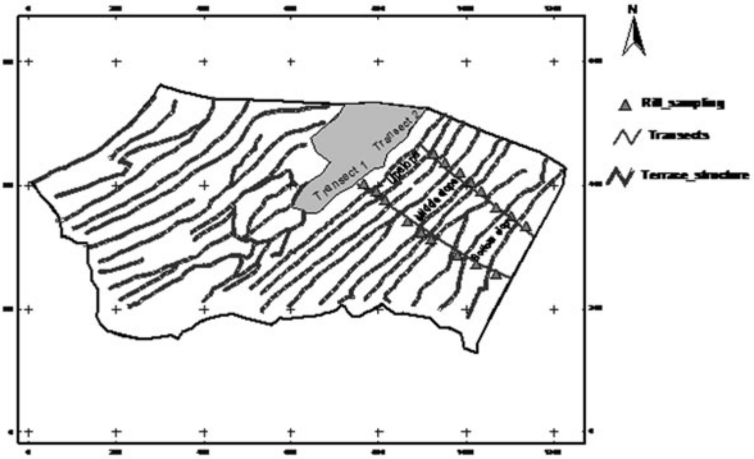

Fig. 11.2 Terrace structure and transects of rill sampling

11.3 Rill Erosion Assessment Methods

Rill erosion assessment methods vary according to the spatial scales. Two methods were used for rill erosion survey. On catchment and parcel level surveys of rill dimensions (cross sections), while on plot scale, digital close range photogrammetric measurements were used.

11.3.1 Rill survey on Small Catchments

Rill erosion survey on three small catchments with slope length between 300 and 500 m was conducted following the direction of runoff flow along the toposequence. The catchments were divided longitudinally into two transects. Sample field plots along transects were grouped into upslope, middle slope, and lower slope positions of the catchment. The sample plots were further classified, and measurements were carried out between intra-terrace areas (top, middle, and bottom positions) (Fig. 11.2). The rill cross-section survey was begun immediately after the occurrence of erosive rainfall events. Rill cross sections and counts were measured three times during July–August 2008. During this period, 570–755 mm cumulative rainfall (i.e., a maximum of 40–48 mm daily rainfall) was recorded. Results of rill count, spacing, depth, width, rill density, and specific rill erosion were analyzed and summarized based on different spatial scales (survey plots, intra-terrace areas, landscape positions) and rill survey periods.

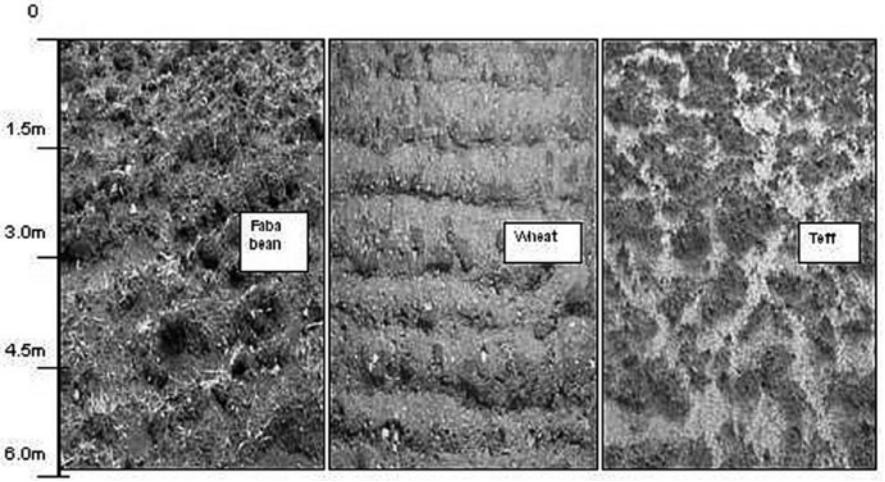

Fig. 11.3 Four 1.5 m longitudinal sections on three crops plots

11.3.2 Rill Survey on 6 m Long and 5 m Wide Plots

Rill erosion survey was conducted on 27 fields of farmers. The measurement of rill dimensions was carried out in the open area between terrace structures that were 5-m-wide and 6-m-long plots. The plot was further divided into four 1.5 m longitudinal sections (0−1.5, 1.5–3.0, 3.0–4.5, and 4.5–6.0 m) as shown in Fig. 11.3. The survey was carried out when the seedbed was freshly tilled and with no cover. The survey plots were grouped to represent three soil tillage roughness conditions: high roughness size and random nature, high roughness size and oriented nature, and low roughness size and random nature corresponding to faba bean, wheat, and teff crop tillage practices. Rill erosion measurement was taken immediately after four erosive rainstorms with total rainfall of 90 mm, an average intensity of 8–17 mm hr^{-1} and 2,400 J m^{-2} rainfall energy. Mean and standard deviations of the rill depth, width, rill density, and rate of specific rill erosion were analyzed for each level of erosion factors. Rate of rill section erosion (E_r) is defined by rill volume per unit area:

$$E_r = \left(\frac{L_r \cdot W_r \cdot D_r \cdot n}{SL \cdot W_c}\right) = \left(\frac{L_r}{SL}\right)(W_r \cdot D_r)\left(\frac{n}{W_c}\right). \tag{11.1}$$

Assuming a parallel rill network in a 1.5-m slope length survey, L_r is approximately equal to slope length (SL), and the number of rills (n) per unit contour width (W_c) is defined by rill density (R_d). Rill width (W_r) multiplied by rill depth (D_r) is the cross-sectional area (A_x) of rills. Therefore, Eq. 11.1 is rewritten as

$$E_r = A_x R_d. \tag{11.2}$$

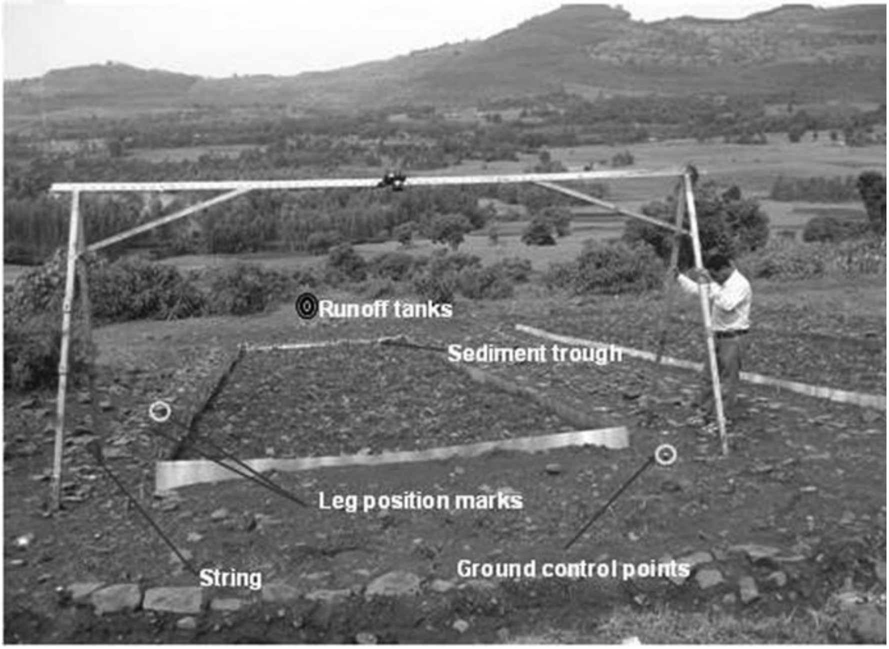

Fig. 11.4 Photogrammetric data acquisition camera set up

11.3.3 *Close Range Photogrammetric Technique Applied on Bounded Plots*

Photogrammetric technique was employed to measure the rill development on bounded plots. Plots with 3.7 m width and 14.4 m length, replicated two times and arranged side by side, were established on freshly tilled and bare cover fields. The plots were bounded with corrugated iron sheets inserted 15 cm into the ground and 20 cm height above the surface in order to protect the inflow of runoff outside the plot. The detailed camera setup, procedures, and methods of photography and digital elevation model (DEM) extraction using Lightweight Portable Security (LPS) software can be referred in Gessesse et al. (2010). Photogrammetric data acquisition was made based on the camera set up shown in Fig. 11.4. A calibrated nonmetric Canon Electro-Optical System (EOS) 1Ds digital camera with Leica Elmarit 2.8/19 mm ROM lens, pixel size of 8.8 μm, and an effective resolution of 4,064 × 2,704 pixels was used to acquire overlapped photographs of the whole plot in a time sequence corresponding to extreme rainfall events with cumulative rainfall of 46, 116, 174, and 410 mm (Gessesse et al. 2010).

Rill density has been used to measure the efficiency of rills for sediment transport. The procedure employed by Gessesse et al. (2010) was used to investigate rill network development which was assessed by rill density, R_d, calculated by dividing the total

Table 11.1 Mean and standard deviation of rill cross sections and rill counts from three catchments

Rill characteristics	Case study catchments		
	Godguadit	Kiltimsebari	Embestig
Rill start from upper terrace (m)	0.62 ± 0.29	1.32 ± 0.37	0.65 ± 0.80
Rill spacing (m)	0.89 ± 0.49	1.75 ± 1.14	8.16 ± 2.95
Rill depth (cm)	8.14 ± 1.21	9.69 ± 1.27	8.92 ± 3.62
Rill width (cm)	26.80 ± 5.25	29.6 ± 6.9	68.09 ± 19.03
Rill cross-sectional area (cm^2)	222 ± 65	299 ± 109	650 ± 386
Rill density (m^{-1})	1.34 ± 0.48	0.72 ± 0.34	0.15 ± 0.08
Rill section erosion ($cm^2\ m^{-1}$)	310 ± 158	236 ± 185	79 ± 87

length of rill segments (L_r) to the corresponding rill drainage area (A_c):

$$R_d = \frac{\sum_{1}^{n} L_r}{A_c}. \tag{11.3}$$

11.4 Rill Erosion Development in Angereb Watershed

11.4.1 Rill Development Along the Toposequence of Catchments

Table 11.1 and Fig. 11.5a and b present average rill cross sections and rill numbers following toposequence of the catchments. Occurrence of rills was in the range between 2 and 22 per sample field. Significant differences were found in rill width, which resulted in different cross-sectional rill erosion at the three catchments. Although rill depth and width are higher at *Embestig* and *Kiltimsebari*, the overall rill erosion rate was high at *Godiguadit* because of the high density of rills. At *Godguadit* site, rill erosion slightly increased from upper to middle catchment and slowly decreased at the lower slope of the toposequence. On the contrary, rill erosion was high at the middle of the catchment and low at both upper and lower slopes at *Kiltimsebari* catchment. But slight linear reduction in rill erosion and rill counts over the slope profile was observed at *Embestig* catchment. This implies that rill formation and development were related to the concavity, convexity, and uniformity of slope shapes associated with barriers along the toposequence of the catchment. High rill development occurred on concave slope shapes at *Godguadit* and *Kiltimsebari.* Similar results were obtained from the analysis of long-term rill erosion data at AnditTid catchment (Source: SCRP AnditTid database).

Rills were distributed nonuniformly both longitudinally and across the slope. The distribution of rill cross sections and rill count along the toposequence of the catchments varies. Rill density varies along by location and by site (Fig. 11.5a). Figure 11.5b shows the location specificity of rill erosion. Convex slope produced comparatively less rill volume. Concave slopes were more susceptible to rill formation than convex and linear slope shapes. Similarly, Moore and Burch (1986)

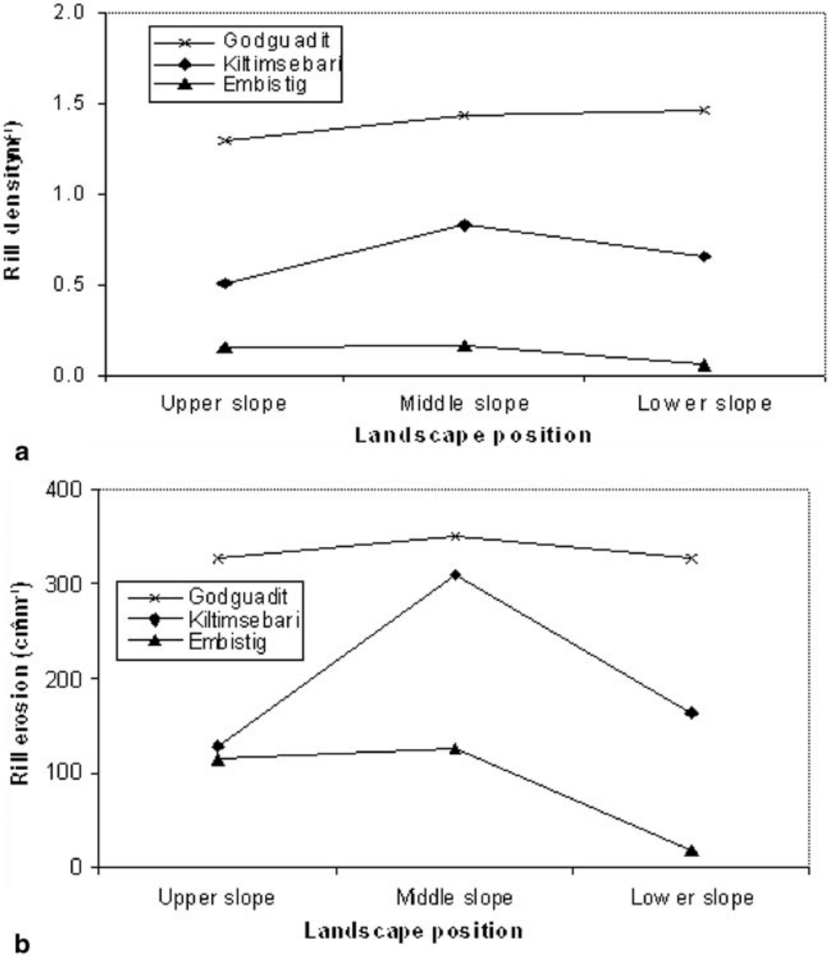

Fig. 11.5 **a** Rill density varies along by location and by site. **b** Location specificity of rill erosion

have shown the impact of convergence on erosion, largely through the development of rills and gullies that increase erosion compared with the divergent slope shapes. Rieke-Zapp and Nearing (2005) also indicated the occurrence of deep rill incision on the concave–linear slope shape.

11.4.2 Rill Formation and Development on the Intra-terrace Area

Monitoring the development of rill erosion along series of terraced fields is used to assess the efficiency of existing terraces against rill formation in the open terrace area (top, middle, and bottom terrace area) and to describe the associated causes.

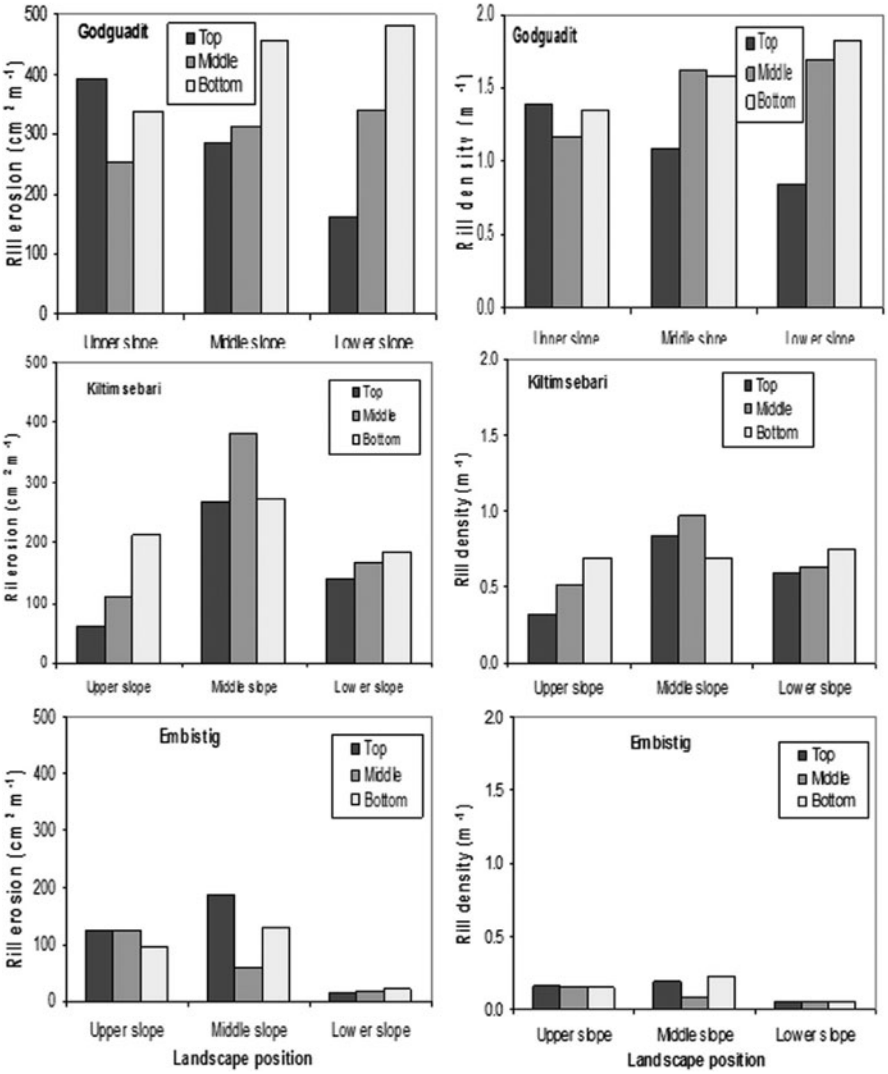

Fig. 11.6 Rill cross sections and rill numbers at three relative positions on the area between terrace structures at each site

Figure 11.6 illustrates rill cross sections and rill numbers measured at three relative positions on the area between terrace structures averaged over the landscape positions. At *Godguadit*site, the rate of rill erosion and rill density measured at the top section of the open terrace area decreased from top to bottom part of the catchment. On the other hand, on the middle and bottom intra-terrace positions, both rill erosion and rill density increased linearly to the down slope of the catchment. At *Kiltim-sebari* site, except in the middle part of the catchment, rill erosion and rill density increased linearly from top to bottom position of the intra-terrace area. Rill erosion at *Embestig*, however, was decreased from top to bottom in the area between terraces particularly on the upper and middle part of the catchment.

The role of stone terraces as barriers to rill development at *Godguadit* and to some extent at *Kiltimsebari* was minimal compared to *Embestig* catchment. At *Embestig,* the relative uniformity in the layout of terraces along the slope profile produced comparably low rill formation at lower slopes. In the same catchment, the reduced number of rills down slope suggested that concentrated runoff emerging from the tree plantation area was filtered and obstructed by series of stone terraces. The scouring capacity of the concentrated runoff was limited by the buffering effect of terraces. Similar results indicated that the shear stress is not effective for rill sediment transport because the runoff energy is dissipated on the terrace elements (Gime'nez and Govers 2005). At *Kiltimsebari*, foot paths and fallow lands at the middle position of the landscape were sources of concentrated runoff, which resulted in the formation of many rills on agricultural fields at the middle of the catchment. On the lower part of *Kiltimsebari*, however, rill development decreased because of the presence of depression areas at the lower part of the catchment.

The pattern of longitudinal rill erosion development in the area between terraces was dynamic and varied from catchment to catchment. Rill erosion and its development at the upper area of the catchment were mainly influenced by the runoff concentration from upstream sources. However, variation of rill formation and development within fields (between terrace structures) were strongly influenced by the slope variability and slope length of the fields. In general, monitoring the rate of rill erosion and rill density on terraced area along the toposequence of the catchments indicated the combined role of terrace design and layout; landscape structures and/or barriers, such as terraces, field boundaries, footpaths, and waterways; land-use practices; and slope shape.

11.4.3 Rill Characteristics on Agricultural Field Plots

The sample fields refer to the cultivated lands where the seedbed is prepared using traditional ox plough. The tillage frequency and surface roughness vary depending on the type of crop planted: 1, 3–4, and 4–5 times for faba bean, wheat, and teff, respectively.

Number of Rills The number of rills surveyed from 1.5 m slope length and 5 m contour width was in the range of 2–13 rills. The average number of rills contributing to the plot outlet increased from 1.30 to 1.69 rills per meter on 1.5–6 m slope length, respectively (Table 11.2). A slight decrease in the rill density was observed and recorded on the down slope section, where transport-limited conditions were more likely to occur, thereby leading to deposition. This was likely due to the reduced rill flow depth and an increased rill width. On the other hand, the rate of new rill initiation decreased with an increase in slope length. The occurrence of maximum rill numbers at 1.5 and 3.0 m slope length was often associated to damaged and poorly built soil conservation terraces upstream of the survey plot. The highest average

Table 11.2 Mean rill characteristics at different slope lengths of the 5 by 6 m agricultural field

Rill characteristics	Slope length (m)				
	1.5	3	4.5	6	Mean
Rill depth (cm)	2.73	2.66	2.94	2.81	*2.8*
Rill width (cm)	8.57	8.99	9.43	9.7	*9.26*
Depth to width ratio	0.35	0.32	0.35	0.33	*0.34*
Rill spacing (m)	0.97	0.77	0.65	0.63	*0.72*
Rill density (m^{-1})[a]	1.3	1.44	1.66	1.69	*1.55*
Rill erosion rate ($cm^2\ m^{-1}$)[b]	29.48	32.94	44.36	43.19	*38.75*
Total rills	122	181	213	223	*739*

[a] Rill density is rill count per contour width

[b] Rill erosion rate is calculated using Eq. 11.3

number of rills was generated on teff fields followed by faba bean, and then wheat tillage practices, respectively.

Rill Cross Sections The rill survey included rills with depth 1.5–8 cm, width 3.5–25 cm, and cross-sectional area 5–105 cm^2. A frequent increase or decrease of average rill depth along the slope was observed, which gives a clue that it was highly influenced by the nature and dynamic changes in micro-topographic surfaces upon the impact of rainfall and runoff flow. However, other rill properties (i.e., depth to width ratio, rill width, rill density, and rate of rill erosion) have clearly indicated the down slope rill development. The rate of specific rill erosion was increased with an increase in slope length up to 4.5 m and became stabilized beyond 4.5 m (Table 11.2). When moving down slope, the mean and standard deviation of rill characters was increased and decreased, respectively, which implies the formation of an organized and stabilized rill development.

11.4.4 *Effect of Tillage Surface Roughness on Rill Formation*

Soil surface roughness referred in this study is the result of tillage frequency and describes the irregularities or micro-topography caused by the traditional *ard* plough pulled by pair of oxen. The tillage implement has created furrow ridge surface with an average furrow depth, bottom width, and top width of 15–25 cm, 6–8 cm, and 28–35 cm, respectively. The soil surface roughness was mainly attributed to the micro-depressions, furrows, and ridges of the tillage practice. Generally, the orientation of roughness was said to be parallel to the tillage direction. The size and orientation of roughness was affected mainly by the frequency of tillage for the respective crops.

Considering all observations, as presented in Table 11.3, average rill depth was 3.55, 2.93, and 2.51 cm; and average rill width was 8.31, 9.66, and 9.30 cm in the order of faba bean, wheat and teff tillage practices, respectively. Greater numbers of rills were measured on relatively smooth surface roughness with parallel rills of 60 cm average spacing on teff plots, whereas, relatively less number of rills of 64 cm spacing on faba bean fields and of 78 cm spacing on wheat fields occurred.

Table 11.3 Mean and standard error (SE) of rill characteristics at different tillage surface roughness

Soil surface roughness (Crop)	Depth (cm)		Width (cm)		Rill density (m^{-1})		Rill erosion ($cm^2\ m^{-1}$)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
High + random roughness (Faba bean)	3.55	0.11	8.31	0.24	1.57	0.06	45.02	2.34
Low + random roughness (Teff)	2.51	0.04	9.30	0.15	1.70	0.02	39.67	0.96
High +oriented roughness (Wheat)	2.93	0.08	9.66	0.21	1.28	0.02	34.79	1.34

Possibly, occurrence of parallel rill network on tillage surfaces of faba bean and wheat was impaired by high roughness and random nature of the surface roughness. The characteristics of rill depth and width were varied with soil surface roughness. The rate of rill erosion was high on tilled surfaces meant for faba bean, followed by teff and wheat. For low surface roughness condition, the rill flow depth was shallow. The linear increase in rill width and occurrence of shallow depth on low surface roughness (i.e., on teff fields) were possibly due to the effect of soil compaction by the animal trampling practice during teff cultivation. Consequently, many small, continuous, and uniformly distributed rills were generated on low roughness surfaces like on teff fields. While the random roughness on faba bean fields has led to uniform rill width and increased flow depth. On such rougher surfaces, rills were greater in depth and fewer in number. High rate of rill confluence (organized rill network) was observed on high size of surface roughness (faba bean fields) as well as on oriented surface roughness (wheat fields). Nevertheless, parallel and continuous rill network system was observed on low roughness surfaces of teff fields.

Similar to our result, the long-term rill survey data at AnditTid catchment have shown high rill erosion on rougher soil surfaces compared to fine and medium soil surfaces. This long-term rill data show that faba bean soil surfaces generated high rate of rill erosion while fallowed plots produced low rate of rill erosion. It suggests that surface irregularities with high size of roughness have greater effect on the flow energy and resulted in greater rill cross section. High and random surface roughness was more likely to increase the concentration of runoff until the preferential flow from small rills was connected to the stable and organized rill system. While in the course of finding more stable preferential flow path, rill depth was increased. Helming et al. (2001) found that while runoff is marginally affected, rough surfaces did show greater soil loss than smooth surfaces because flow concentration may cause an increase in the local erosion. On a rough surface, flow concentrates between the soil clods, routing the runoff within several flow paths on a small portion of the surface (Govers et al. 2000). This has important implication for the spatial distribution of sediment sources and flow pattern for rill formation. The role of micro-topography on the formation of new rills decreased down slope. In general, micro-topography played a net decreasing effect on the parallel rill network development, which was mainly attributed to an increase in the runoff sink areas caused by the depressions developed upslope of the ridges.

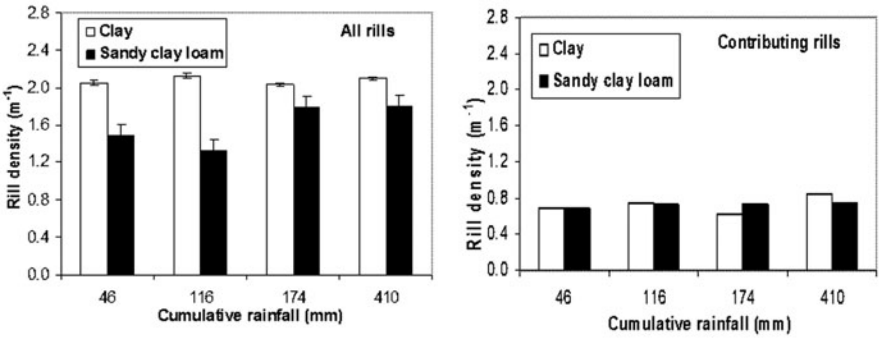

Fig. 11.7 Mean rill density calculated from digital elevation model (DEM)-generated time series

In summary, it can be concluded that stabilized and well-organized rill development on the area between terraces occurred beyond 4.5 m slope length measured from upper terrace. On agricultural fields with 15–25 % slope gradients, the 4.5 m slope length is suggested as the minimum terrace spacing in order to reduce significant rill erosion under extreme storms. The number and size of rills vary according to the orientation and size of soil surface roughness. High concentrated runoff and organized deep rills were formed with increased random surface roughness. It is true that under low stable soil condition with low bulk density (referring tilled soil), there was high detachment by the raindrop impact prior to runoff generation. However, after surface sealing, a corresponding increase in the amount of runoff water can contribute to greater rill erosion (Gomez and Nearing 2005). On relatively smooth soil surface roughness, however, wide and shallow braided rills, as well as continuous and parallel rills, were generated, and a large amount of overland flow was produced due to compaction effect due to animal trampling.

11.4.5 Rill Network Development and Rill Prone Areas on Tilled Surfaces

The photogrammetric data were used to generate time series DEMs. The development of rill network and areas sensitive to rills were generated by subtracting the subsequent time series DEMs in order to determine rill density and topographic parameters. Rill density has been used as a characteristic measure of rill erosion and rill network development. The mean rill density calculated from the generated time series DEMs is presented in Fig. 11.7. On plots of 14 m slope length and 3.2 m width, the range of rill density for all rills varied from 1.33 to 2.10 m^{-1} (corresponding rill spacing of 75 to 45 cm) during all rainfall events. Considering all contributing and non-contributing rills to the plot outlet, the mean rill density was 2.08 and 1.62 m^{-1} for clay and sandy clay loam, respectively.

Rill network development was assessed through classifying rills into non-contributing and contributing rills to the outlet of the test plot. High discrepancy in rill density between all rills and contributing rills has indicated a rill network development. Regardless of the rill cross section, longitudinal rill development has shown variation with distance from upper plot boundary. More rills were, therefore, formed on the top section of the plots (within 3–4 m slope length). Many of the smaller rills incised appear to end or merge into larger rills on depression areas. Higher probability of rill confluence was, thus, observed for rills routed along the tillage furrow direction and resulted in low number of contributing rills to the end of the plot. In most cases, the rill network was controlled by the distribution and abrupt change in the soil surface roughness. The higher the soil surface roughness, the more will be the density of smaller rills and less contributing rills to the plot outlet. The rill networks were developed as a result of the interconnection of soil surface depressions when flow concentrates in the channels. The presence and random (or oriented) distribution of the depressions have resulted in the confluence of rills and formation of network of rills. Comparison of results of rill density and rill network in the current study under Ethiopian farming condition with the Water Erosion Prediction Project (WEPP) model assumption of 1 m rill spacing (Flanagan and Nearing 1995) implies the model has limitation in considering rill network development and, thus, underestimates rill erosion. This study is an attempt to show the characteristics of spatial and temporal rill development as an input to improve parameters of erosion models.

Similar to the rill survey results discussed earlier, the results obtained using the close-range photogrammetric (CRP) technique have also indicated that soils with high soil surface roughness were more prone to initiate many small rills and led to wide area coverage of rill initiation than smooth soils. The observed rill prone areas were associated with rougher soil surfaces and local soil cohesion. Because those plots with high initial surface roughness like clay texture plots with the presence of some stones did not immediately have smooth soil surface condition, due to the distributed impact of rainfall and overland flow, and high local relief created by the stones. In such condition, the surface modification toward smooth surface was very gradual, and as a result there were spatially distributed runoff concentration areas. This signifies that rough soil surface needs more rainfall for sealing and for an organized preferential rill flow system to achieve. On the contrary, for those soils with relatively smooth initial soil surface roughness, the change in roughness was immediately observed to affect the rill prone area during a given rainfall impact. On these smooth soil surfaces, the roughness was increased relative to the initial size due to subsequent rill formation. This effect led to reduce the threshold area of rill formation.

Mancilla et al. (2005) pointed out that at depression points, there is a greater possibility for rill initiation if the flow is sufficiently high. However, if there are no depressions, water will create incisions in areas where the soil does not have enough cohesion to resist the hydraulic stress from the runoff flow. Accordingly, rill initiation occurred on plough ridges where these areas are associated with low bulk density. Looking at the longitudinal distribution or development of rill prone areas, it can be said that rill initiation decreases with an increase in slope length. However, rill initiation is independent of slope length under conditions where there is oriented tillage surface or systematic roughness. Generally, the role of initial surface micro-topography appears to have a strong control on the formation of initial rills.

11.5 Erosion from Farm Ditches

In this section, the characteristics of runoff drainage ditches and their erosion contribution on cultivated lands in the highlands of Ethiopia are discussed. Open drainage ditch is one of the indigenous practices widely used by farmers in the highlands of Ethiopia to drain off excess runoff, and its construction is executed in every cropping season (Aklilu and de Graaf 2006; Million 1996). The open ditches are constructed by pressing *maresha*, a traditional ard plow pulled by oxen, deep into the ground. The primary aim of the open drainage ditches is to provide an adequate and readily accessible channel through which the concentrated overland flow can easily be drained before developing into concentrated flow channels. Thus, traditional ditches drain excess water from the field, protect the soil from being washed away by runoff, and reduce concentration of surface runoff generated within the cultivated land.

The magnitude of ditch erosion depends on how well or how poorly a farmer's ditches are oriented. In most cases, the ditches are constructed with gradients significant enough to cause erosion, sometimes even up and down slope. Drainage ditches in the case study areas (*Angereb* and *Enkulal*watersheds) were constructed with an average gradient of 4–7 %. Accumulation of sediment at the outlet of ditches is a good indicator of ditches as potential sources of erosion. Not only the accumulated sediment, but also the temporal change or development in the cross section is an indicator of the relative magnitude of erosion from ditches.

The results presented in this section are, therefore, based on the assessment of runoff drainage ditches on cultivated lands in *Angereb* and *Enkulal* watersheds in the Lake Tana subbasin. Periodical assessment of ditch dimensions (depth, width, and length) during the rainy season (early, middle, and late period of rainy season) was carried out on 246 and 176 ditches in *Enkulal* and *Angereb* watersheds, respectively. The magnitude of erosion contribution from ditches was evaluated by measuring the rate of change of ditch cross section over time and/or its sediment transport rate. The spatial distribution or density of ditches greatly varies from field to field depending on the type of crop grown and drainage condition of soils. Because of this nonuniform distribution of ditches, assessment of sediment transport rate per ditch (displacement rate of sediment from top to down slope) was indirectly estimated using change in cross-sectional area per unit length along the ditch and at different periods in the rainy season.

11.5.1 Characteristics of Farm Ditches

Slopes usually dictate the orientation of ditches. In the lower slopes, ditches are made at low gradient, while on steeper slopes, ditches are made at high angle to the main slope. However, in some farms, the ditches were made along the maximum slope. This may lead to facilitate and aggravate erosion by water. In *Angereb*, the average top width and depth of the drainage ditches were in the range of 40–50 cm and 13–18 cm, respectively. In *Enkulal* watershed, the dimensions are reduced to 35–40 cm and 15–20 cm due to the mild slope gradients (Table 11.4). The density of the ditches and its dimension are dependent on the nature of the soil, slope of land, and type of crop cultivated. Coarse-textured soils were found to be drained with widely spaced ditches, while clay soils were drained with closely spaced ditch systems. High density of ditches is commonly observed on teff-covered fields planted on gentle and flat slopes. It has most frequently been ploughed down the main line of the slope with varying gradients. Properly constructed drainage ditches can prevent erosion and gullying of land on slopes by catching surface runoff before it reaches the critical stage. In Angereb watershed, except those plots with high stone cover, every farmer has constructed at least three and at most nine ditches inside the field to safely remove the excess runoff. The number of ditches per parcel in *Enkulal* watershed varied between 3 and 52 irrespective of the type of crop cover. The high number of ditches is usually recorded on teff plots.

Seasonal monitoring of ditches has shown that 8.0, 12.0, and 20 mm changes in depth were measured in 2 months period (July–September) at *Godguadit, Kiltimsebari* and *Embestig* sites, respectively. Similarly, the respective change in width of ditches was 26.0, 29.0, and 21.0 mm. At *Enkulal*, as a result of low slope gradients, it has been observed that the change in depth and width in 2 months period indicates accumulation of transported sediment along the channel. The results further showed that ditches especially during erosive rains encouraged runoff erosion, the extent of which was further aggravated by increasing land and ditch slopes. Other studies in the highlands of North Shewa around Debre Birhan have presented soil loss rate of 20–35 t ha^{-1} (equivalent to 1.7–3.0 mm soil depth) on cultivated lands with slopes less than 10 % (Yonas et al. unpublished). This implies that the erosion potentials of ditches and its impacts are high.

11.5.2 Sediment Transport Rate of Ditches

Ditches serve as a sediment-transporting channel. The transport efficiency of the ditches was observed by measuring sediment accumulation area in the channel per unit length. It is the change in the cross section of the ditch. At *Enkulal* watershed, the sediment transport rate was increased from top to down the ditch and over the rainy season. In the mid of July, the sediment transport rate per ditch was 0.19, 1.33 and 1.52 $\text{cm}^2\ \text{m}^{-1}$ at the top, middle, and bottom of the ditch, respectively. The transport rate increased to 0.93, 3.39, and 4.32 $\text{cm}^2\ \text{m}^{-1}$ in the middle of August. However, in

Table 11.4 Average depth and width of farm ditches at Angereb and Enkulal watersheds

Survey periods	Angereb watershed						Enkulal catchment	
	Godguadit catchment		Kiltimsebari catchment		Embistig catchment			
	Depth (cm)	Width (cm)	Depth (cm)	Width (cm)	Depth (cm)	Width (cm)	Depth (cm)	Width (cm)
July	16.8 ± 2.7	46.1 ± 8.6	13.3 ± 2.0	41.7 ± 3.4	15.7 ± 2.1	44.8 ± 6.2	19.1 ± 0.7	38.3 ± 1.2
August	17.6 ± 3.4	48.4 ± 8.9	12.7 ± 2.1	42.4 ± 5.5	16.5 ± 2.2	44.4 ± 6.3	16.7 ± 1.6	36.4 ± 1.0
Septem.	17.5 ± 3.1	48.7 ± 8.6	14.5 ± 2.4	44.4 ± 4.1	17.7 ± 2.0	46.9 ± 8.7	14.0 ± 0.1	36.6 ± 4.9

Table 11.5 Sediment transport rate per ditch ($cm^2\ m^{-1}$) at different catchments in Angereb and along the ditch in Enkulal watershed

	Angereb watershed		
Survey Period	Godguadit catchment	Kiltimsebari catchment	Embistig catchment
July	0.45	0.185	0.99
August	0.49	0.179	1.04
September	0.495	0.215	1.18
Mean	*0.478*	*0.193*	*1.07*
	Enkulal watershed		
	Top of the ditch	Middle of the ditch	Bottom of the ditch
Mid-July	0.19	1.33	1.52
Mid-August	0.93	3.39	4.32
Mid-September	3	0.59	3.58
Mean	*1.27*	*2.7*	*3.97*

September, the transport efficiency was at a decreasing rate most likely due to the decline of erosive rainfall events (Table 11.5). At *Angereb*, the rate of sediment transport was slightly increased over the rainy season. Specifically, the rate of transport is more active at *Godguadit* catchment. However, the efficiency of transporting sediment along the ditch channel is much lower as compared to the rate measured at *Enkulal*. The capacity of ditches as a transporting channel for the eroded soil material from the open area between ditches was low at *Angereb*. Rather, there was active ditch erosion.

Under heavy rain storm conditions combined with excessive ditch gradients, ditches serve as hot spots for accelerated erosion. Unless there is proper construction it provides high risk of erosion downstream in the form of rills and gullies and leads to conflicts among adjacent land owners. The negative impacts of this practice are apparently observed in the field by forming gullies along adjacent farm boundaries, damage the terrace structures, and serving as a sediment-transporting channel where sediments accumulated at the outlets. Consequently, many land users who are practicing open farm ditches do not notice the risk of traditional open ditches to properly address erosion problems since they are constantly struggling only against the control of highly recognized and visible forms of erosion (Aklilu and de Graaf 2006).

11.6 Erosion Control Practices

In response to the land degradation and accelerated erosion problems in the Ethiopian Highlands, a range of conservation measures of soil conservation, moisture conservation, and runoff management functions have been practiced in massive scales, although the trend shows that the projects have had a limited success. Since the early 1970s, for example, food for work (FFW) programs were assigned with SWC activities. Currently, the implementation continues through public mass mobilization for watershed-based natural resources development measures including stone terraces, soil bunds, check dams, cutoff drains, waterways, in-situ moisture conservation practices, such as micro-basin, eye brow and trenches, biological measures, and area enclosures.

Despite the massive SWC programs in the last three decades, the transfer and adoption of the promoted SWC technologies remained low (Hurni 1984; Million 1996; Herweg and Ludi 1999; Weldeamlak and Sterk 2003; Mitiku et al. 2006). According to (Mitiku et al. 2006) among the reasons for low transfer and adoption by farmers are: the top-down approach in extension activities and lack of location-specific SWC technologies. Similarly, Hurni (1986) indicated that great attention was not given to the area specific soil erosion process-based conservation measures before introducing large-scale SWC program to Ethiopia. Ineffectiveness of SWC structures perceived by farmers was an important factor discouraging farmers from participating in SWC activities (Weldeamlak 2003).

Failures in SWC suggest that more detailed information should be used for appropriate layout and design of SWC measures—what type of SWC is needed and exactly where. It is also suggested that the performance of SWC should be better monitored over time. Knowing the critical locations of a slope means being able to minimize the risk of irreversible damage, to avoid failure with SWC, and, thus, to make it more efficient (Herweg and Stillhardt 1999). For a specific area, it is, therefore, necessary to consider where and how to start SWC.

The design and layout of a terrace involve the proper spacing and location of terraces, the design of a channel with adequate capacity, and development of a formable cross section. Terrace spacing should not be so wide as to cause excessive rilling and the resultant movement of large amount of soil into the terrace channel. The runoff from the terraced area should not cause overtopping of the terrace, and the infiltration rate in the channel should be sufficiently high to prevent severe damage to crops (Taffa 2002). In his economic evaluation of SWC measures, de Graaff (1996) states that the extent to which a measure is efficient depends on the degree to which it contributes to its objective of reducing soil, nutrient, and water losses, and that the extent to which measure is effective depends on the response to yields or to the increased utility that is brought about by the amount of soil, water, and nutrients retained, which could also minimize downstream effects.

Past experiences in soil conservation have shown that SWC measures are characterized by improper layout and cross sections, lack of integration, and lack of maintenance. Assessment of the technical performance of stone terraces was made in *Angereb* watershed. Stone terraces are in widespread use and distributed over the cultivated plots in the study catchments. But no farmers support physical soil conservation structures combined with biological ones, except when the local shrub known as *embacho* is left growing naturally along the terrace structures. It can be said that individual farm plots (an average area of 0.33 ha) have at least one and a maximum of eight stone terraces or soil bunds, though their effectiveness is questionable. The overall assessment result indicates that stone terraces were not structurally stable and not effective to perform its function properly. The physical conservation measures are characterized by very little storage capacity, damage to structures due to runoff, overtopping the terraces and tillage underneath the terrace structures, unstable terrace cross section on steep slopes, and unnecessarily wide spacing between successive terraces. There is no common and standard terrace layout and design for the same slope and soil conditions. As a result, fragmented terraces are a common cause of on-site and off-site erosion damage.

Inadequate design in the cross section of stone terraces has led to overtopping of runoff and instability of terrace structures on steep slopes and made them liable to mechanical damage by animals. Out of the surveyed fields with total terrace length of 7,920 m, only 10 % have stored sediment behind terraces. Due to wide terrace spacing (range from 5 to 25 m), the design storage capacity of terraces filled in short period. The low efficiency of stone terraces resulted in rill formation that in turn brings about 10–46 % biomass yield reduction on top position within the terrace area compared to bottom position (Gessesse and Hurni 2011). These result in less-efficient soil conservation. This demands improvements to enhance efficiency of the soil conservation or erosion control practices. Here, some best and improved practices are described.

Integrating Trenches with Terraces The efficiency of stone or soil bunds is enhanced by integrating trenches with dimensions modified to fit plot slope and terrace conditions. It is constructed on the top side of terraces to partially retain runoff water and sediment from the terrace area. This substitute for graded runoff storage basins or graded channels. The integration of trench with terraces improves efficiency of the terrace and provides multiple functions:

- Retention of excess runoff water which otherwise overtops the terrace and causes damage to the structure and to downs slope plots
- Avoidance of sediment loss and off-site damage from excess drainage runoff from terrace channels on side waterways and adjacent plots
- Retention of sediment eroded from terrace area
- An increase in the amount of water that infiltrates through reduction of the overland runoff component
- An increase in available soil moisture during terminal drought with consequent improvement in the yields of crops cultivated below the terrace structure
- An increase in interflow and possible long-term improvement in recharging

Integrating Biological Measures Free grazing is a challenge in the face of attempts to promote multi-purpose tree plantation and biological conservation measures with terrace structures. Despite the grazing problem, in addition to local shrubs growing naturally along terrace structures, some farmers are currently adapting value-added plantations, such as spice plant called *Tena Adam*, grass pea, and Ficus thonningi (*chibha*) tree plantation along terraces for animal feed that fit into the annual cropping system.

Improving Terrace Cross Sections Damage to stone terraces due to unstable cross sections is common. It is also difficult to maintain or improve old stone terraces on steep slopes by adding more stones. Improvements are made on the top cross section of the terrace structure. The height of structures on the upper side is built up to the ground surface, while the lower side riser height is increased to retain maximum sediments. These improvements increase structural stability and reduce liability to mechanical damage. The inclined top cross section of the structure is developed through time by adding soil and biological measures when storage capacity is filled by eroded sediment.

11.7 Conclusion

In the Blue Nile basin of Ethiopian Highlands, where erosion is the main cause of land degradation, identifying the relative importance of rill erosion and farm ditch erosion that directly influence total soil erosion is extremely important for planning, designing, and implementing appropriate erosion control measures. Erosion in the form of rills is widespread on agricultural lands. Monitoring of spatial and temporal rill erosion development on agricultural lands of 6, 15, and 300–500 m slope lengths has revealed the greater role of tillage-induced surface roughness at field scale and slope shapes (concavity and convexity) and land use and management practices at catchment scale. The presence of conservation terraces, footpaths, and waterways inside the catchment has also played a great role for the longitudinal rill development by diverting or dissipating the concentrated runoff. Regardless of the scale of observation, spatial pattern of rill formation and development over different slope lengths are more or less similar. Relative comparison of crop tillage practices without cover condition has showed that faba bean tillage management was more susceptible to seasonal rill erosion, followed by teff and wheat tillage surfaces under no cover condition. However, it has to be noted that the investigation did not include erosion before the final seedbed preparation, which might give different magnitude of rill erosion for teff tillage management as the teff field is left without cover during early rainy season.

Open drainage ditch practiced on agricultural fields is one of the indigenous practices widely used by farmers in the highlands of Ethiopia to drain off excess runoff. However, assessment of its erosion contribution gave a clear picture that ditches serve both as source of erosion and as sediment-transport channel for the eroded soil from farms. In one rainy season, the depth and width of ditches constructed on moderate to steep slopes increase from 8 to 20 mm and 20 to 30 mm, respectively. From a single farm ditch, on average, sediment is transported at a rate between 0.5 and 4.0 cm^2 per meter of ditch. It is observed that the erosion rate from farm ditches exceeds the soil loss tolerant limit in Ethiopian Highlands which is estimated at 10 t ha^{-1} year^{-1} (Hurni 1985; Hellden 1987). This indicated the importance of protecting and controlling ditch erosion without compromising the need to drain excess water.

Many soil conservation measures were implemented to tackle soil erosion and land degradation but some are not fitted to the farming system and majority is characterized by low efficiency to perform its function properly. Improvement measures are required so that the efficiency can be sustainable. Thus, there is a need to facilitate a participatory action learning approach to fill the knowledge gap of farmers, in order to identify and assess emerging erosion indicators like rill and ditch erosion themselves before it is developed into large-scale damage and practice improved soil conservation. This approach could solve the growing challenge of small-scale farming on hill slopes to make a balance between erosion hazard and interventions that meet farmers' immediate objectives and ecological sustainability.

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Chapter 12
Hydro-Epidemiology of the Nile Basin: Understanding the Complex Linkages Between Water and Infectious Diseases

Michael C. Wimberly and Alemayehu A. Midekisa

Abstract The human population of the Nile basin has been vulnerable to water-associated diseases since the dawn of history. In the modern landscape, water development projects and expanded irrigation are considered vital for increasing agricultural productivity and improving the socioeconomic status of rural communities. However, these projects also have the potential to modify hydrological processes in a way that increases the risk of water-associated diseases. To explore these interactions, we first outlined the major hydrological determinants of three important water-associated diseases within the Nile basin: cholera, a water-borne disease; schistosomiasis, a water-based disease; and malaria, a water-related disease. We then reviewed the scientific literature that has examined the influences of dams, irrigation schemes, and other water-management practices on these diseases within the Nile basin. Our synthesis of the literature emphasizes the importance of integrating public health concerns into the planning of new water development projects in the Nile basin and also highlights the potential for utilizing the underlying hydro-epidemiological relationships to enhance mapping and forecasting of water-associated disease risk under current and future climates.

Keywords Hydro-epidemiology · Nile River basin · Infectious diseases · Cholera · Malaria

12.1 Introduction

The Nile basin encompasses one of the largest and most important river drainages in the world, covering an area greater than 3,400,000 km^2 and including portions of 11 countries. Because of its vast size, this area incorporates a broad range of environmental conditions from deserts to tropical rainforests. The Nile River has

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enormous historical significance; its flows provided the water and nourished the soils that supported one of the earliest human civilizations in Egypt. Water-associated diseases, including schistosomiasis and malaria, have been documented in ancient Egypt and have impacted human populations in this region throughout history (Contis and David 1996; Nerlich et al. 2008). Today, some of the poorest and most vulnerable human populations in the world live within the Nile basin, and this region is a focal point for drought, famine, and infectious disease outbreaks. These crises are frequently intertwined and are often closely linked to water issues that are exacerbated by climatic variability and human land-use activities. The purpose of this chapter is to explore the complex interrelationships between hydrological processes and infectious diseases in the Nile basin through a review and synthesis of the scientific literature.

Many diseases are associated with water through a variety of pathways, and they can be categorized based on the specific mechanisms for these interactions. Three major groups of water-associated diseases (water-borne diseases, water-based diseases, and water-related diseases) are highly prevalent in the Nile basin and will be the focus of this synthesis (Yang et al. 2012). *Water-borne* diseases are caused by microorganisms or chemicals that are directly transmitted via ingestion of contaminated water. Well-known examples include cholera, caused by the bacterium *Vibrio cholerae*; dysentery, caused by the bacterium *Shigella dysenteriae* and other bacteria in the genera *Shigella* and *Salmonella*; and typhoid fever, caused by the bacterium *Salmonella typhi*. *Water-based diseases* are caused by parasitic organisms that spend at least part of their life cycle in the water. They include schistosomiasis (also known as bilharzia) caused by trematode worms that utilize snails as an intermediate aquatic host and guinea worm disease (dracunculiasis) caused by the nematode worm *Dracunculus medinensis* which utilizes copepods as intermediate aquatic hosts. *Water-related* diseases are those for which water is needed to support the breeding of the insect vectors that transmit the disease. The most well known and widespread of these vectors are mosquitoes, and numerous mosquito-borne diseases occur within the Nile basin. These include malaria, caused by *plasmodium* microparasites; yellow fever, caused by a flavivirus; lymphatic filariasis, caused by several species of nematode worms; and Rift Valley fever, caused by a phlebovirus.

Other types of water-associated diseases, including water-carried, water-washed, and water-dispersed diseases, will not be considered in this review because their overall prevalence in the Nile basin is low relative to the three major categories outlined above (Yang et al. 2012). However, these types of diseases may be locally prevalent in particular areas within the basin. Hydrological processes also have important, although more indirect, effects on a variety of other disease agents. Soil-transmitted helminthic infections are caused by multiple species of parasitic worms that are transmitted through direct contact with contaminated soil, and the risk of these infections is at least partially dependent on temperature, precipitation, soils, physiography, and other factors that influence the environmental reservoirs of these parasites (Bethony et al. 2006). Ticks are an important disease vector in the Nile basin as well as the rest of Africa, transmitting a variety of diseases to both humans and animals (e.g., Maina et al. 2012). Unlike mosquitoes, ticks do not directly depend on aquatic habitats to complete their life cycles. However, they spend most of the off-host portion of their life cycle at or near the soil surface and are therefore highly sensitive to climate and its effects on moisture in the upper soil and litter layers (Olwoch et al. 2008).

Because of the growing human population and increasing demand for food production and energy in Africa, there is a need to expand the availability of water resources (Boelee and Madsen 2006). This need is being addressed through a variety of water development projects, including the construction of irrigation schemes, dams, and water storage facilities such as tanks, ponds, and reservoirs. Irrigation and water storage can increase the quantity and stability of water availability for drinking and agriculture, and hydropower dams can additionally supply electricity and help alleviate energy shortages. These water development projects have the potential to expand considerably in the future. Whereas the total irrigated area in the African continent is currently 12.2 million hectares, the irrigation potential of the continent is 42.5 million ha (Boelee and Madsen 2006). However, there is also growing evidence that these water resource development projects can facilitate the transmission of water-associated diseases by providing favorable environments for vectors, hosts, and pathogens (Boelee and Madsen 2006; Keiser et al. 2005; Steinmann et al. 2006). As a result, there is a need to consider the health impacts of these modifications to the hydrological system and develop new strategies that can help to maximize the economic benefits of these projects while minimizing infectious disease risk (McCartney et al. 2007). Improving our understanding of the underlying hydro-epidemiology of water-associated diseases and their potential connections to water resource management will be necessary to achieve this goal.

In the next section, we provide a more in-depth assessment of three important diseases in the Nile basin that all have a major hydro-epidemiological component. To cover the breadth of water–disease interactions, we have selected one disease from each of the three major categories of water-associated diseases that are prevalent in the Nile basin: cholera, a water-borne disease; schistosomiasis, a water-based disease; and malaria, a water-related disease. Our goal in presenting these case studies is to highlight specific aspects of the life cycles of these pathogens that are linked to the climatic drivers, hydrological processes, and human actions that control the distribution of water in the environment. A separate section focuses on the health impacts of water resource development, followed by synthesis and conclusions.

12.2 Case Studies of Water-Associated Diseases

12.2.1 Cholera

Cholera is a water-borne disease caused by the bacterium *V. cholerae*, for which humans are the only known animal host. During cholera epidemics, the disease is transmitted through ingestion of contaminated food and water, and high pathogen loads are sustained through fecal contamination of wells, rivers, lakes, and other sources of drinking water. In the periods between outbreaks, aquatic ecosystems can serve as natural reservoirs for *V. cholerae*. The bacterium can survive and grow in riverine, estuarine, and coastal environments where it is associated with a variety of flora and fauna, including phytoplankton, algae, and zooplankton (Hunter 1997). Favorable conditions for cholera include warm temperatures that exceed 10°C for a period of several weeks and estuarine and marine environments with salinity ranging from 5–30 parts per thousand. However, field and laboratory studies have suggested that vibrios can also survive in freshwater with high water temperature and elevated organic nutrient concentrations (West 1989).

Historically, the major environmental reservoirs for *V. cholerae* have existed in South Asia, particularly the Bay of Bengal from which cholera has spread worldwide in a series of modern pandemics (Mutreja et al. 2011; Faruque et al. 1998). The seventh global pandemic began in 1961 with widespread outbreaks across Asia. In 1971, cholera reemerged in Europe and Africa for the first time in more than 100 years. By the early 1990s, the cholera pandemic had reached the Americas and also resurged across the African continent. Although cholera has subsided across most of the globe, including Asia, Europe, and the Americas, similar declines have not been observed in Africa (Naidoo and Patric 2002; Gaffga et al. 2007). The large number of cases and high levels of endemicity across Africa suggest that cholera is now entrenched across the continent. Published data on cholera case numbers, incidence, and endemicity all suggest that the countries of the Nile basin occupy one of the geographic hot spots for cholera in Africa. Between 2000 and 2008, all of countries encompassed by the Nile basin except Egypt reported cholera cases (Ali et al. 2012). In particular, the Great Lakes region of Africa, including lakes Victoria, Edward, and Albert in the upper Nile basin, has been highlighted as an important focus of continuous cholera outbreaks since the late 1970s (Nkoko et al. 2011).

Cholera thrives in dense human populations with high levels of poverty and limited supplies of safe drinking water. Poor sanitation and resulting fecal contamination of drinking water and food are well known to be major risk factors for cholera (Tumwine et al. 2002). As a result, communities with low socioeconomic status that lack adequate health-care systems are particularly at risk (Olago et al. 2007). Heavy rainfall and associated flooding are also widely recognized as important risk factors for cholera outbreaks. Floods cause direct contamination of water supplies and also create humanitarian crises as a result of population displacements that lead to non-sanitary conditions with limited access to clean drinking water. However, only a small percentage of cholera outbreaks from 1995–2005 were associated with flooding in East Africa as compared to West and South Africa (Griffith et al. 2006). In contrast, refugee camps and other internal population displacements were associated with a higher percentage of cholera outbreaks in East Africa compared to other parts of the continent. For example, one of the worst cholera outbreaks of the seventh pandemic occurred in the vicinity of Goma, a city in the Democratic Republic of the Congo located on the shores of Lake Kivu and just across the border from Rwanda (Echenberg 2011). A main cause of this outbreak was the Rwandan genocide, which led to major population displacements and the establishment of crowded refugee camps with unsanitary conditions that facilitated the rapid spread of the disease.

The mechanisms through which cholera has been sustained in Africa are not completely understood, but a variety of environmental factors have been hypothesized to play a role. Seasonal patterns of cholera cases are associated with the seasonality of rainfall, and interannual variability in cholera cases is associated with temperature and rainfall anomalies (Nkoko et al. 2011; Paz 2009). In particular, increases in cholera outbreaks have been found to occur during the warmer-than-normal conditions that prevail during El Nino events (Nkoko et al. 2011; Olago et al. 2007). Multiple studies conducted in the headwaters region of the Nile basin have found spatial concentrations of cholera cases around lakes, suggesting that these aquatic environments may serve as temporary reservoirs for cholera between outbreaks (Bompangue et al. 2008; Nkoko et al. 2011; Shapiro et al. 1999).

12.2.2 Schistosomiasis

Schistosomiasis (also known as bilharzia) encompasses an array of diseases caused by trematode worms that utilize aquatic snails as obligate intermediate hosts. Africa is the home of 85 % of the global population at risk of schistosomiasis, and these populations account for 97 % of all infections worldwide (Steinmann et al. 2006). Of the five major species of schistosomes, *Schistosoma haematobium* and *S. mansoni* are both distributed widely throughout the Nile basin (Gryseels et al. 2006; Schur et al. In Press). *S. haematobium* is transmitted by snails in the genus *Bulinus* and causes urinary schistosomiasis, whereas *S. mansoni* is transmitted by snails in the genus *Biomphalaria* and causes intestinal schistosomiasis. Manifestations of schistosomiasis in humans range from acute disease that primarily infects travelers with no acquired immunity to anemia, stunting, liver disease, increased cancer risk, and a variety of chronic ailments that afflict population in areas where schistosomiasis is endemic (King and Dangerfield-Cha 2008; Gryseels et al. 2006). Chronic schistosomiasis infections can cause significant disability and impose substantial social and economic burdens on the affected communities (King 2010).

Schistosomes have a complex life cycle in which eggs are shed by the human hosts in urine or feces. The eggs hatch in freshwater, releasing miracidia that invade the intermediate hosts, which are specific species of freshwater snails. The miracidia then multiply asexually in the snails to form sporocysts that are released into the water as cercariae that penetrate the skin of human hosts and cause infection. Because the parasite is dependent on the intermediate host to complete its life cycle, the occurrence of schistosomiasis is constrained by the availability of suitable aquatic habitats. The host snails are sensitive to a variety of environmental conditions including water chemistry, depth, flow, turbidity, shading, and the characteristics of aquatic vegetation (Hunter 1997). Although these snails are generally associated with slow-moving water, specific habitat associations depend on the snail species. For example, *Biomphalaria sudanica* is typically found in shallower, vegetated habitats located in marshes or near lakeshores, whereas other species such as *B. choanomphala* and *B. stanleyi* are associated with deeper lacustrine habitats (Kazibwe et al. 2006; Standley et al. 2012).

Transmission of schistosomiasis requires direct human contact with water, and thus the risk of schistosomiasis depends on human behavior in addition to the aquatic environment. Infection occurs through direct human contact with pathogen-laden water sources, which often occurs when gathering water for drinking and cooking. As a result, piped water, laundry and shower facilities, and other improvements that reduce human contact with water bodies have been shown to reduce the prevalence and severity of schistosomiasis infections (Esrey et al. 1991). In addition, poor sanitation and associated contamination of water bodies with feces and urine lead to dispersal of eggs into the aquatic environment. Therefore, the development of latrines and other sanitation projects can also limit the transmission of schistosomes into water bodies and reduce the risk of human infection (Esrey et al. 1991).

12.2.3 Malaria

Malaria, a mosquito-borne disease caused primarily by the microparasites *Plasmodium vivax* and *Plasmodium falciparum*, is one of the most common infectious diseases in the world and is a major public health problem throughout much of the southern portion of the Nile basin (Fig. 12.1). With the exception of the headwaters of the White Nile, much of the region has a relatively low prevalence of malaria infection and can be characterized as mesoendemic (regular but highly seasonal transmission) or hypodendemic (intermittent transmission). Large malaria epidemics occur most frequently in highland and semiarid regions and are often associated with interannual fluctuations in rainfall and temperature. These epidemics can be particularly devastating because they occur in areas where large portions of the population lack immunity to malaria (Abeku 2007).

Malaria is transmitted between human hosts by anophelene mosquito vectors that depend on water for egg laying and larval development. Their specific habitat requirements vary among species (Sinka et al. 2010). For example, *Anopheles gambiae* breeds in temporary, sunlit pools with relatively low levels of vegetation. In contrast, *Anopheles arabiensis* is generally associated with drier areas, breeds in a wider range of habitats than *A. gambiae*, and is more likely to bite outdoors and to bite animals than *A. gambiae*. *Anopheles funestus*, another important malaria vector, is associated with naturally occurring habitats such as wetlands and lakeshores with emergent vegetation and a mix of sunlit and shaded environments. These species exhibit different geographic ranges within the Nile basin, and the distinctive bionomics of these species thus have implications for malaria transmission in different regions (Fig. 12.2). In particular, *A. arabiensis* and *A. funestus* are all more broadly distributed within the Nile basin than *A. gambiae*, which is limited to the southern portion of the basin.

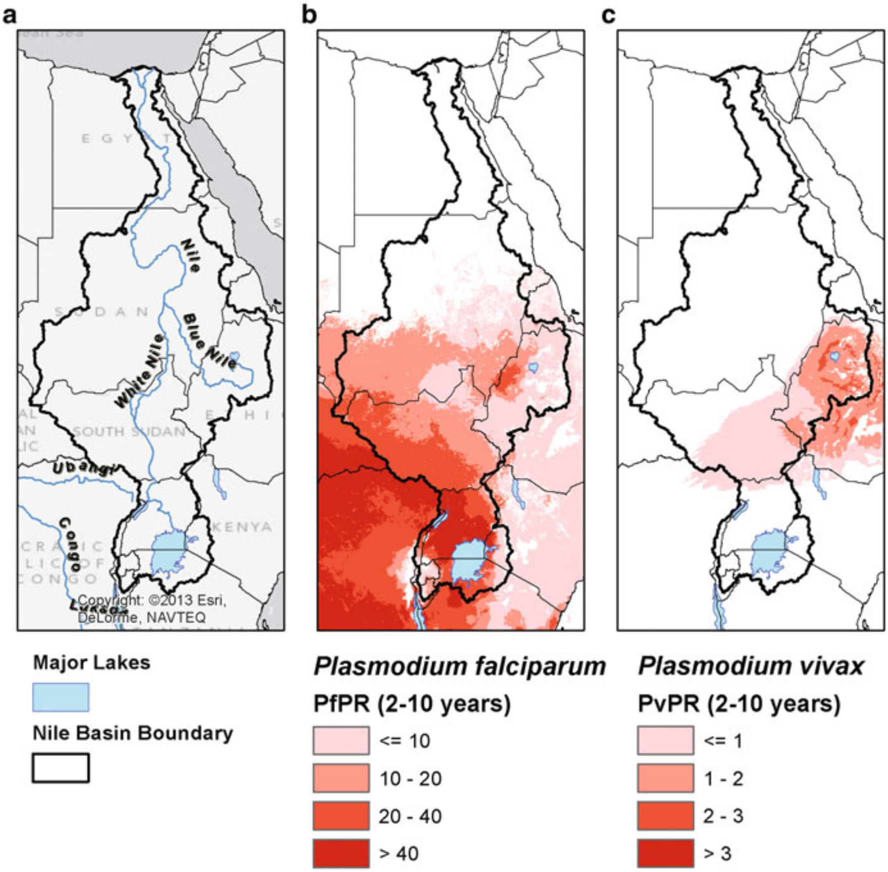

Fig. 12.1 **a** The Nile basin with major rivers, lakes, and country boundaries. **b** *Plasmodium falciparum* parasite rate for ages 2–10 (*PfPR*). **c** *Plasmosium vivax* parasite rates for ages 2–100 (*PvPR*). Malaria maps were obtained from the Malaria Atlas Project (Gething et al. 2012; Gething et al. 2011)

The strong seasonality of malaria across much of the Nile basin is tightly linked with its monsoon climates and their effects on both the mosquito vector and the plasmodium parasite (Cheung et al. 2008; Nicholson 1996). In particular, the highest seasonal rates of malaria incidence and the most severe malaria outbreaks have historically occurred following major rainy seasons. In the Amhara region of Ethiopia, the long rains (*Kirmet*) extend from June through September and provide the majority of total annual precipitation. In an analysis of historical surveillance data from 2000–2010, the monthly numbers of malaria cases from September to December were higher than any other months of the year, with case numbers peaking in October (Wimberly et al. 2012). Other regions of East Africa also exhibit distinctive

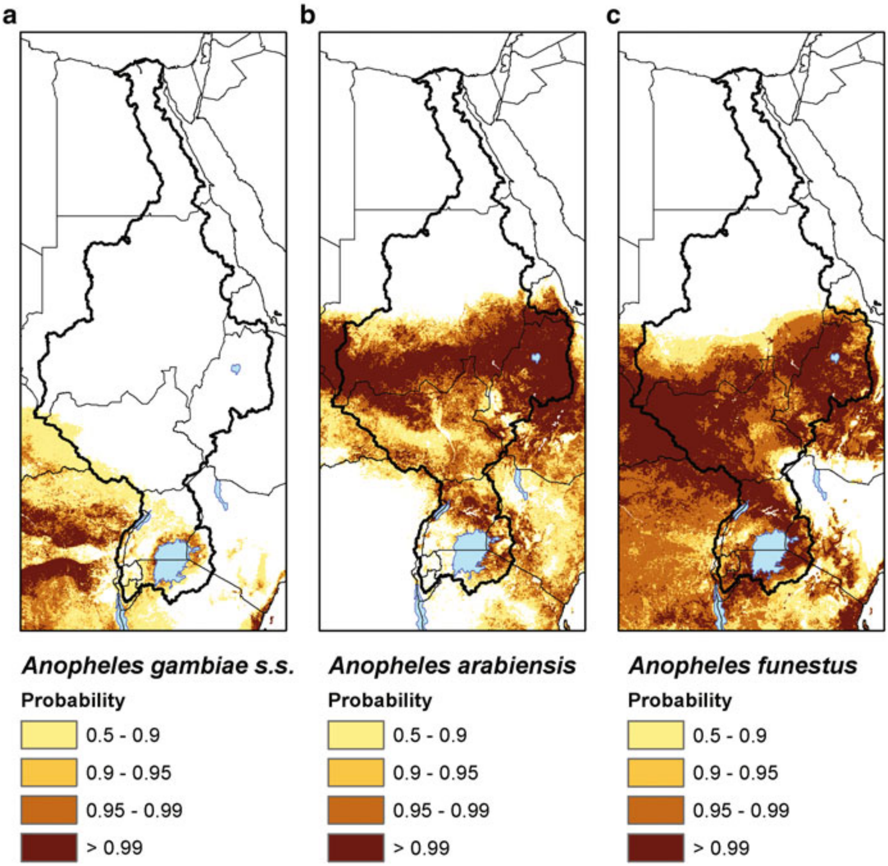

Fig. 12.2 Probability of occurrence of three major malaria vector species in the Nile basin. **a** *Anopheles gambiae.* **b** *Anopheles arabiensis.* **c** *Anopheles funestus*. Mosquito maps were obtained from the Malaria Atlas Project (Hay et al. 2010)

patterns of seasonality. In the highlands of Kenya and Uganda, the dry season extends from June to October with a period of short rains occurring from October to December and the long rains occurring from March to May. In these areas, there is often a smaller early seasonal peak in malaria cases following the short rains, and another larger peak of malaria cases is during the main epidemic season following the long rains (Pascual et al. 2008).

Within the Nile basin, more localized patterns of mosquito abundance and malaria risk are associated with geomorphic landscape characteristics and their influences on hydrological processes and the resulting prevalence of mosquito habitats. For example, malaria incidence is often highest in valley bottoms or close to wetlands than in drier portions of the landscape (Cohen et al. 2008; Ernst et al. 2006). Similarly, temporal patterns of malaria incidence are linked with seasonal and interannual fluctuations in temperature and precipitation (Teklehaimanot et al. 2004; Alonso et al. 2011; Pascual et al. 2008; Midekisa et al. 2012). These relationships reflect the influences of moisture on breeding habitats of mosquitoes and the influences of temperature on developmental rates for both mosquitoes and the malaria parasite (Mbogo et al. 2003; Koenraadt et al. 2004). However, the strength of the relationship between weather and malaria cases, the relative importance of different weather variables, and the time lag at which outbreaks can be predicted all vary with geographic location (Zhou et al. 2004; Mbogo et al. 2003). In particular, the relative importance of temperature and precipitation for predicting malaria cases in Ethiopia has been found to vary in cold versus hot environments and in urban versus rural areas (Teklehaimanot et al. 2004). In general, it is expected that precipitation is likely to be the major environmental driver of malaria outbreaks in semiarid regions, whereas the effects of temperature are greater in cooler highland areas (Abeku 2007).

12.3 Water Resource Development and Health Impacts

Water resource development projects such as dams, irrigation canals, and water-harvesting schemes in Africa have paved the way for expanded generation of electricity, helped to control flooding, opened new opportunities for arable land, fostered expansion of urbanized areas, and generally improved the standard of living for people in the vicinities of these projects (Fenwick 2006). In particular, there has been demand for the increased construction of dams in the Nile basin (McCartney and King 2011). However, these projects also affect hydrology in ways that can expand habitats of the mosquitoes that transmit vector-borne diseases and the aquatic hosts of water-borne diseases (Fenwick 2006; Lammie et al. 2006; McCartney and King 2011). These changes may increase the risk of water-associated diseases, including guinea worm, schistosomiasis, lymphatic filariasis, and malaria (Lammie et al. 2006; Keiser et al. 2005; Steinmann et al. 2006). Therefore, the potential health impact on inhabitants living nearby water resource development projects should be taken in to account when planning these projects.

The interaction of water resources development, economic development, and risk of mosquito-borne diseases is a complex phenomenon, as emphasized in the "paddies paradox" highlighted by Ijumba and Lindsay (2001). The increased agricultural productivity and associated economic development that result from irrigation projects can improve the economic status of the community, leading to better health-care access and increased use of bednets and other preventive measures in the affected areas. As a result, even though irrigation projects can lead to large increases in vector abundance, they generally do not pose a risk to communities with high level of immunity in places of stable malaria transmission (Keiser et al. 2005; Ijumba and Lindsay 2001). On the contrary, irrigation and associated increases in mosquito abundance pose a far greater risk in highland and semiarid areas of unstable malaria transmission where inhabitants have low immunity to the disease. In the highland Ruizizi

Valley of Burundi, villages in close proximity to irrigation sites had higher vectorial capacity and elevated malaria prevalence compared to villages located farther from irrigation sites (Coosemans 1985). In the semiarid Ziway area of central Ethiopia, an irrigated village similarly had higher malaria prevalence than a nearby nonirrigated village (Kibret et al. 2010). Much of the Nile basin is considered to have low malaria prevalence and unstable mesoendemic or hypoendmic transmission (Fig. 12.1), and it can be expected that there is a potential for irrigation and other water resource management to increase malaria risk in these areas.

Several studies have also reported linkages between dams and malaria in the Nile basin. Although the large impoundments created by dams do not provide a suitable breeding habitat for the anophelene mosquitoes that transmit malaria, dams can raise groundwater levels, create puddles at the edge of the impoundment as water levels are drawn down, and lead to water seepage that creates swampy habitats below the dam (Lautze et al. 2007). These effects are exacerbated by the fact that artificial impoundments may lengthen the season over which breeding habitats are available. Increased dam construction in the Uasin Gishu highlands in Kenya was associated with greater risk of malaria transmission (Khaemba et al. 1994). An assessment of the Turkwel Gorge hydroelectric dam of Kenya also reported that there was an increase in malaria risk for inhabitants living in close proximity to the reservoir following the construction of the dam (Renshaw et al. 1998). In the Rift Valley region of Ethiopia, malaria cases for residents who lived within 3 km of the Koka Dam were 1.5 times as high as for residents living 3–6 km from the reservoir (Lautze et al. 2007). Another study in the Tigray region of northern Ethiopia found that the incidence of malaria was almost seven times higher for villages in close proximity to dams as compared to villages farther from dam sites (Ghebreyesus et al. 1999). In addition to dams, other types of water-management activities used to support irrigation can also impact malaria risk. For example, a study in the central highlands of Ethiopia found that increasing rainwater harvesting was perceived by local residents to be associated with a longer malaria transmission season and, consequently, a higher risk of malaria (Kassahun 2008).

Dams and associated irrigation projects increase the risk of water-associated disease transmission by providing suitable habitats for the snails that are hosts for schistosomiasis (Steinmann et al. 2006). Irrigation also increases the potential for schistosomiasis transmission by providing more opportunities for human–water contact and increasing the potential for contamination of water with urine and feces. The construction of the Aswan Dam in Egypt led to a year-round irrigation scheme that increased populations of snails that are the hosts for schistosomiasis, resulting in higher level of infection in the human population (Watts and El Katsha 1997). The Gezira Agricultural Scheme in Sudan, one of the oldest water resource development projects in the Nile basin, was completed in 1924 and provides electricity and irrigation south of Khartoum (Boelee and Madsen 2006). Although this irrigation scheme has greatly enhanced the production of cash crops such as cotton, it has also significantly increased the prevalence of both urinary and intestinal schistosomiasis in the human population. In southern and central Tigray, Ethiopia, the prevalence of *S. mansoni* in humans was higher in irrigated areas than in nonirrigated areas and higher in areas with a long history of irrigation than in recently constructed irrigation schemes (Dejenie and Petros 2009). Similarly, schistosomiasis prevalence increased from 0 to 70 % following the implementation of the Mwea irrigation scheme in Kenya (Renshaw et al. 1998).

12.4 Synthesis and Conclusions

There are a number of prevalent water-borne diseases within the Nile basin that significantly impact the health of this region's human population. Each of these diseases is connected with hydrological processes through a distinctive set of causal pathways. In particular, vector-borne or zoonotic diseases such as malaria or schistosomiasis are highly dependent on the influences of hydrology on the specific habitats of their respective vectors and hosts. As a result, it can be difficult to make a broad generalization about water-borne diseases. However, this review has documented a number of commonalities that can begin to provide a framework for understanding this suite of diseases and developing strategies to improve prevention, control, and elimination efforts.

The three major diseases reviewed (cholera, schistosomiasis, and malaria) are all linked to environmental variability in space and time. Large epidemics of both cholera and malaria can occur within the Nile basin, and outbreaks of both these diseases have been linked to seasonal and interannual variability in temperature and precipitation. Spatial patterns of schistosomiasis prevalence in humans and host snail distributions and infections are associated with geographic patterns of climate and physiography. The implications of these strong climatic linkages are twofold. First, they emphasize the region's sensitivities to future climate change (Hulme et al. 2001). A better understanding of the potential burden of water-associated diseases under projected future climates is needed, although the complexities of climate–disease linkages and the confounding influences of a variety of other important epidemiological factors make this task an enormous challenge (Hay et al. 2002). Second, these environmental associations can be leveraged for mapping and forecasting disease risk, with the aim of enhancing early-detection and early-warning systems for water-associated disease outbreaks (Ford et al. 2009; Thomson and Connor 2001).

The linkages between water-associated diseases and the development of water-management projects such as dams and irrigation schemes present both a challenge and an opportunity. On the one hand, these types of projects have been clearly shown to increase the risk of diseases such as malaria and schistosomiasis under many conditions through direct impacts on habitats for disease vectors and hosts. On the other hand, these projects also increase the standard of living of the population and thus can also indirectly reduce the burden of disease by supporting improvements such as clean water supplies, better sanitation, enhanced nutrition, increased access to bed nets and other preventive measures, and improved health infrastructure. Furthermore, experience has shown that it is possible to design water-management projects so that disease risk can be reduced through active management of water levels and flows (Konradsen et al. 2013). Because water resource projects such as dams, irrigation schemes, and water storages are human-made hydrological features, there is enormous potential for engineers to coordinate with public health experts at the planning stage to reduce favorable environments for disease transmission (Boelee and Madsen 2006). Future water resource development projects should thus be based on integrated approaches that address potential impacts on multiple water-associated diseases, consider the range of potential climate change scenarios that may influence disease risk in the future, and enhance the socioeconomic status of the population in ways that reduce disease risk.

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Part III
Lakes and Watersheds

Chapter 13
Monitoring State of Biomass Recovery in the Blue Nile Basin Using Image-Based Disturbance Index

Essayas K. Ayana, Fasikaw A. Zimale, Amy S. Collick, Seifu A. Tilahun, Muhammed Elkamil, William D. Philpot and Tammo S. Steenhuis

Abstract The heavy dependence of the Ethiopian rural population on natural resources, particularly land, to maintain their livelihood is an underlying cause for the degradation of land and other natural resources. The Ethiopian highlands, which are the center of major agricultural and economic activities, have been eroding for many years. Various actors have undertaken reforestation programs with an aim to

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mitigate the land degradation problem; however, the status of these plantations has never been evaluated at a basin scale. The image-based disturbance index (DI) measures the status of the ecosystem on the basis of the ratio of long-term enhanced vegetation index (EVI) and the land surface temperature (LST). This study applied the DI to assess the current state of biomass in the upper Blue Nile basin with a focus on areas where degradation mitigation measures are implemented through reforestation campaigns. The DI maps are validated through field visits to 19 selected sites and inventory data obtained from the World Food Program (WFP) over five sites. The results showed that the largest expansion of plantations has taken place in five subbasins and is between 6 and 8.5 % of the subbasin area with expansion in the remaining 11 subbasins ranging from 3 to 5 %. Despite the very low annual rate of expansion, it can be concluded that the mitigation measures implemented through reforestation campaigns contribute to the total recovered forest area.

Keywords Biomass recovery · Nile basin · Deforestation · Afforestation · Erosion · Remote sensing

13.1 Introduction

Land degradation is a major problem in Ethiopia. It takes place in the form of soil erosion, gully formation, soil fertility loss, and severe soil moisture stress, which is partly the result of loss in soil depth and organic matter (Hagos et al. 1999). The excessive dependence of the Ethiopian rural population on natural resources, particularly land, as a means of livelihood is an underlying cause for degradation of land and other natural resources (Bekele 2008). Agriculture accounts for 45 % of the gross domestic product (GDP), 85 % of export revenue, and 80 % of employment (EPA 1997). The demand for farmland, timber, fuel wood, and grazing lands drives the overexploitation of forest resources (Gebremedhin et al. 2003) in the Ethiopian highlands where the bulk of the population lives. As a consequence, the Ethiopian highlands have experienced accelerated soil erosion for many years.

The annual soil erosion in Ethiopia ranges from 16 to 300 tons/ha/year depending mainly on the slope, land cover, and rainfall intensities (Hawando 1997; Tebebu et al. 2010). A reclamation study by the Food and Agriculture Organization (FAO) estimated the degraded area on the highlands at 27 million ha, of which 14 million ha is very seriously eroded with 2 million ha of this having reached a point of no return (Constable and Belshaw 1986). High population growth and the need for further agricultural expansion into marginal areas of fragile soils or critical habitats for biodiversity will lead to significant environmental degradation and deterioration of resilience for future environmental shocks unless intervention measures are introduced (Jagger and Pender 2003).

With an aim to mitigate land degradation problems in Ethiopia, the federal and local governments and various nongovernmental organizations (NGOs) have undertaken soil and water conservation measures. The World Food Program (WFP) “Project 2488,” Managing Environmental Resources to Enable Transitions to More Sustainable Livelihoods (MERET) project, the Millennium “one man two tree” campaign, and other similar initiatives are part of the ambitious soil and water conservation efforts that have been made by the Ethiopian government (Nedessa and Wickrema 2010). Some studies show that by the mid-1980s, nearly 180,000 hectares had been afforested and 460,000 ha had been treated through soil conservation practices (Admassie 1998), together amounting to 5 % of the area in the highlands requiring conservation (Shiferaw and Holden 1999).

13.2 Review of the Disturbance Index Theory

The capacity of the landscape to sustain biomass longer (biomass longevity) is an important marker of its state of degradation. Such a capacity can be improved by measures such as increasing organic matter, increasing plow depth (in agricultural fields), conserving water on the landscapes, and devising better drainage infrastructure (in waterlogged areas). In this research context, biomass longevity refers to the landscape's ability to support the growth of vegetation that has been put in place through past reforestation campaigns. Such plantings are sustainable only when there is enough water available for photosynthesis and human interference is controlled. These plantations avoid further degradation by reducing rainfall impact and interrupting surface runoff. Because of the cooling effect of vegetation on the ground, soil evaporation is reduced and infiltration is facilitated, making more water available for the increased biomass.

The evaluation of the state of biomass can be made by quantifying biomass disturbance trajectories using vegetation indices (Michener and Houhoulis 1997; Ruiz and Garbin 2004; Jin and Sader 2005; Leeuwen 2008; Ferreira et al. 2010; Spruce et al. 2010). Here, the image-based disturbance index (DI) tool suggested by Mildrexler et al. (2007) is used to assess the trend in the area expansion of these plantations. The method is used to assess the status of the biomass on the basis of the ratio of long-term enhanced vegetation index (EVI) and the land surface temperature (LST) as measured by the Moderate Resolution Imaging Spectroradiometer (MODIS).

Vegetation indices and LST are the most vulnerable biotic and abiotic components, respectively, of a terrestrial ecosystem to detect alteration during disturbance events (Huete et al. 2002). The EVI, which is sensitive to vegetation changes, is calculated from red, near infrared, and blue bands (Huete et al. 2002):

$$EVI = G \times \frac{(NIR - Red)}{(NIR + C1 \times Red - C2 \times Blue + L)} \tag{13.1}$$

where *NIR, Red,* and *Blue* are surface reflectance at the respective bands; L is the canopy background adjustment factor; $C1$ and $C2$ are the coefficients of the aerosol resistance term; $L = 1$, $C1 = 6$, and $C2 = 7.5$ are coefficients in the EVI algorithm; and G (gain factor) = 2.5 (Huete et al. 1994, 1997).

Vegetated areas generally yield high EVI values as they reflect more in NIR band but less in the visible band. More importantly, LST is strongly related to vegetation density due to the cooling effect of the vegetation through latent heat transfer (Coops et al. 2009). Thus, higher vegetation density results in lower LST. Capitalizing on these phenomena, long-term measurements in the form of remotely sensed images

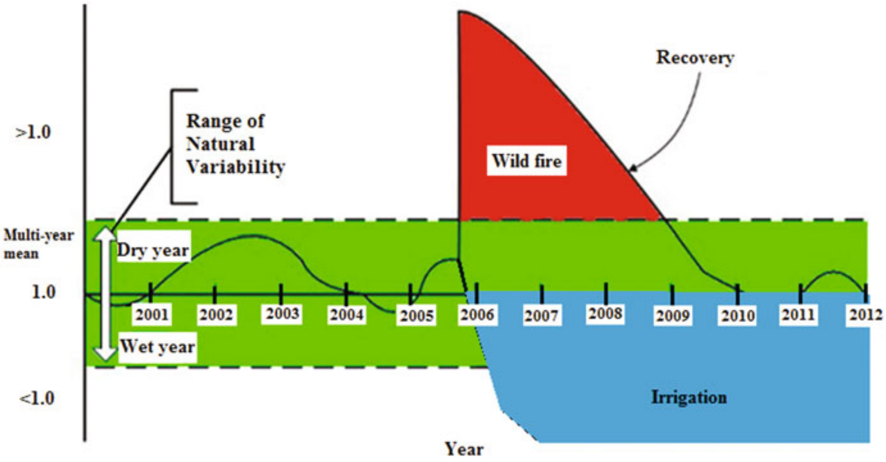

Fig. 13.1 The disturbance index plot (Mildrexler et al. 2007) explains the undergoing process; instantaneous events (e.g., wild fire) cause a sharp decline of biomass and a recovery taking place over extended time

can be used to observe the temporal change in the biomass in the larger spatial extent of the river basin. Causes for disturbance should, however, be properly identified.

There are various causes for changes in biomass that result in positive or negative disturbances. Drought and wildfire are major stressors that affect forest ecosystem functioning and processes (Leeuwen 2008). A number of studies have mapped fire disturbance using the EVI (Coops et al. 2009; Forzieri et al. 2010). Disease, geological incidences (landslide, volcano, etc.), infrastructure expansion, resettlement, and clear cutting also cause positive disturbance. Vegetation recovery due to reforestation and irrigation result in negative disturbance values.

Disturbances may also be short-lived or prolonged (Fig. 13.1). The usual cycle of cropping and harvesting causes increased EVI and reduced LST in the peak vegetation season followed by reduced EVI and increased LST at harvest. On the other hand, drought, disease, and urbanization result in prolonged reduction in the EVI and, thereby, an increase in LST for longer duration. Thus, the length of prevalence of the DI indicates the type of phenomenon causing the disturbance (positive or negative). Seasonal increases or decreases in DI that occur, mainly due to vegetation phenology, fall within an explainable range of variability.

Various image sources are available for use in the DI calculation. Although high-spatial-resolution satellite images may offer a more detailed view of land surfaces, their limited area coverage and temporal sampling have restricted their use to local research rather than large-scale monitoring (Ruiz and Garbin 2004). To be used for regional-scale studies, the high-spatial-resolution images require significant image processing skills. For example, using Landsat Thematic Mapper/Enhanced Thematic Mapper (TM/ETM) images for vegetation monitoring in the upper Blue Nile basin requires the mosaicking of 17 image tiles, applying geometric correction, radiometric normalization and transformation, cloud screening, and atmospheric correction.

The fact that the images are not taken on the same dates further complicates the atmospheric correction, making these images challenging for use by professionals with limited remote-sensing data processing skills. On a regional scale and in heterogeneous environments, such as the Blue Nile region, moderate-resolution images are preferred over finer resolution images for their reduced data volume and processing requirement and increased temporal coverage. Ruiz and Garbin (2004) used Advanced Very High Resolution Radiometer (AVHRR) 8-km images to estimate the burn area for tropical Africa. Coops et al. (2009) and Mildrexler et al. (2009) applied MODIS images to monitor a large swath of area in Northern America. In the current study, archives of satellite data from MODIS are used. Despite their relatively coarse resolution, these images have been successfully used to study vegetation cover change at regional to global scales (Hill et al. 2008). MODIS images provide the advantages of high temporal resolution and smaller data volume and require minimum technical skill for analysis. More importantly, in using MODIS images, much of the uncertainty associated with atmospheric corrections can be avoided.

The objective of this research is to evaluate the state of the conservation measures in the upper Blue Nile basin which are put in place through reforestation campaigns using the DI computed with MODIS images. The resulting DI maps are validated through field visits to areas flagged by the analysis and independent inventory data from WFP. The expected outcome of this study is a measure of the total recovered area, spatial distribution of the recovered areas within the basin, and the recovery trend. As equivalent tools are currently nonexistent, the results of this research will help decision makers to apply similar methods to monitor the recovery trend of biomass in conserved areas for the future. It will also help to locate areas in which reforestation has been successful so as to recommend those practices for scaling up at a river basin scale.

13.3 Method and Materials

13.3.1 Study Area

The Blue Nile is located between 16° 2’ N and 7° 40’ N latitude, and 32° 30’ E and 39° 49’ E longitude (Fig. 13.2). It has an estimated area of 311,437 km^2 (Yilma and Awulachew 2009). The Blue Nile basin (Abbay), with a total area of about 200,000 km^2 (20 % of Ethiopia’s land mass), and accommodating 25 % of the population, is one of the most important river basins in Ethiopia. About 40 % of agricultural products and 45 % of the surface water of the country are contributed by this basin (Erkossa et al. 2009). The Blue Nile represents about 8 % of the total Nile catchment area but contributes about 60 % of the flow of Nile at Aswan, Egypt. A highland plateau, steep slopes adjoining the plateau that tilt to the west, and the western low lands with gentler topography characterize the basin. The steep slopes and the plateaus extend from 1,700 m (Bahir Dar) to 4,000 m (northeast highlands) above sea level. Geologically, the basin is comprised of 32 % exposed crystalline basement, 11 % sedimentary formations, and 52 % volcanic formations. The dominant

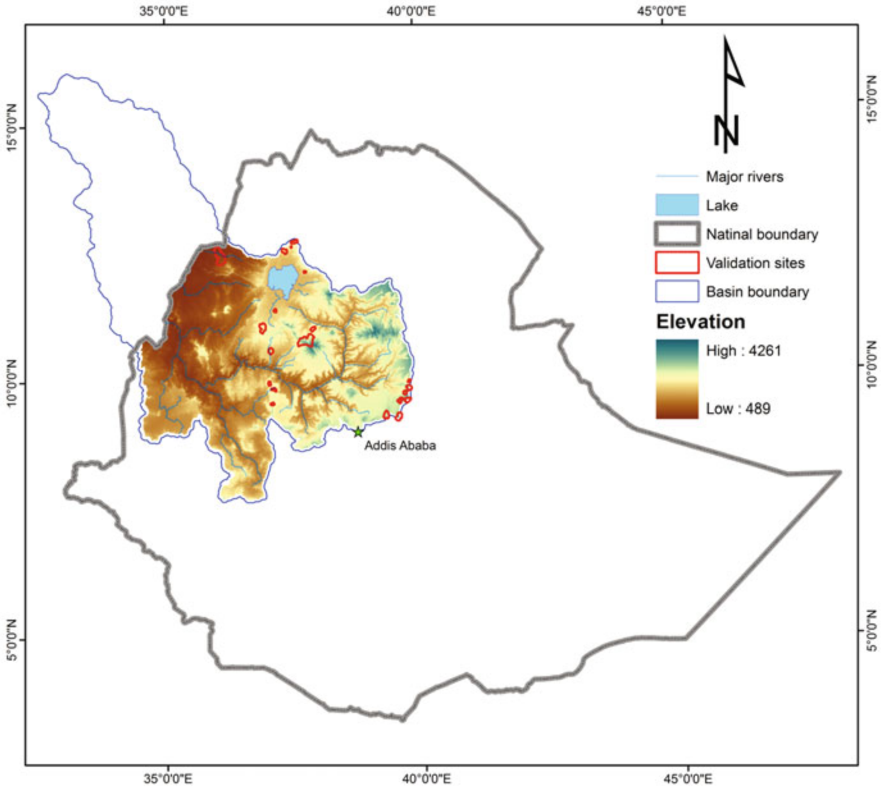

Fig. 13.2 *Upper Blue* Nile Basin (Abbay Basin) and selected ground validation sites

soil texture is Vertisol, covering about 15 % of the Basin (Gebrehiwot et al. 2011). The Blue Nile basin has a short rainy season that extends from March to May, a main rainy season that extends from June to September, and a dry season extending from October to February. The rainfall within the basin shows high seasonality with the peaks in July. The annual rainfall in the Blue Nile ranges from 880 to 2,200 mm (Taye and Willems 2012).

13.3.2 Methodology

13.3.2.1 DI Map Development

The DI map is developed by computing the ratio of annual maximum composite LST and EVI on a pixel-by-pixel basis, such that:

$$DI_i = \frac{LST_{imax}/EVI_{imax}}{\sum_{i-1}\overline{(LST_{max}/EVI_{max}\ )}} \tag{13.2}$$

where DI_i is the DI value for year i, $LST_{i\max}$ is the annual maximum 8-day composite LST for year i, $EVI_{i\max}$ is the annual maximum 16-day EVI for year i, $LST_{\max}$ is the multiyear mean of $LST_{\max}$ up to, but not including, the analysis year $(i-1)$ and $EVI_{\max}$ is the multiyear mean of $EVI_{\max}$ up to, but not including, the analysis year $(i-1)$. The DI is a dimensionless value that, in the absence of disturbance, approaches unity.

The annual $LST_{\max}$ and $EVI_{\max}$ values are computed for each of the 10 years (2003–2012) and the $LST_{\max}$ for each year is then divided by the corresponding $EVI_{\max}$ value on a pixel-by-pixel basis, resulting in a ratio of $LST_{\max}$ to $EVI_{\max}$ from 2003 to 2012. These annual DI layers are then divided by the long-term average of the index for that pixel, averaged over all previous years (Eq. 13.2). For example, the DI for the year 2005 is calculated as the ratio of $LST_{\max}$ to $EVI_{\max}$ of 2005 divided by the multiyear mean for the years previous to 2005 (i.e., mean of 2003 and 2004). Any DI values within the range of natural variability will be considered as having undergone no change, whereas, pixels outside of this central range are flagged as subject to disturbance.

The biophysical relationship outlined by Nemani and Running (1997) is also tested for validity. For each land cover type, the annual maximum LST and EVI raster are produced and the mean of the raster values recorded as mean-maximum LST and mean-maximum EVI.

13.3.2.2 Identifying Disturbed Areas

Coops et al. (2009) recommend values within ± 1 standard deviation of the long-term mean be considered as within the natural variability range. Both instantaneous (fire, disease, and the like) and prolonged (drought, urbanization, and the like) phenomena extend out of this natural range of variability. Therefore, a departure higher than ± 1 standard deviation will be flagged as potential disturbance areas. The ability of the calculated DI to capture these phenomena should be verified by a field survey in strategically selected flagged areas. In addition, the validation work involves the compilation and thorough review of ancillary data collected from organizations implementing reforestation campaigns.

13.3.3 Data

13.3.3.1 Image and Vector Data

MODIS images of 8-day maximum LST (MOD11A2) and 16-day EVI (MOD13A2) products from 2002 to 2010 are downloaded. The International Satellite LandSurface Climatology Project, Initiative II MODIS International Geosphere–Biosphere Program (ISLSCP II MODIS IGBP) land cover (Friedl et al. 2010) data are used to stratify mean-maximum LST and EVI over the study area. The data consist of 18 land cover types with water, forest, shrub land, savanna, cropland, built-up, snow, and barren land as main categories. Vector data layers are used to extract the DI values to analyze biomass recovery patterns at subbasins level. The disturbed area (positive or negative) for the 16 subbasins is extracted and the total area calculated for each subbasin on a year-by-year basis. Boundaries for validation sites are manually digitized and imported into a handheld geographic information system (GIS).

13.3.3.2 Field Data

Based on the DI map generated, 19 sites were selected and field campaigns were carried out to compare the DI map results with actual ground conditions and to verify the type and extent of the disturbance and peasants' perception of the different conservation measures. Semi-structured interviews with key informants were conducted at several households. Focus group discussions were held to facilitate information exchange on the environmental impact of the disturbance areas and the overall participation of the community in initiating, undertaking, and sustaining the gains.

13.3.3.3 Ancillary Data for Validation

Ancillary data include details on watershed conservation and microirrigation projects within the basin. As irrigated areas certainly add to the negatively disturbed area (which may wrongly be considered as recovered areas), the field validation campaigns help in identifying irrigated areas and excluding them from the area calculation of recovered areas.

The data on conservation work within the basin are obtained from agricultural bureaus of Amhara region and the WFP MERET project (Fig. 13.3). The ancillary data include list of location, areas, and time of implementation of plantations. The land covers where the Soil and Water Conservation (SWC) works concentrate are assumed to be those where no existing agricultural activity takes place. Thus, water bodies, grasslands, permanent wetlands, croplands, and urban/built-up areas are masked out. On the remaining land cover types, the areas showing biomass recovery trends are taken to be pixels with DI values less than one standard deviation from the long-term mean. The total recovering area is then calculated for the 16 subbasins in the 2004–2012 time span. The proportion of the recovering area to the subbasin area is used to standardize the results and for ease of comparison.

13.4 Result and Discussion

13.4.1 Validity of Disturbance Trajectory

Figure 13.4 shows the biophysical relationship between mean-maximum LST and mean-maximum EVI for the 2003–2012 dataset. The figure depicts the disturbance trajectory for the different ISLSCP II MODIS IGBP land cover types.

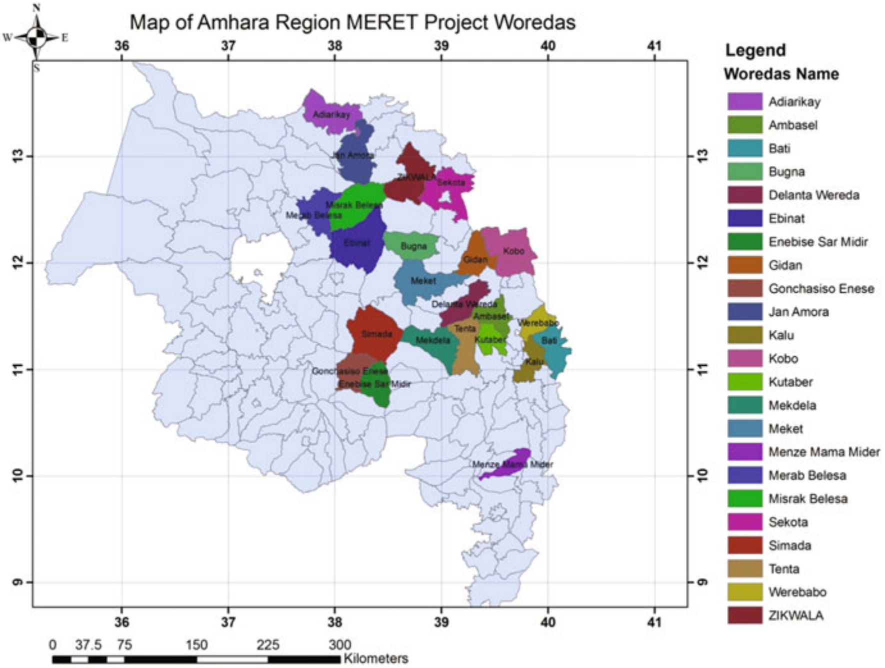

Fig. 13.3 Districts of community-managed watershed projects in Amhara region, five of the districts are used to validate the DI maps. (Source: MERET project, https://sites.google.com/site/meretproject04/. Accessed 1 November 2012)

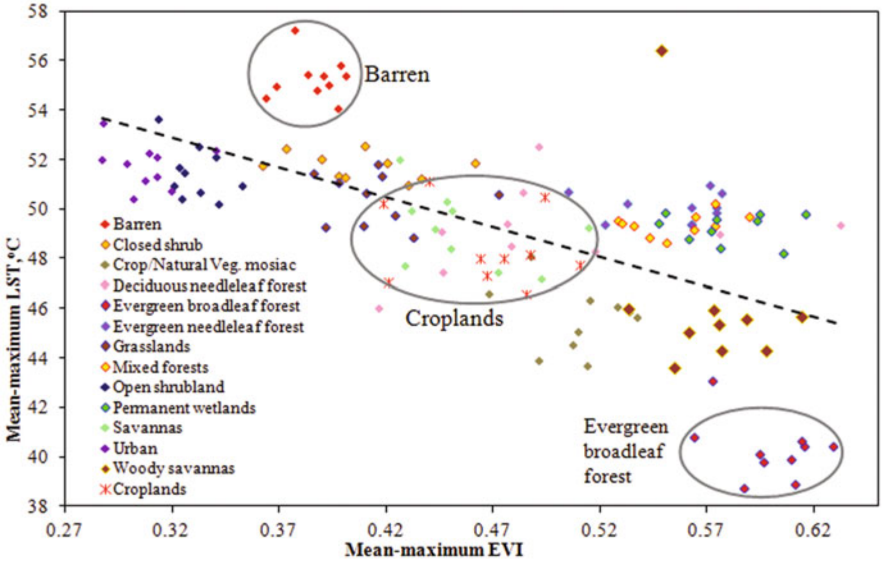

Fig. 13.4 Biophysical relationship between mean-maximum EVI and LST (2003–2012), higher LST is associated with low biomass due to lower latent heat transfer. LST on barren, open shrub, savanna, and woody savanna peaked in 2011 with reduced EVI

Table 13.1 Biomass recovery trend (2008–2012) as percentage of area ((ha/ha) × 100) recovered at subbasin level

Name	Area proportion with DI below one standard deviation of the long term mean				
	2008	2009	2010	2011	2012
Anger	1.4	1.2	2.5	2.2	0.7
Beles	1.3	0.3	1.9	0.5	0.9
Beshelo	4	8.5	2.7	2.1	2.3
Dabus	1.3	0.7	2	1.7	2
Didessa	1.1	4	4	1.4	0.9
Dinder	1.7	0.3	2	0.4	0.5
Fincha	3.7	3.5	5.6	2.5	1.8
Guder	1.5	1.3	8.4	1.1	1.2
Jemma	4.4	3.8	6	5.2	2.7
Muger	3.3	1.5	6.9	4.4	1.5
North Gojjam	1.1	2.1	5.2	1.8	4.4
Rahad	0.6	0.2	1.4	0.8	0.4
South Gojjam	2.6	1.7	3.5	2.8	1.6
Tana	1.3	2.7	2	2.2	3.5
Welaka	5.8	2.8	3.9	2.6	2.3
Wenbera	1.4	0.7	0.8	1.5	0.8

The mean-maximum LST and mean-maximum EVI are strongly negatively correlated with higher LST associated to low biomass due to lower latent heat transfer. This validates the hypothesis that the energy balance relationship for the land cover grouping is related to the disturbance trajectory. High mean-maximum LST values are not anomalies; instead, they are the effect of fire seasonally set to clear agricultural fields and stimulate growth. As the fire removes all biomass, the evaporative cooling potential diminishes and albedo increases due to a blackened surface (Running 2008).

13.4.2 Biomass Recovery Trend

The long-term (i.e., 10-year) average DI for the selected land cover classes was 1.47 and for the whole basin it was 1.53 with standard deviations 0.64 and 0.69, respectively. The threshold value for one standard deviation below the long-term mean is thus 0.83 (i.e., 1.47–0.64). Field visits helped to identify that the majority of the areas identified as spots of biomass recovery are plantations initiated by the previous government after the 1984 drought. Eucalyptus trees dominate plantations with a considerable mix of coniferous trees and some indigenous trees in the center and southeast of the basin. This is in agreement with the national statistics in that out of the reported 161,000 ha that the state planted up to the year 1989, Eucalyptus accounts for more than 55 % (EFAP 1994).

Table 13.1 shows the area of recovered biomass for the years 2008–2012, reclassified based on the threshold given as proportion of the subbasin area. Taking the

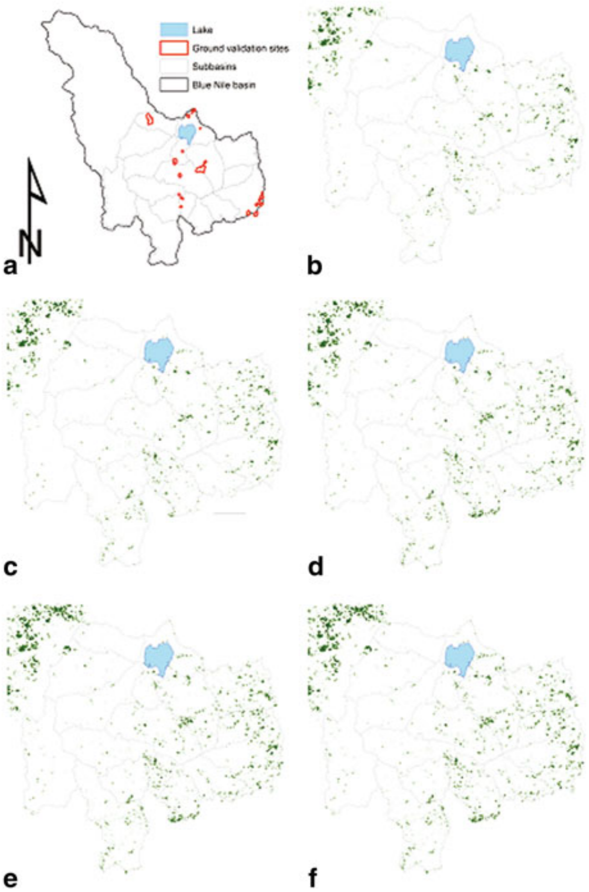

Fig. 13.5 **a** Subbasins. **b**–**e** DI maps for 2008–2012: *green* areas are recovering areas; irrigated land adjacent to the Blue Nile River (Sudan) appears as a recovering area due to the year-round high biomass availability due to adequate water supply and energy availability for photosynthesis

Lake Tana subbasin as an example, the results for 2008 and 2012 can be interpreted. In 2008, 1.3 % of the subbasin area had LST to EVI (i.e., DI) ratio, which is less than one standard deviation to the long-term DI, whereas in 2012 the area expanded to 3.5 % of the subbasin area. The results of the DI analysis showed a negative biomass recovery trend for 12 out of the 16 subbasins. North Gojjam, Dabus, Rehad, and Tana basins showed a positive biomass recovery trend.

Figure 13.5 depicts subbasins, ground validation sites, and DI maps for 2008–2012. The five subbasins with largest biomass recovery are Muger, Dabus, Weleka, Dinder, and Beles. The recovered areas represent 6–7 % of the subbasins. Fincha, Wenbera, Tana, South Gojjam, and Anger subbasins are least recovering with recovered areas of 3–4 %. The total basin level biomass recovery is 2 % as of 2012. The annual recovered area is in a declining trend in all the subbasins except Tana and North Gojjam subbasins. The positive trend in these two subbasins may be explained by the steady increase in irrigated land at the Koga irrigation (Tana subbasin) scheme which expanded to 6,000 ha towards the end of 2011 (Eguavoen and Tesfai 2012).

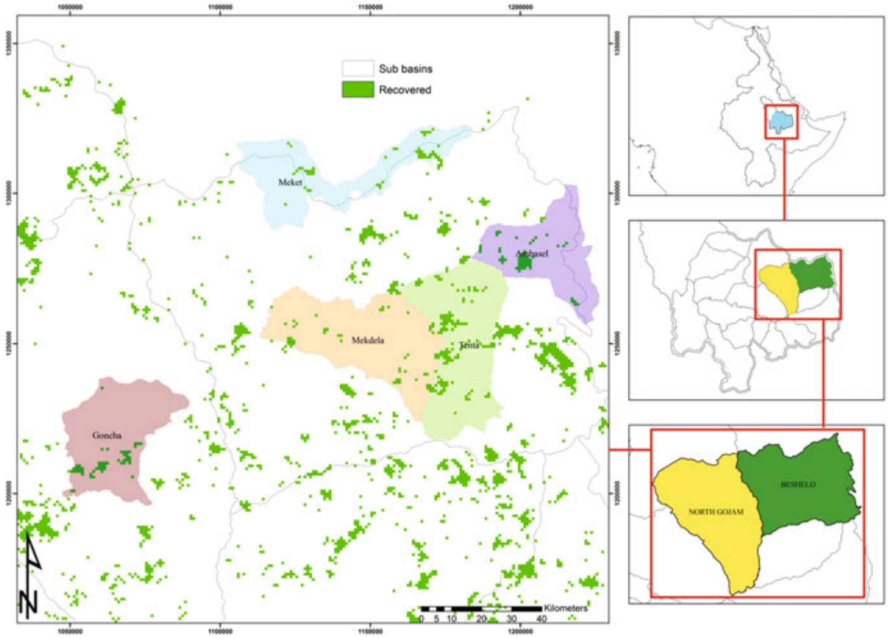

Fig. 13.6 Biomass recovery trend in five community-managed watersheds supported by the MERET project since 2003 is compared with the biomass recovery trend in their respective subbasins with similar biomass recovery trajectories observed at both scales

In the North Gojjam subbasin, a considerable expansion of commercial Eucalyptus plantations has been observed during the field visit.

13.4.3 Comparison with Ancillary Data

Plantations initiated after the 1984 famine have become the dominant features of the Ethiopian highland landscapes. With a relatively longer protection, the plantations survive deforestation except in the case of those plantations planned for fuelwood consumption. The plantation campaigns are aimed at dislodging farmers from steep slope areas and covering the land with plantation. In 80 % of the field validation sites visited, farmers responded that planning was not participatory. In all of these plantations, communities participated against their will and oftentimes land for plantation was acquired by evicting farmers plowing the steep slopes. Bewket and Sterk (2002) reported similar observations. Recent SWC works had implemented a different approach in that the activities are undertaken as community managed SWC projects. Even though the outcome of these conservation works cannot be seen on the DI analysis output as in the case of the large plantations undertaken by the previous government, comparison of reported recovered area is found to be consistently identical with overall biomass recovery trend of the subbasins in which these projects are situated as shown in Fig. 13.6.

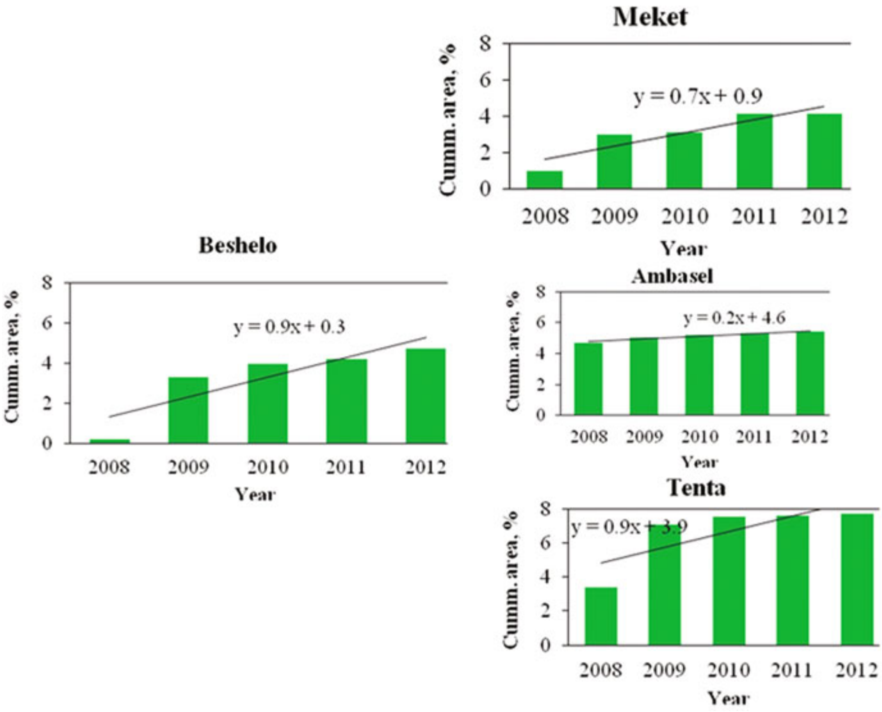

Fig. 13.7 The trend in total recovered area of Beshelo subbasins determined from the DI analysis was identical to the biomass recovery trend reported by the community-managed SWC trend in five community-managed watersheds supported by the MERET project since 2003 and are compared with the biomass recovery trend in their respective subbasins with similar biomass recovery trajectories observed at both scales

Recovered area statistics of five watersheds in two subbasins as recorded by WFP are compared with the DI maps for the subbasins where these watersheds are located. Four watersheds are in Meket, Tenta, Ambassel, and Mekdela provinces located within the Beshelo subbasin (Fig. 13.7) and one watershed is located in Goncha province in the North Gojjam subbasin (Fig. 13.8). The total recovered area in these watersheds showed a similar trend to their respective subbasins. The low level of total recovered area in 2008 in the subbasins is identical to the total recovered area in the provinces.

13.5 Conclusion

Tracking the state of biomass recovery trend is a necessary step in evaluating the effectiveness of SWC measures. The DI tool was previously tested on continental USA using 2 years of MODIS EVI and LST products (2003–2004). It was difficult to represent the range of natural variability using 2 years' data. In this research,

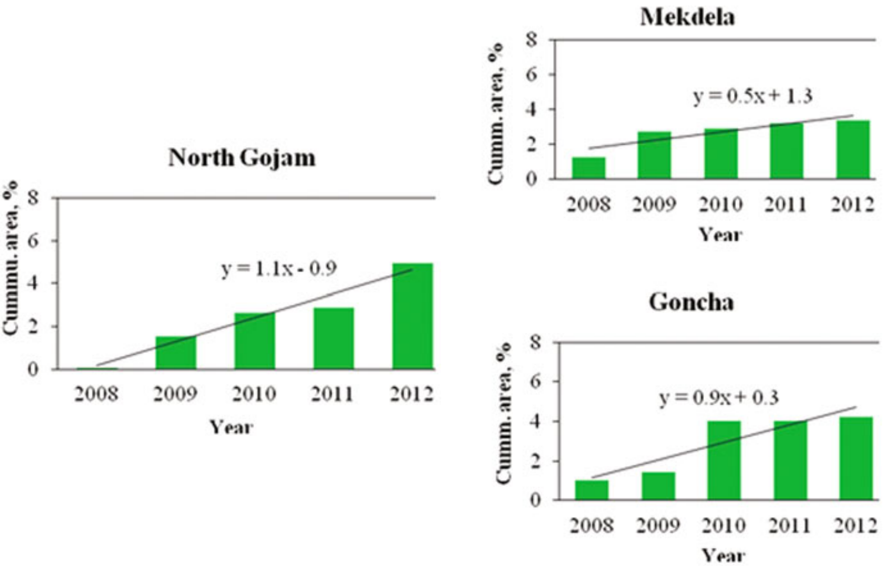

Fig. 13.8 The trend in total recovered area of North Gojjam subbasins determined from the DI analysis was identical to the biomass recovery trend reported by the community-managed SWC trend in five community-managed watersheds supported by MERET project since 2003, and are compared with the biomass recovery trend in their respective sub basin with similar biomass recovery trajectories observed at both scales

10-year (2003–2012) data were used in applying the tool to monitor the state of biomass in the Blue Nile River basin. As a result, disturbance detection of ecosystems with high interannual variability is improved and false disturbance detection is minimized. The DI maps can be also be easily updated with an additional year of data. Nonetheless, precaution should be taken in interpreting the maps. With a number of irrigation projects under implementation, it is also important to note that inflated biomass recovery figures may result. The interpretation on the index should thus be further rectified by masking out irrigation land. The major limitation of the method is its shortfall in detecting small-scale and fragmented SWC works. This shortfall is attributed to the coarser resolution EVI and LST data availability. Such SWC works are typical in community-managed watersheds and should be quantified in some way. Additional steps are required to apply the method for use in small-scale SWC using finer resolution images.

The implementation strategy of the plantations determines their sustainability. The top-down approach in the past did not bring about significant results. Plantations are often associated with subsidence of the groundwater level mainly manifested by drying up of local springs. The current community-managed SWC approach is instrumental in uprooting past oversights and instating a participatory approach. The investment returns of the new approach are yet to be seen in the future. The cost–benefit analysis of investment on SWC should incorporate the change in soil composition, water availability, production of woody biomass, and crop and horticultural productivity. In this regard, the DI can be applied as a typical tool to measure the production of woody biomass.

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Chapter 14
Bathymetry, Lake Area and Volume Mapping: A Remote-Sensing Perspective

Essayas K. Ayana, William D. Philpot, Assefa M. Melesse and Tammo S. Steenhuis

Abstract A major challenge in constructing the storage characteristics for a lake is the inaccessibility to the shores due to operational limitation of survey campaigns. Lake bottom profiles are often extrapolated beyond the actual survey lines. The potential of satellite images to construct the storage characteristics of the shore areas is explored. Moderate-resolution Imaging Spectroradiometer (MODIS)-Terra images with 250- and 500-m resolutions are used to map the area of Lake Tana, Ethiopia, where daily-observed lake level data are available. The area estimates were obtained using two simple image calculation procedures: normalized difference vegetation index (NDVI) and normalized difference water index (NDWI)-enhanced NDVI (ENDVI). The lake level for each image day is used to reconstruct the shore bathymetry. The accuracy gains over the existing storage characteristics curve are evaluated by using the new shore bathymetric map to estimate lake levels. The result suggested that the existing bathymetric model is not applicable for the near-shore area where lake bottom depths are extrapolated. A new bathymetric model using MODIS images reproduced the water level with root-mean-square error (RMSE) of 0.20 m as compared to 0.87 m using the existing bathymetric model. Despite their coarser resolution, MODIS images can be a valuable tool for lake area mapping and can be used to improve lake storage measurement accuracy.

Keywords Lake Tana · Remote sensing · Bathymetry · Lake area · NDVI

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14.1 Introduction

A major challenge in constructing the storage characteristics for a lake is the inaccessibility to the shores due to operational limitation of survey campaigns. As a result, lake bottom profiles are often extrapolated beyond the actual survey lines. The bottom profile at the shore is, however, dynamic in areas where considerable sediment load enters the lake along the shore. Thus, extrapolating storage characteristic curves beyond the actual survey location introduces significant error in lake area and level estimation. The objective of this study was to evaluate how remotely sensed images can improve bathymetric map at the lakeshore and, thereby, improve lake water volume estimation. The potential of satellite images to construct the storage characteristics of the shore areas is explored. Moderate-resolution imaging spectroradiometer (MODIS)-Terra images with 250- and 500-m resolutions are used to map the area of the Lake.

Various remotely sensed images and image synthesis have been used to map lake area. White (1978) used Landsat-1 images to map reservoir area in New Mexico. Duane Nellis et al. (1998) observed temporal and spatial variation in Tuttle creek reservoir in Kansas using Landsat TM data. Liebe et al. (2005) used Landsat ETM+ images to measure lake surface area in Ghana. Ma et al. (2007) used 10-day synthesis SPOT/VEGETATION images to monitor change in Ebinur Lake area. Liebe et al. (2009) developed a method to monitor small reservoirs using ENVISAT ASAR[1] images along with the storage characteristics of the reservoirs. Radar images offer the advantage of image availability on cloudy days. However, these images require image-processing skills and can be difficult to interpret due to partly submerged vegetation, the effect of Bragg scattering, and adjacent flat smooth shorelines (Liebe et al. 2005). Temporal and spatial resolutions also affect the dependability of the images. ENVISAT ASAR, Landsat enhanced thematic mapper (ETM)+, and advanced spaceborne thermal emission and reflection radiometer (ASTER) pass over only once every 16 days and are less suitable for flood forecasting. Moreover, the spatial resolution of these satellite products results in massive data volumes. Pax-Lenney and Woodcock (1997) have shown that coarse spatial resolution imagery is often a necessary trade-off in order to keep the data volumes reasonable and to allow sufficiently frequent temporal coverage. Hence, one needs a reliable method to extract accurate information from medium- to low-resolution image sources.

Finally, atmospheric correction applied on these images has become a major source of uncertainty. This is because different end users apply different algorithms for atmospheric correction. However, recently remotely sensed images have become available on a daily basis that are uniformly corrected for atmospheric effects. One such achievement is the MODIS-Terra version-5 validated products. The MODIS-Terra version-5 images, with its sweeping 2,330-km wide field of view (FOV), are designed to provide measurements in large-scale global dynamics including changes in Earth's cloud cover, radiation budget, and processes occurring in the oceans,

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[1] Advanced synthetic aperture radar.

on land, and in the lower atmosphere. MODIS collects data for every point of the earth's surface every 1–2 days in 36 discrete spectral bands. The spatial resolutions of MODIS bands are 250 (bands 1, 2), 500 (bands 3–7), and 1,000 m (bands 8–36) (LPDAAC 2010). The release of these products has alleviated the previous drawbacks since images of smaller data size with consistent atmospheric correction are made available daily. MODIS images provide the advantage of increased sensitivity (Hu et al. 2004). In addition, retrieval of MODIS images has been made easier with a web-based interactive tool available to preview, select, and re-project the images. The MODIS-Terra version-5 images incorporate quality rating products that include the cloud state, which are important when selecting images during the rainy season in which frequent heavy clouds overshadow the lake. We used these images to estimate the area of Lake Tana, Ethiopia, where a significant amount of lake level data is also available.

14.2 Study Area

Lake Tana (Fig. 14.1) is situated on the basaltic plateau of the northwestern highland of Ethiopia (12° N, 37° 15′ E, and 1,800 m altitude) covering an area of over 3,000 km^2. The lake drains a catchment area of 16,000 km^2. Six permanent rivers and 40 small seasonal rivers feed the lake. The shallow lake is Ethiopia's largest lake, containing half the country's freshwater resources, and is the third largest in the Nile basin (Vijverberg et al. 2009). A bathymetric survey undertaken in 2006 had shown that the lake has a maximum depth of 15 m and stretches 65 km west–east and 74 km south–north (Ayana 2007). The most pronounced advantage of Lake Tana is its storage characteristics, in that it stores flow of the rainy season (June to September) for use in the remaining dry season (Vijverberg et al. 2009). The lake storage amounts to more than two times that of the five large reservoirs in Ethiopia[2], rendering a relatively low cost per unit of utilizable water (Gebeyehu 2004).

14.3 Materials and Methods

14.3.1 Lake Bathymetry and Area

A bathymetric model relates the water level to the water surface area at that water level. Ayana (2007) developed the bathymetric model for Lake Tana in 2006. The model was derived from the interpolation of 4,424 depth measurements using the kriging interpolation method (Burrough et al. 1998). The interpolation fits to test

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[2] Gilgel Gibe, Koka, Finchaa, Amerti, and Melka Wakena provide an aggregate storage capacity of about 4.4 billion m^3.

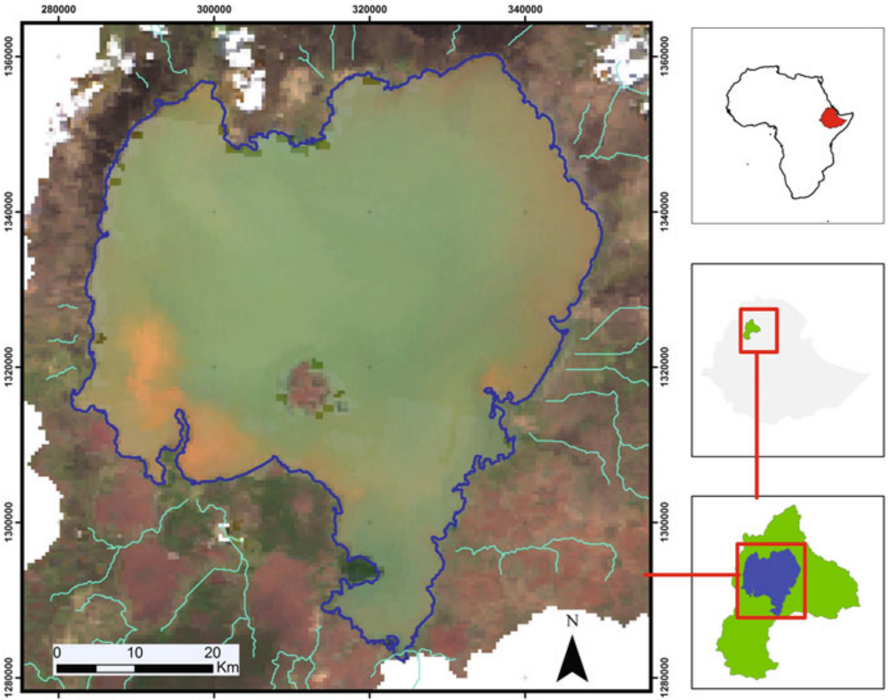

Fig. 14.1 MODIS 250-m true color image of Lake Tana and its catchment (13 June 2000). At the start of the rainy season, large turbid plume is flowing into the lake turning the shore and stream entry locations to *reddish brown*, raising the water reflectance

points with R^2 of 0.98 and resulted in the following relationship:

$$H = 6 \times 10^{-6} A^3 - 8 \times 10^{-7} A^2 + 1.1 \times 10^{-3} A + 1774.1, \qquad (14.1)$$

where H is the water surface elevation in meters at the given lake surface area A (in square meters) (Ayana 2007).

Depth measurements were restricted to 1 km from the lakeshore due to depth limits for instrument operation and boat access, necessitating extrapolation of the lake bottom surface for locations beyond the survey line. As a result, the error variance around the lakeshore was estimated to be as high as 2.50 m (Ayana 2007). Lake levels for the 2000–2006 time span were obtained from the Ministry of Water Resources (MoWR), Ethiopia.

14.3.2 Image Data

Two distinct sets of MODIS-Terra version-5 images of 250- and 500-m resolutions were downloaded. The images incorporate quality rating products, including the cloud state, which is important when selecting images during the rainy season when frequent heavy clouds overshadow the lake (LPDAAC 2010). To obtain a wide spread in measured areas, we used a measured lake level data plot when selecting MODIS images. The first set of 18 images downloaded coincided with high and low lake levels during the 2000–2006 time spans. In order to improve the near-lakeshore bathymetry, we selected a second set of 47 images between 2002 and 2003 at which time the lake level is at its lowest. In this set, two to five images were selected for each month maintaining a 5–9-day interval except during months in the rainy phase of the monsoon when MODIS images were not usable due to cloud cover over the lake. For each image bands, 1, 2, and 6 were used; band 1 is the *red* band spanning 620–670 nm, band 2 is a near-infrared (*NIR)* band spanning 841–876 nm, and band 6 is a short-wave infrared (SWIR) band spanning 1,628–1,652 nm.

14.3.3 Data Analysis

Two simple metrics (or indices) and a supervised classification are used to determine lake surface area at several lake level stages. The potential of the improved MODIS image data sets to map lake area is assessed using thresholds of *normalized difference vegetation index* (NDVI) and *normalized difference water index (NDWI)-enhanced NDVI* here in after referred to as *enhanced NDVI* (ENDVI).

Metric 1: NDVI It is a measure of the degree of greenness in the vegetation cover of a land surface and can, therefore, effectively discriminate between clear water and land surface including papyrus (*Cyperus papyrus*) (Adam and Mutanga 2009). The NDVI is derived from reflectance measurements in the red (band 1) and NIR bands (band 2) centered at 645 and 858 nm, respectively. The NDVI is calculated as[3]

$$NDVI = \frac{\rho_{NIR} - \rho_{\mathrm{Re}\,d}}{\rho_{NIR} + \rho_{\mathrm{Re}\,d}} = \frac{\rho_{band2} - \rho_{band1}}{\rho_{band2} + \rho_{band1}}, \tag{14.2}$$

where ρ_{NIR} and ρ_{Red} are the reflectance in the NIR and red bands, respectively.

NDVI values range from − 1 to 1, with values near zero corresponding to unvegetated land and values approaching 1 corresponding to dense vegetation. Because water absorbs strongly in the IR, the NDVI for water is generally negative. In this study, a pixel is designated "water" if the NDVI is less than zero (Tucker 1979).

The advantage of the NDVI is that it only requires two bands and is, therefore, simple to use. In the literature (Rees 2001), it has been noted, however, that the reliability of the NDVI in estimating the lake surface is affected by sediment in the water. Sediment increases the reflectance in both the red and the IR and can complicate the discrimination (Ma et al. 2007). This could be even more of a problem with submerged vegetation which would elevate the reflectance in the IR. Lake Tana has sediment in the water at the start of the rainy season when the lake level is at its

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[3] ρ_{band} refers to reflectance of a given band, for example, ρ_{Red} refers to reflectance from red band.

lowest, and the loose soil at the shores is washed into the lake water near the shore. Resuspension of the sediment at the shore will also be increased by the inflowing sediment-rich floodwaters from the rivers.

Metric 2: ENDVI In order to overcome the shortcoming of NDVI for sediment-rich water, an enhancement procedure is introduced that uses bands 2 and 6 (as expressed in the NDWI) to distinguish between land and turbid water when the NDVI is positive. The NDWI is a satellite-derived index from the NIR (band 2, 858 nm) and SWIR (band 6, 1,240 nm) (Gao 1996) channels. The NDWI is calculated as

$$NDVI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}} = \frac{\rho_{band2} - \rho_{band6}}{\rho_{band2} + \rho_{band6}}, \tag{14.3}$$

where ρ_{NIR} and ρ_{SWIR} are the reflectance in the NIR and SWIR bands, respectively.

According to the *ENDVI* metric, a pixel is assigned to "water" if the NDVI is less than zero and the NDWI is greater than zero. Thus,

$$EDVI = \ if\,(NDVI < 0, \text{“}water\text{”}\ else\ if\, NDWI > 0, \text{“}water\text{”}\ else\ \text{“}land\text{”}). \tag{14.4}$$

The work flow diagram (Fig. 14.2) summarizes the processes applied in the method.

Supervised classification consists of two processes, training and classification. Supervised classification uses information about the known distribution of classes to initiate the process (Rees 2001). In this work, two classes are defined "Water" and "Land" based on the characteristics of user-supplied samples of water and land in each image. In this study, the maximum likelihood classification algorithm within ENVI, an image-processing tool, is used in the classification process. The maximum likelihood classification assumes that spectral values of training pixels are normally distributed according to a multivariate normal (Gaussian) probability density function. Each pixel is assigned to the class to which it is most likely to belong based on the probability distribution of the training data. Two-dimensional scatter plots of the red (band 1) and NIR bands (band 2) are used in ENVI to identify the training pixels for the supervised classification.

14.3.4 Comparison of Satellite-Based Methods

The NDVI, ENDVI, and supervised classification had resulted in six maps for each selected image in 250- and 500-m resolutions. The areas derived using these images were compared to the areas obtained from the bathymetric model (Eq. 14.1) using the lake level data for the image date. The residual variance (RMSE) and coefficient of determination (R^2) between the area from the bathymetric model and from the metrics (NDVI and ENDVI) were used to evaluate the accuracy of the methods.

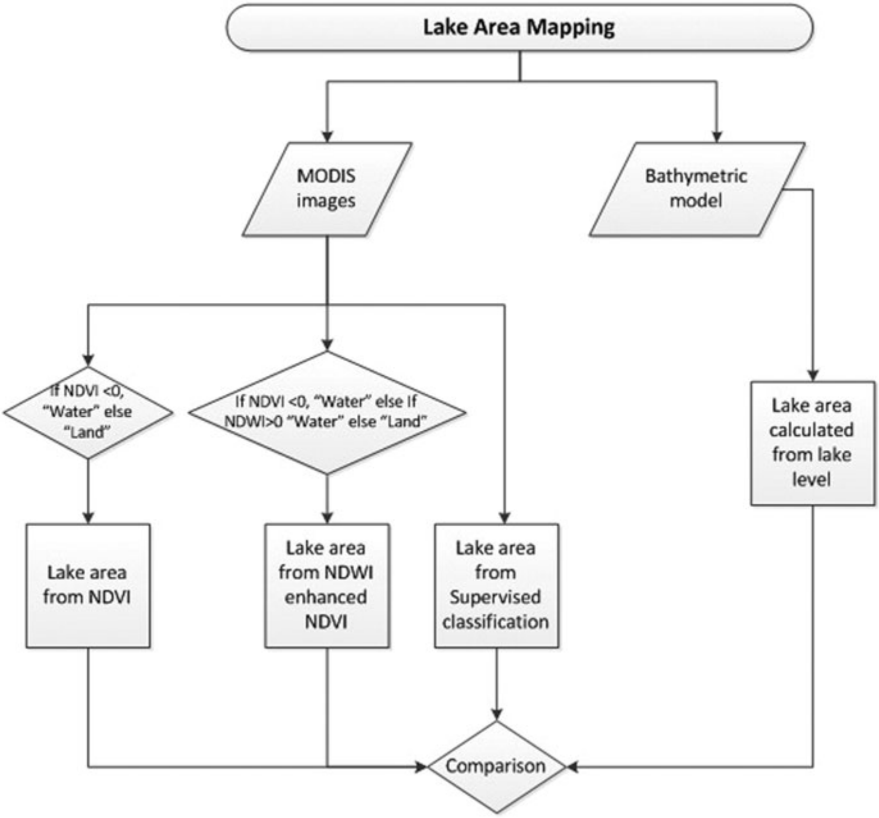

Fig. 14.2 Work flow for area estimation

14.4 Results and Discussion

Lake surface areas extracted from MODIS images and the corresponding lake areas obtained from the bathymetric model (Eq. 14.1) are shown in Table 14.1. The lake level (column 2) is the measured gauge level at the selected date for which the images are analyzed. In the next columns (columns 4–9), the areas mapped using *NDVI* (Eq. 14.2), *ENDVI* (Eq. 14.3), and *supervised classification* are shown for both the 250- and 500-m resolution images.

Areas mapped from *NDVI* and *ENDVI* are compared with surface areas determined from the bathymetric model of the lake. The image-based reservoir area using *ENDVI* correlates slightly better with the bathymetry-based reservoir area ($R^2 = 0.83$) (Fig. 14.3a) than with the NDVI ($R^2 = 0.81$) (Fig. 14.3b).

Supervised classification did not perform well (Fig. 14.4). Using all the 18 images, the supervised classification resulted in an R^2 value of 0.23 for the 250-m resolution and 0.27 for the 500-m resolution. The poor correlation was due primarily to

Table 14.1 Comparison of image-mapped lake surface area and the area determined from the storage characteristic curve

Image date	Lake water level at image date, m	Area, bathymetric model km^2 (Eq. 14.1)	Area from MODIS image					
			NDVI		NDWI-enhanced NDVI		Supervised classification	
			250 m	500 m	250 m	500 m	250 m	500 m
10 Sep 2000	1,787.52	3,087	3,024	3,005	3,025	3,004	3,054	3,014
16 Sep 2000	1,787.58	3,091	3,032	3,015	3,037	3,016	3,025	2,971
17 Sep 2001	1,787.46	3,082	3,034	3,026	3,027	3,024	3,053	3,026
20 Sep 2001	1,787.46	3,082	3,013	2,985	3,005	2,983	3,073	2,980
21 Sep 2001	1,787.50	3,085	3,010	2,992	3,010	2,986	3,098	3,017
22 Sep 2001	1,787.47	3,083	3,032	3,012	3,032	3,010	3,069	3,032
22 Sep 2002	1,786.41	3,001	3,010	2,981	3,010	2,978	3,004	2,943
24 Sep 2002	1,786.42	3,002	2,962	2,935	2,962	2,931	3,003	2,880
10 Jun 2003	1,784.32	2,822	2,944	2,943	2,946	2,940	2,849	2,797
12 Jun 2003	1,784.40	2,830	2,942	2,943	2,944	2,940	2,862	2,817
26 Sep 2003	1,786.62	3,017	2,983	2,947	2,982	2,980	3,027	2,759
28 Sep 2003	1,786.64	3,019	3,003	2,984	3,003	2,980	3,010	2,993
9 Jun 2004	1,784.89	2,873	2,960	2,958	2,962	2,956	2,945	2,971
4 Oct 2005	1,786.50	3,011	3,003	2,986	3,003	2,980	3,012	2,926
7 Oct 2005	1,786.54	3,012	3,011	2,989	3,011	2,986	2,536	3,041
10 Oct 2005	1,786.53	3,010	2,988	2,971	2,990	2,966	2,146	2,517
15 Jun 2006	1,784.88	2,873	2,916	2,901	2,921	2,897	1,921	2,222
16 Jun 2006	1,784.87	2,872	2,945	2,933	2,950	2,928	2,291	2,725

contaminated pixels (Fig. 14.4). The supervised classification outperforms the metrics when applied to *clean images* (e.g., 10 September 2000; 17 September 2001; 22 September 2002; 10 June 2002; 12 June 2003; 28 September 2003; and 4 October 2004) with an R^{2}of 0.92 and 0.87 for 250- and 500-m resolutions, respectively.

The metrics also performed differently at higher ($\geq$ 1,786.5 m) and lower ($<$ 1,786.5 m) water levels and also at different image resolutions (Table 14.2). At higher lake levels, both metrics resulted in comparable results, while at lower water levels, both methods are found to be less sensitive to image resolution. The overall accuracy of the metrics is only marginally improved after enhancement using the ENDVI, although the enhancement of the NDVI maps using NDWI renders them less sensitive to change in image resolution. Generally, the ENDVI metric is less sensitive to image resolution in that with increased resolution (from 500 to 250 m) the resulting improvement in RMSE is only 13 % while for the NDVI metric 49 % is obtained (Table 14.2). It is important to note here that the improvement in accuracy resulted in a fourfold increase in data volume and, hence, one should make a compromise between acceptable level of accuracy and costs associated with data storage issues.

Despite the good agreement as measured by R^2 between the bathymetric model and the satellite-derived products, estimates of lake area differed significantly (Table 14.1). *NDVI* and *ENDVI* area estimates for lake levels below an elevation

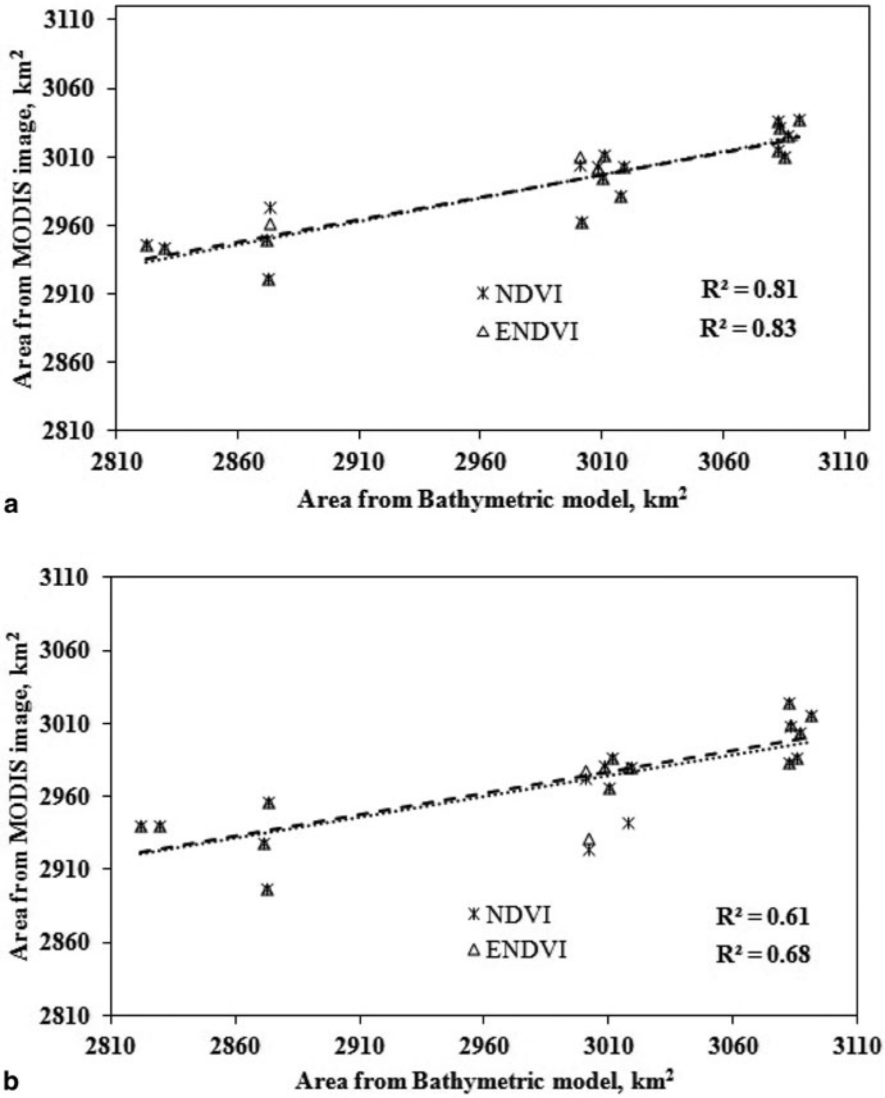

Fig. 14.3 Correlation between bathymetric model and image-mapped lake surface area: **a** 250-m images and **b** 500-m images

of 1,786 m[4] were less than levels from the bathymetric model estimated area with Eq. 14.1. Area estimates from MODIS are consistently larger than estimates using Eq. 14.1 for lake water levels above 1,786 m. Thus, the precision of the measurements between the NDVI and ENDVI methods with the bathymetric survey-derived

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[4] All elevations in meters above mean sea level.

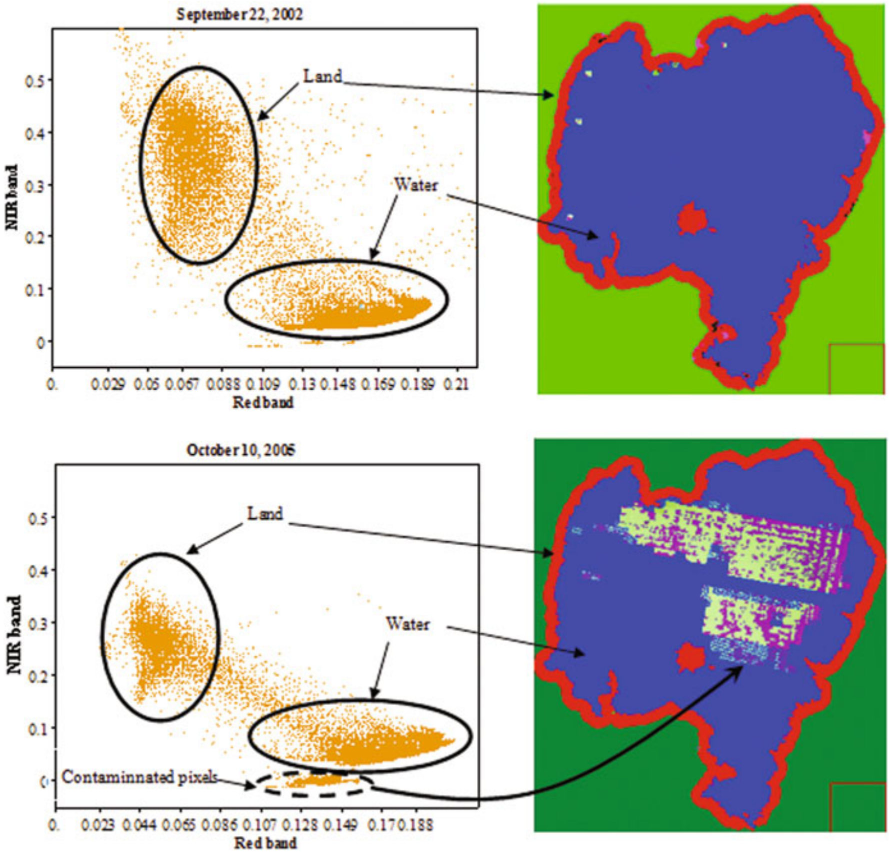

Fig. 14.4 A scatter plot of the near-infrared (NIR) versus red bands; ordinary image classification methods (e.g., supervised classification used here) often fail to overcome shortcomings in image quality due to contamination. In the September 22, 2002 image, the classification is more accurate due to the clean image, whereas in the October 10, 2005 image, defective pixels are classified as two classes (seen in *cyan and turquoise colors*)

Table 14.2 Correlation between lake area derived from MODIS images and the storage characteristics curve

Method	NDVI		ENDVI		Supervised classification	
Image resolution, m	250	500	250	500	250	500
RMSE, km^2						
High lake level	47	66	48	66	286	177
Low lake level	84	80	86	79	457	277
Overall accuracy						
RMSE, km^2	67	130	66	76	352	215
R^2	0.81	0.61	0.83	0.64	0.23	0.27

data was good, but the accuracy was poor. In this section, we will examine why the area estimates do not agree. To do this, we selected 47 images in the period from January 2002 to December 2003 when the lake level decreased by over 2.50 m. The 2002 images were used to derive the bathymetric model and the 2003 images were used to validate the accuracy of the model by calculating back the lake level. A new bathymetric model is generated using the ENDVI metric-mapped lake surface area and the measured lake level of the image date.

The modified equation for the shore area is given by

$$H = 0.0205A + 1724.3. \tag{14.5}$$

The new bathymetric model suggested a linear surface around the lakeshore in contrast to the cubic polynomial fitted by the initial model (Fig. 14.5). The accuracy of the new bathymetric model is validated by estimating the lake water level (Table 14.3) using lake area from 2003 images. The RMSE for such water level estimate using the new MODIS-derived bathymetric model is reduced to 0.20 from 0.87 using the initial bathymetric model. The area estimate by the bathymetric survey is much smoother as one would expect when the points are extrapolated from smooth lake bottom. The measurements of the bathymetric survey (that were taken approximately 1 km off the shoreline) do not overlap with the satellite-derived images.

In Fig. 14.5b, the area estimated from MODIS images and by the bathymetric survey is plotted as a function of the lake level. The new bathymetry (Fig. 14.5) suggested a steep bank just offshore from approximately 1,784.5–1,786.5 m elevation and then a shelf that has a slight slope. During the wet season, as the velocity of the incoming water breaks abruptly at entry to the lake, the sand settles at the shore. The remaining silt load remains in suspension and spreads slowly into the lake. With the longer water residence time (Kebede et al. 2006) part of the silt load then settles over a larger area forming a relatively flatter bottom.

14.5 Conclusion

The use of MODIS-Terra version-5 images as a tool for lake area mapping offers the advantages of higher temporal resolution and reduced data size. The higher temporal resolution enables an analysis of short term, yet significant changes in lake area and monitoring of coastal areas. Further investigations must be carried out to assess to what lake size the MODIS images are capable for mapping area. At the beginning of the rainy season where the lake level is at its lowest, the effect of exposed lakeshore vegetation compounds with the sediment plume and degrades the accuracy of the methods. Combined with the easy retrieval tools available and the simple mapping techniques that we tried to demonstrate in this research, the potential of MODIS-Terra version-5 images to monitor lake area is high. There is a high correlation between lake areas predicted by MODIS and those from the bathymetric survey indicating that the MODIS area estimates are consistent in time. The bathymetric survey of Ayana (2007) did not measure the depth of the lake within 1 km from the shore because of

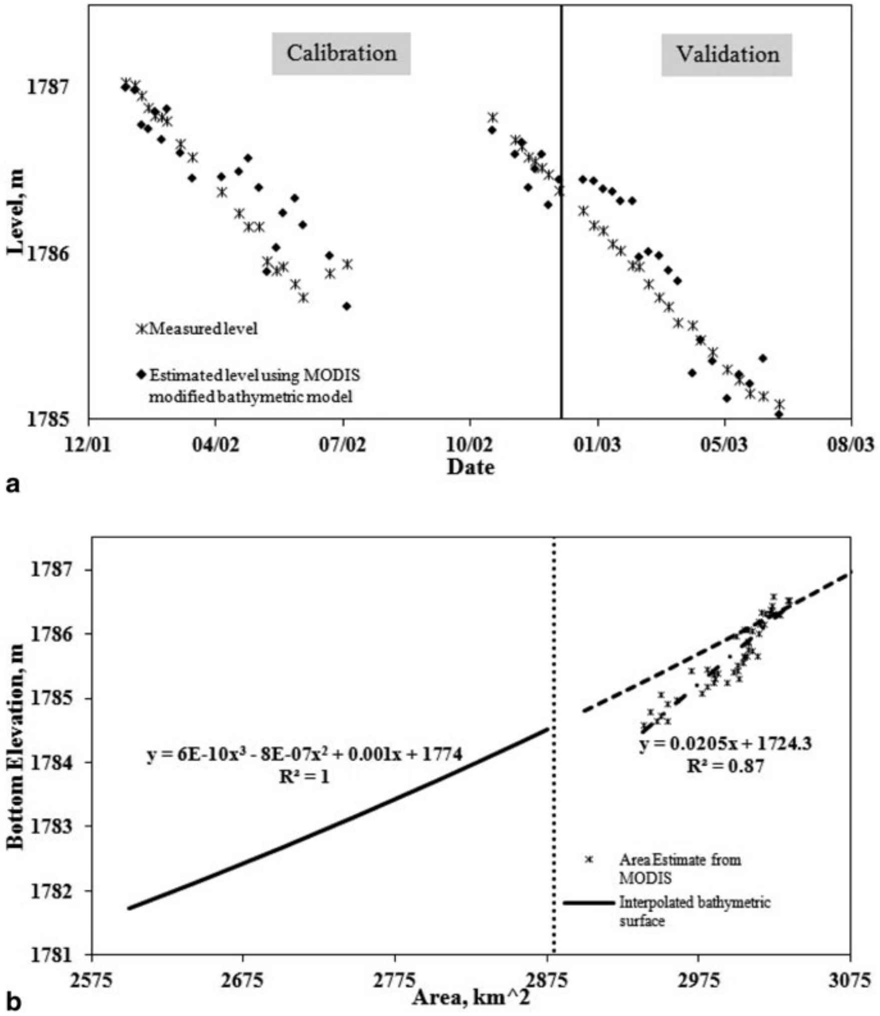

Fig. 14.5 **a** Comparison of measured and estimated lake levels using January 2002 to December 2003 MODIS images. **b** Near-shore bathymetry generated from MODIS images was capable of capturing water level of the lake more accurately than existing bathymetric model

inaccessibility of the shore, and, therefore, the satellite-derived water level lake area relation is likely more accurate than the bathymetric survey.

A major drawback of MODIS images is cloud contamination. However, the metrics (i.e., NDVI and ENDVI) used are found to be foolproof for images slightly contaminated by cloud as compared to the commonly applied classification algorithms (e.g., supervised classification). Monitoring is more critical during the rainy season as the lake area varies abruptly due to high inflow from streams draining to the lake. But this may be difficult due to high cloud cover over the lake. Therefore,

Table 14.3 Calibration (2002) and validation (2003) of MODIS-derived near-shore bathymetric model

Date	Measured level	Estimated level using existing bathymetric model	Area estimate from MODIS	Estimated level using MODIS-modified bathymetric model	Error[a]	
					Δ_1	Δ_2
(1)	(2)	(3)	(4)	(5)	(6)	(7)
23 Jan 2002	1,786.53	1,786.83	3,034.20	1,786.50	− 0.30	0.03
30 Jan 2002	1,786.52	1,786.82	3,033.29	1,786.48	− 0.30	0.04
4 Feb 2002	1,786.45	1,786.69	3,023.20	1,786.28	− 0.24	0.17
10 Feb 2002	1,786.38	1,786.68	3,022.07	1,786.25	− 0.30	0.13
15 Feb 2002	1,786.33	1,786.74	3,027.06	1,786.35	− 0.41	− 0.02
20 Feb 2002	1,786.32	1,786.64	3,018.69	1,786.18	− 0.32	0.14
24 Feb 2002	1,786.3	1,786.75	3,027.87	1,786.37	− 0.45	− 0.07
7 Mar 2002	1,786.16	1,786.59	3,014.93	1,786.11	− 0.43	0.05
16 Mar 2002	1,786.08	1,786.50	3,007.64	1,785.96	− 0.42	0.12
8 Apr 2002	1,785.87	1,786.50	3,007.69	1,785.96	− 0.63	− 0.09
22 Apr 2002	1,785.74	1,786.52	3,009.62	1,786.00	− 0.78	− 0.26
29 Apr 2002	1,785.66	1,786.57	3,013.22	1,786.07	− 0.91	− 0.41
8 May 2002	1,785.66	1,786.46	3,004.74	1,785.90	− 0.80	− 0.24
14 May 2002	1,785.45	1,786.15	2,980.11	1,785.39	− 0.70	0.06
21 May 2002	1,785.4	1,786.24	2,987.08	1,785.54	− 0.84	− 0.14
11 Jun 2002	1,785.24	1,786.32	2,993.79	1,785.67	− 1.08	− 0.43
5 Jun 2002	1,785.32	1,786.42	3,001.52	1,785.83	− 1.10	− 0.51
26 May 2002	1,785.42	1,786.37	2,997.39	1,785.75	− 0.95	− 0.33
2 Jul 2002	1,785.38	1,786.21	2,984.61	1,785.48	− 0.83	− 0.10
16 Jul 2002	1,785.44	1,786.03	2,969.86	1,785.18	− 0.59	0.26
7 Nov 2002	1,786.32	1,786.67	3,021.54	1,786.24	− 0.35	0.08
30 Nov 2002	1,786.15	1,786.63	3,017.99	1,786.17	− 0.48	− 0.02
25 Nov 2002	1,786.19	1,786.58	3,014.45	1,786.10	− 0.39	0.09
5 Dec 2002	1,786.08	1,786.46	3,004.68	1,785.90	− 0.38	0.18
11 Dec 2002	1,786.06	1,786.53	3,010.10	1,786.01	− 0.47	0.05
16 Dec 2002	1,786.02	1,786.58	3,014.61	1,786.10	− 0.56	− 0.08
21 Dec 2002	1,785.98	1,786.39	2,999.59	1,785.79	− 0.41	0.19
30 Dec 2002	1,785.88	1,786.49	3,007.21	1,785.95	− 0.61	− 0.07

Table 14.3 (continued)

Date	Measured level	Estimated level using existing bathymetric model	Area estimate from MODIS	Estimated level using MODIS-modified bathymetric model	Error[a]	
					Δ_1	Δ_2
17 Jan 2003	1,785.76	1,786.49	3,007.15	1,785.95	– 0.73	– 0.19
26 Jan 2003	1,785.67	1,786.49	3,006.83	1,785.94	– 0.82	– 0.27
2 Feb 2003	1,785.64	1,786.46	3,004.42	1,785.89	– 0.82	– 0.25
9 Feb 2003	1,785.56	1,786.44	3,003.56	1,785.87	– 0.88	– 0.31
3 Mar 2003	1,785.42	1,786.21	2,984.45	1,785.48	– 0.79	– 0.06
25 Feb 2003	1,785.43	1,786.41	3,000.66	1,785.81	– 0.98	– 0.38
16 Feb 2003	1,785.52	1,786.41	3,000.61	1,785.81	– 0.89	– 0.29
26-Mar 2003	1,785.18	1,786.15	2,980.21	1,785.39	– 0.97	– 0.21
18-Mar 2003	1,785.24	1,786.21	2,984.78	1,785.49	– 0.97	– 0.25
10 Mar 2003	1,785.32	1,786.22	2,985.79	1,785.51	– 0.90	– 0.19
2 Apr 2003	1,785.08	1,786.12	2,977.05	1,785.33	– 1.04	– 0.25
13 Apr 2003	1,785.07	1,785.79	2,949.95	1,784.77	– 0.72	0.30
20 Apr 2003	1,784.98	1,785.91	2,959.93	1,784.98	– 0.93	0.00
20 May 2003	1,784.74	1,785.79	2,949.89	1,784.77	– 1.05	– 0.03
11 May 2003	1,784.8	1,785.70	2,942.81	1,784.63	– 0.90	0.17
29 Apr 2003	1,784.91	1,785.83	2,953.81	1,784.85	– 0.92	0.06
29 May 2003	1,784.66	1,785.75	2,947.10	1,784.72	– 1.09	– 0.06
8 Jun 2003	1,784.64	1,785.84	2,954.56	1,784.87	– 1.20	– 0.23
21 Jun 2003	1,784.59	1,785.64	2,938.03	1,784.53	– 1.05	0.06

[a] $\Delta_1$and Δ_2 refer to lake level estimate error using the existing and modified bathymetric model, respectively

radar images will be an ideal substitute during such gaps. Methods developed using ENVISAT ASAR images have resulted in a coefficient of correlation as high as 0.95 (Liebe et al. 2009). However, MODIS images have proved to be increasingly important resources in resource mapping because these data are robust, inexpensive, simple to use, and provide frequent synoptic coverage.

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Chapter 15
Land Use and Land Cover Changes in Northern Kordofan State of Sudan: A Remotely Sensed Data Analysis

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Abstract The North Kordofan region is semiarid and characterized by recurrent episodes of drought which led to increasing desertification. The agricultural and forest production in North Kordofan State (NKS), however, is adversely hampered by climate change, particularly the unreliable and fluctuated rainfall and desertification. Hence, it is expected that the land use/land cover (LULC) classes in the state would have dramatically changed during past decades. This study tries to detect the changes in LULC in NKS during the period between 1973 and 2001. We assess the desertification process using vegetation cover as an indicator. We used remotely sensed data from Landsat multispectral scanner (MSS; captured in 1973) and enhanced thematic mapper plus (ETM+; captured in 2001) to detect LULC conversion dynamics. Pre- and postclassification change detection methods were compared. A supervised image classification (maximum likelihood) is then performed to identify LULC classes. Ten major land cover classes are discriminated. These are forests, farms on sand, farms on clay, fallows on sand, fallows on clay, woodlands, mixed woodlands, grasslands, burnt/wetlands, and natural water bodies. The results revealed that using a preclassification image differencing procedure, positive (9.66 and 6.70 % of total area when near-infrared (NIR) and normalized difference vegetation index (NDVI) were used, respectively), negative (9.77 and 6.62 % of total area when NIR and NDVI were

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used, respectively), and no (80.57 and 86.68 % of total area when NIR and NDVI were used, respectively) vegetation changes were observed in the study area during the period 1973–2001. The study also indicates a negative change trend when principal component analysis (PCA) and change vector analysis (CVA) methods are employed. With respect to the postclassification method, the results show significant conversions in LULC classes, where new classes such as farms and fallows on clay soils were introduced in 2001, while woodlands in 1973 were completely shifted to farm on sand, farm on clay, fallow on sand, fallow on clay, grassland, and mixed woodland in 2001. The study demonstrates different signs of desertification in the study area related to change patterns in LULC classes, such as increase in farms on sand and clay soils at the expense of wood and grasslands. It is concluded that the vegetation cover in North Kordofan was negatively changed due to socioeconomic factors and desertification in the area was the main sign of such negative LULC changes.

Keywords LULC changes · North Kordofan · Sudan · Remote sensing · Landsat · NDVI · Classification

15.1 Introduction

Arid and semiarid lands are dry ecosystems that are characterized by irregular and low rainfall. Over a quarter of the Earth's land surface is either arid or semiarid (Adam et al. 1978). These arid and semiarid ecosystems are very fragile and subjected to drought cycles that consistently diminish their vegetation cover. This makes the economic contributions of such ecosystems unsustainable. Due to a number of natural, anthropogenic, and socioeconomic factors land use/land cover (LULC) patterns are being changed over a long period of time, i.e., decades (Coppin et al. 2004). Therefore, monitoring of LULC changes has become the main focus of the environmental and ecosystem management research projects. An in-depth understanding of the causes of LULC changes requires accurate and timely type of data sets. Remote sensing offers relatively inexpensive, repetitive, near-real-time, and synoptic data over large area (Lillesand and Kiefer 2001; Aronoff 2005) that can be useful for multidate digital change detection of arid and semiarid ecosystems.

The utilization of remotely sensed data of different spatial and spectral characteristics for change detection is well documented in the literature. The selection of multidate satellite imagery in terms of spatial and spectral resolutions, that is suitable for detecting an ecosystem change, is crucial in achieving accurate results. The multidate images need to be geometrically registered and atmospherically corrected in order to account for any spatial distortion and to normalize (standardize) the spectral data (Duggin and Robinove 1990; Dai and Khorram 1998).

Before the development of robust change detection procedures, visual image interpretation method was employed to detect land cover changes. However, such kind of method is not repeatable as the results can extremely vary according to the perception of interpreters. Generally, digital change detection methods are categorized into preclassification and postclassification algorithms (Lunetta 1999). For the preclassification approaches, the images are compared by different means such as image differencing before they can be classified into different clusters, while the postclassification algorithms follow one of the protocols of various image classification methods. The reliability of the results of change detection largely relies on the robustness of the classifier applied. A challenging task yet for detection of an ecosystem change is to understand the change detection process (Collins and Woodcock 1996).

Sudan, which is one of the Nile basin countries, extends over a variety of eco-climatic zones, ranging from desert in the north with nil annual rainfall to the wet monsoon zone in the south with approximately 1,000 mm annual rainfall (Chavunduka and Bromley 2011). The country faced numerous drought and famine periods during the 1960s and 1980s. Semiarid regions of the Sudan are, thus, heavily affected by desertification, which is driven by climatic changes as well as human activities (FAO 2009). Spatial information on Sudan's LULC dynamics is poor and, thus, insufficient (Hielkema et al. 1986; Larsson 2002). Recent studies have employed remotely sensed data to study the relation between ecosystem changes and land degradation (Glover and Elsiddig 2012) on one hand and between land degradation and conflicts in Sudan (Brown 2010; Sulik and Edwards 2010) on the other hand.

North Kordofan State (NKS) of Sudan possesses more than 25 million heads of livestock and 8.5 million acres of arable land (Behnke 2012; El hag et al. 2012; Fazari 2012). It contributes about 30 % of Sudan's non-oil exports including livestock, gum arabic, hibiscus, groundnuts, and watermelon seeds (Fazari 2012). The NKS is located at the northern edge of the savannah belt. The region is semiarid and characterized by recurrent episodes of drought, which led to increasing desertification. The agricultural and forest production in NKS, however, is adversely hampered by climate change, particularly the unreliable and fluctuated rainfall and desertification. Hence, it is expected that LULC classes in the state would have dramatically changed during past decades. This study aims to detect the changes in LULC in NKS during the period between 1973 and 2001.

15.2 Methodology

15.2.1 Study Area

The study area is NKS of Sudan. NKS extends from latitude 12°40′N to 14°20′N and longitude 28°10′E to 31°40′ and its capital is Elobeid (Fig. 15.1). The state is located in the central-western part of Sudan at the northern edge of the savannah belt. NKS possesses more than 25 million heads of livestock and 8.5 million acres of arable land. It contributes about 30 % of Sudan's non-oil exports including livestock, gum arabic, hibiscus, groundnuts, and watermelon seeds.

Fig. 15.1 A map of Sudan and the study area

The climate in NKS ranges from arid in north to semiarid in south with an annual rainfall of 196 and 326 mm in 2011 for arid and semiarid regions, respectively, and a long-term average of 239 and 324 mm for the two regions, respectively (Robinson 2012). The rainfall is fluctuated and it occurs during summer (June to September) with the peak being in August. The mean annual temperature is about 20 °C; however, during the summer the temperature rises to about 45 °C during the daytime.

The soil in the northern part of NKS consists mainly of sand sheets and sand dunes, which are stabilized by vegetation. These are locally named *Qoz*. Towards the south of the state, the soils are alluvial in origin with a silty clay texture and locally named *Gardud*. With regard to the vegetation cover, NKS is a sparsely vegetated region as a result of the low amount of rainfall. The vegetation is exposed to extreme conditions, mainly drought, which can stretch over several years with little or no rain at all during some years (e.g., 1985). In the northern part of the area, the Merikh (*Leptadenia pyrotechnica*) is very common as shown in Fig. 15.2a.

The understory consists mostly of Tomam grass (*Panicum turgidum*). The valleys in this area support trees such as Kitir (*Acacia millifera*; Fig. 15.2b), Seyal (*Acacia tortilis* var spirocarpa), and Higlig (*Balanites aegyptica*). To the south, the vegetation cover becomes taller and denser. Common trees and shrubs are Tabeldi (*Adansonia digitata*), Hashab (*Acacia senegal*), Kitir (*Acacia millifera*), Ushr (*Calotropis procera*), and Dahasir (*Indigofera pancifolia*). Trees and shrubs alternate with areas of open grassland. These open grasslands support rearing a large number of animals such as sheep, camels, cattle, and goats. If adequate rainfall is available, the climate

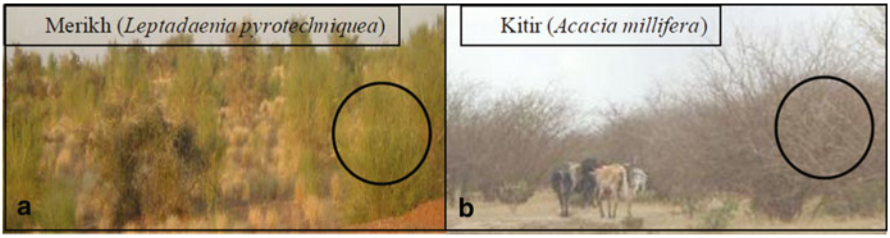

Fig. 15.2 Vegetation (*circles*) in the northern (**a**) and the southern part (**b**) of NKS

of NKS supports the production of some summer crops such as sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), watermelon (*Citrulus lanatus*), sesame (*Sesamum indicum*), and groundnut (*Arachis hypogaea*) as well.

15.2.2 Image Acquisition and Preprocessing

Two cloud-free Landsat images (path 187/51) were captured from the study area. One image is Landsat multispectral scanner (MSS) data captured on January 1, 1973, and the other one is Landsat enhanced thematic mapper plus (ETM+) data acquired on January 16, 2001. The Landsat MSS image was used as a reference data set, while Landsat ETM+ was considered as a newer image for detecting the changes in LULC forms in the study area for the covered period of time.

The Landsat MSS image had a line dropout problem with bands 4 and 6. Consequently, a low-pass median filter (3 × 3 pixels) method was performed to rectify the image. The two images were then geometrically rectified using well-distributed ground control points (GCPs) collected from the study area with the aid of a Geko 101 global positioning receiver. To account for any variation on the image spectral data due to time of acquisition, seasonality, etc. (Lillesand and Kiefer 2001), atmospheric correction was employed to normalize the spectral data of the two images. This was carried out using a Chavez's Cost model (Chavez 1996) which is a modified image-based dark object subtraction method.

15.2.3 Ground Truth Data Collection

Two field visits were conducted on June and December 2004 to collect GCPs for the major LULC classes, dominant trees and weeds on the study area. Since we sampled for the dominant classes, we did not expect any major changes on the landscape features of the study area within 2 years (i.e., since the Landsat ETM+ images were captured), and 110 and 160 GCPs were collected during the first and second field trips, respectively.

Some socioeconomic data were also gathered through group discussions and interviews with local inhabitants and officials using a purposive sampling method. Climatic data such as rainfall as well as agricultural inventories were obtained and used with other secondary data as ancillary information to improve our understanding of the process that might have led to LULC changes in the study area.

15.2.4 Image Analysis

Transformation In order to reduce the redundancy of the remotely sensed data and to improve the distinguishability among landscape feature classes, some transformation procedures were applied, namely:

1. Normalized difference vegetation index (NDVI): This index is sensitive to the amount of and changes in the green vegetation (Rouse Jr. et al. 1973). It requires spectral data from two wavebands only, viz. red (R) and near-infrared (NIR) and it is calculated using the following formula:

$$NDVI = \frac{NIR - R}{NIR + R} \tag{15.1}$$

2. Principal component analysis (PCA): PCA is a multivariate statistical method that is useful for reducing any possible spectral redundancy and concentrating any vegetation information on the image into the top principle components (PCs; Almeida and De Souza 2004).
3. Tasseled cap analysis (TCA): TCA allows the reduction of dimensional feature space and it transforms the image into greenness, yellowness, and brightness features (Kauth and Thomas 1976).

Classification and Accuracy Assessment A supervised image classification method using maximum likelihood algorithm was performed to discriminate among feature classes on the imagery and to map the dominant LULC classes in the study area. It is because a supervised classification procedure produces relatively more accurate class definition and higher overall accuracy (OA) than its counterpart, unsupervised classification approach (Tso and Mather 2009). The classification experiment was carried out on the atmospherically corrected 1973 and 2001 images and 2001 transformed PC as well as TCA images. Since 1973 image was considered as a reference image, a postclassification filter was applied to spatially smooth the classified images. The accuracy of the classified maps was assessed using producer's accuracy (PA), the user's accuracy (UA) as well as the OAs. OA is a percentage share of the number of correctly classified instances relative to the number of test ones, while UC represents the probability that an instance belongs to specific class and the classifier accurately allocates it to such a class. PC expresses the likelihood of that; a certain class is being correctly distinguished. Kappa statistic (Cohen 1960) was also calculated from the confusion matrix results to evaluate the reliability of the classification and to measure the agreement between the predicted feature labels and the reference ones. Kappa ($\hat{k}$) value of one indicates 100 % agreement, while a value of zero indicates full disagreement.

Change Detection We explored the use of two change detection methods. These are pre- and postclassification procedures. The preclassification method is a pixel-based technique which compares the temporal variations of pixel vectors. In the present study, the preclassification change detection method was conducted as follows:

1. Image differencing: Spectral reflectance at the NIR bands and NDVI data of the two images were used, and NIR and NDVI change images were produced. The change in the study area was then categorized as (a) no change, (b) negative change, or (c) positive change, based on one standard deviation threshold from the mean.
2. A composite method: The highest PCs of the two images were obtained and then the PC images were classified by employing a hybrid unsupervised/supervised classification algorithm into different change classes using the PC eigenvector values.
3. Change vector analysis (CVA): This method was applied to the brightness and greenness components of the tasseled cap transformation. Directional and magnitude multidimensional change vectors were determined according to Eqs. (15.2) and (15.3) as follows:

$$\text{Directional change} = (GT2 - GT1)/\sqrt{(BT2 - BT1)^2 + (GT2 - GT1)}. \quad (15.2)$$

$$\text{Magnitude change} = \sqrt{(BT2 - BT1)^2\ (GT2 - GT1)^2}, \quad (15.3)$$

where

$GT1$ Greenness component at time one,
$GT2$ Greenness component at time two,
$BT1$ Brightness component at time one, and
$BT2$ Brightness component at time two

On the other hand, a postclassification method was carried out on the classified images to detect and locate the LULC changes. Image differences procedure was performed and change matrices were calculated.

15.3 Results

15.3.1 Classification and Accuracy Assessment

The results of image classification are shown in Figs. 15.3 and 15.4. The same 1973 LULC classes were existing in 2001, except the woodland class which has disappeared. In addition, two new classes were introduced in 2001, namely farm and fallow on clay. However, the area covered by each class varies between the two periods (i.e., 1973 and 2001) as demonstrated in Table 15.1.

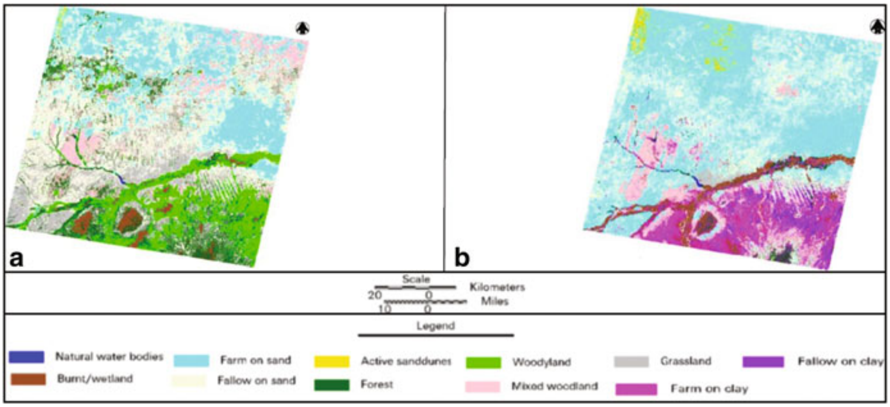

Fig. 15.3 Dominant land use/land cover classes in the study area in 1973 (**a**) and 2001 (**b**)

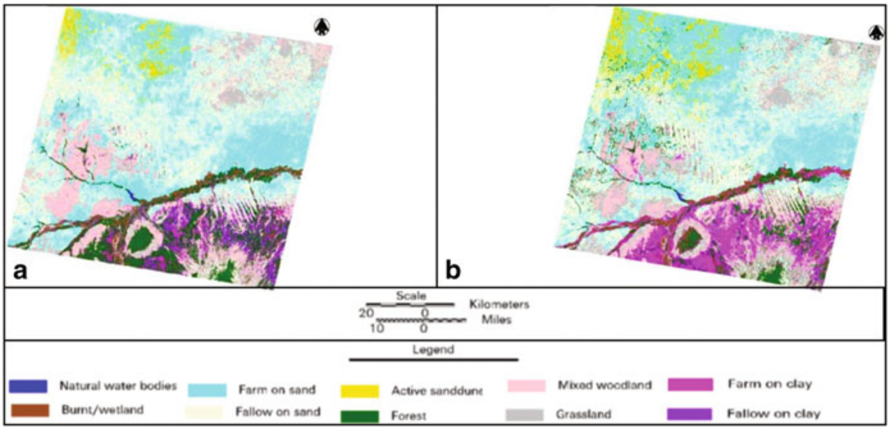

Fig. 15.4 Dominant land use/land cover classes in the study area in 2001 of PC (**a**) and TC (**b**) transformed images

The results of Table 15.1 indicate that the most dominant classes were farm and fallow on sand and the less dominant class was natural water bodies. With reference to OA assessment, classified image from PCA transformation showed the highest accuracy (%) (78.21; $\hat{k} = 0.76$) followed by atmospherically corrected image (78.13; $\hat{k} = 0.76$), and finally TCA image (72.64; $\hat{k} = 0.69$). When the individual accuracies were assessed, it is found that the most frequent highest PAs and UAs were for delineating natural water bodies, active sand dunes, and burnt/wetland, regardless of the period during which the images were captured or the transformation method applied (Table 15.2). This result was confirmed by the values of kappa where the same LULC classes obtained the most frequent highest agreements ($\hat{k}$) among the ground truth instances and the classified ones.

Table 15.1 Area (ha) of LULC classes in the study area

LULC class	Landsat MSS 1973 atmospherically corrected image	Landsat ETM+ 2001 atmospherically corrected image	Landsat ETM+ 2001 PC image	Landsat ETM+ 2001 TCA image
Natural water bodies	910.69	1,384.47	1,247.13	1,284.93
Burnt/wetlands	73,853.67	166,908.60	59,719.95	72,488.79
Farm on sand	603,543.01	965,053.89	587,203.47	602,285.49
Fallow on sand	809,238.83	739,089.36	100,757.65	857,321.37
Woodland	263,444.51	NE	NE	NE
Active sand dunes	2,988.75	38,820.60	65,051.01	107,797.95
Forest	292,939.59	41,589.00	268,487.64	235,377.72
Mixed woodland	256,925.07	353,305.71	396,945.99	366,675.84
Grassland	404,628.51	104,238.45	186,800.49	261,536.40
Farm on clay	NE	161,161.11	42,449.13	154,019.34
Fallow on clay	NE	136,058.85	92,147.58	48,822.21

NE not existing

Table 15.2 Producer's (PA) and user's (UA) accuracies (%) of the LULC classes

LULC class	Landsat MSS 1973 atmospherically corrected image		Landsat ETM+ 2001 atmospherically corrected image		Landsat ETM+ 2001 PC image		Landsat ETM+ 2001 TCA image	
	PA	UA	PA	UA	PA	UA	PA	UA
Natural water bodies	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Burnt/wetlands	100.00	80.00	71.88	92.00	87.50	84.00	76.47	72.22
Farm on sand	75.0	56.25	74.1	80.0	75.00	72.00	61.11	88.00
Fallow on sand	87.5	76.36	80.9	68.0	62.50	80.00	62.07	72.00
Woodland	100.0	66.67	NE	NE	NE	NE	NE	NE
Active sand dunes	100.0	100.0	100.0	95.2	100.0	76.00	100.0	64.00
Forest	66.6	100.0	72.0	72.2	75.00	84.00	69.57	64.00
Mixed woodland	62.5	90.91	65.7	92.0	68.97	80.00	62.07	72.00
Grassland	61.1	78.57	90.0	72.0	66.67	64.00	78.57	88.00
Farm on clay	NE	NE	66.7	72.0	80.77	84.00	87.50	56.00
Fallow on clay	NE	NE	92.86	52.0	80.77	84.00	57.14	50.00

NE not existing

15.3.2 Change Detection

The results of image differencing methods are summarized in Table 15.3 and maps of change are presented in Fig. 15.5. When NIR data were employed, the mean of the output NIR data was −1.684 and the standard deviation was 11.017. Consequently, pixels that had values greater than 9.33 were considered as positively changed areas and those that had values less than −12.701 were considered areas of negative change, and NIR data that ranged between −12.701 and 9.33 indicated no change. With

Table 15.3 Degree of changes detected in the study area using image differencing methods

Degree of change	Area (ha)		Change percentage	
	NIR	NDVI	NIR	NDVI
Positive change	361,035.45	250,410.24	9.66	6.70
Negative change	365,184.81	247,238.28	9.77	6.62
No change	3,010,887.54	3,239,459.28	80.57	86.68

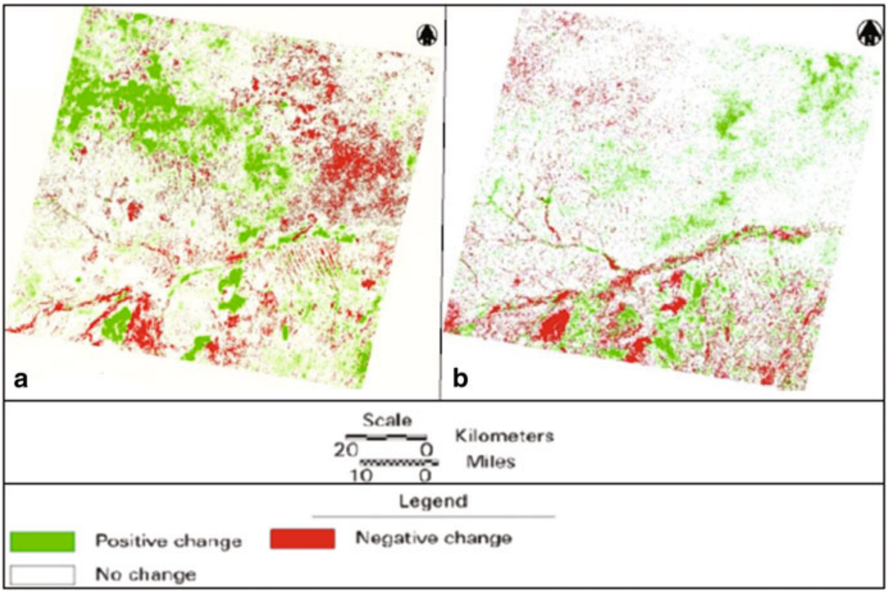

Fig. 15.5 Vegetation change pattern with the use of difference of near-infrared bands (**a**) as well as NDVI values (**b**) of 1973 and 2001 images

respect to NDVI data subtraction, the change was categorized into positive, negative, and no change using one standard deviation (0.065) threshold from the mean (0.02).

With reference to the composite method of PCs, our study demonstrated that the PC1, which was derived from the composite of six ETM+ and four MSS wavebands, accounted for 88.9 % of the variance in the remotely sensed data.

The results of hybrid unsupervised/supervised classification experiment of the composite PCs image were interpreted to change in forest, change in farming on clay soils, change in mixed wood, change in sand dunes, and change in farming on sand (Fig. 15.6). It was quite difficult to scale the level of the change; however, the general trend was negative (Table 15.4).

The CVA of brightness and greenness components of TCA produced magnitude and direction images. The magnitude ranged between 4 and 162 while the angle of direction ranged between −87 and −4°. It was obvious that the direction of change was negative. This result was in contradiction with findings of the image

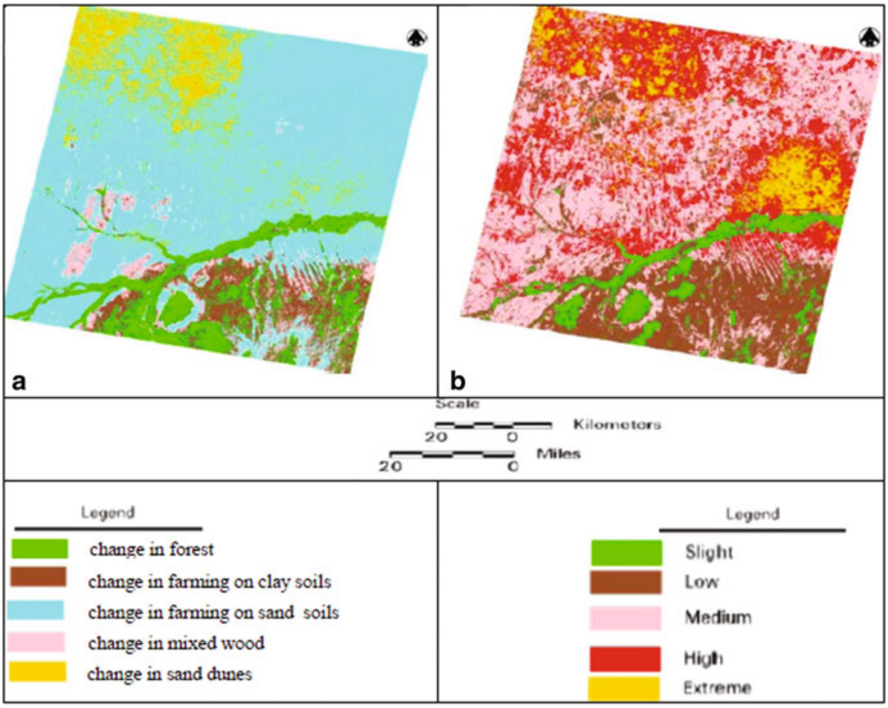

Fig. 15.6 Change classes of PC image of 1973 and 2001 (**a**) and change vector analysis (**b**)

Table 15.4 Mean principal components (PC) of LULC change classes of PC composite image of 1973 and 2001 Landsat imagery

LULC change class	PC1	PC2	PC3
Forest	90.10	– 13.31	1.44
Farming on clay soils	122.71	– 08.72	– 3.38
Mixed wood	152.83	– 11.96	– 3.62
Sand dunes	247.73	– 04.94	– 2.20
Farming on sand	197.45	– 14.07	– 1.08

subtraction method but coincided with the outcomes of PCA analysis. Hybrid supervised/unsupervised classification produced five change classes, explicitly slight, low, medium, high, and extreme changes (Table 15.5; Fig. 15.6).

15.4 Discussion and Conclusions

In order to obtain relatively more accurate results, a supervised classification approach is employed in the present study. However, the results show relatively high classification errors which could be due to spectral similarities among the different LULC classes. For example, it was difficult to separate Hashab (*Acacia senegal*) plantation and settlement areas (town/villages). The settlements were built from woody

Table 15.5 Degree of change detected in the study area using change vector analysis

Degree of change	Area (ha)	Change (%)
Slight	134,939.16	4.98
Low	563,679.72	20.81
Medium	1,128,878.19	41.67
High	656,312.76	24.23
Extreme	224,980.11	8.31

materials of the native vegetation (e.g., trees, shrubs, and grasses); therefore, their spectral characteristics might have been similar to those of Hashab. The domination of the farm and fallow on sand classes could be due to the fact that the main land use practice is rain-fed crop cultivation. On the other hand, the major soil type is infertile sand which needs to be left without cultivation (fallow) for a number of growing seasons. It was found that the less dominant class in the study area is natural water bodies. This might have led, in turn, to seasonal inhabits immigration towards the relatively more wet areas to the south and irrigated and rain-fed mechanized schemes to the east. In addition to sandy soil, clay soil also exists in these areas; therefore, farm and fallow on clay classes were introduced in 2001 classification maps. This might be due to the fact that NKS officials adopted food security program started from the 1990s to increase crop production in the State (Robinson 2012); hence, the areal extent of the field crops was increased towards the south and east.

It is obvious that PCA data had increased the classification accuracy. This could be attributed to the fact that PCA extended the possibility of pattern recognition since the imagery data were transformed into a new, uncorrelated coordinate system or vector space (Almeida and De Souza 2004). On the other hand, the unexpected result of relatively lower classification accuracy when TCA image was utilized could be due to the sparse distribution nature of the vegetation in the study area.

The results of the present study showed dominant positive change in the northern part of the study area, while a negative dominant change was detected in the southern part. This finding was a result of subtracting NIR wavebands and NDVI values of 1973 and 2001 images. This is in agreement with the finding of Eklundh and Olsson (2003) who indicated an increasing trend in NDVI values in the Sahel region which covers the northern part of NKS. In addition, a negative change and no change were shown in the middle-eastern part of the study area, when the spectral properties at NIR waveband and NDVI data were subtracted, respectively. This is not an unexpected result since this part of the study area was extensively used for rain-fed agriculture. Thus, the land might have been covered by crops, grasses, fallow fields, and/or crop residues, which led to relatively decreased NIR reflectance values and an increased NDVI. A decreased soil and crop residue reflectance at NIR waveband is a sign of positive change or no change at all. This finding implies that the employment of vegetation indices is better in detecting changes than the use of spectral characteristics at NIR waveband.

The PCA and CVA methods for change detection did not yield precise and detailed quantitative information about the change of each LULC class. It is worth mentioning that PCA and CVA procedures comparatively yielded similar results.

However, these two methods indicated a negative change while the image subtraction protocol indicated a positive change. This controversial result is difficult to be explained; nonetheless, we support the finding of a negative vegetation change. Similarly, interviews and group discussions with the inhabitants of NKS demonstrated that vegetation cover was transformed; some trees and grass were replaced by new ones. Moreover, they claimed a decrease in crops' productivity and attributed this to the desertification. Desertification according to their definition was positively correlated with low rainfall and sand encroachment. Moreover, interviewees mentioned that tree cover in NKS is less during the recent years (2000s) compared with the previous years (1970s).

The postclassification method showed an increment in farms on sand and clay soils. This is in agreement with the findings of Ardö and Olsson (2003). Notwithstanding, others such as Olsson (1985) reported that the increase in the cropland occurred in order to face the increasing food demand associated with population increase in NKS. On the other hand, active sand dunes had also increased, which could be an indicator of desertification in the study area. The occurrence of desertification can also be indicated by the crop inventories statistic, which showed slightly fluctuated crop productivity as a result of low rainfall.

The remotely sensed data used in this study represent only two selected dates and were not sharpened by additional data between the two dates. Additionally, the study area is considerably large with many inaccessible locations. This led us to adopt a sampling scheme, which coincides with roads and settlement areas. The present study employs conventional classification procedures, while there are other well-known robust machine-learning classifiers such as random forests and support vector machines. The utilization of these methods could have produced more accurate classified maps for detecting LULC changes.

Nevertheless, based on the findings of this study, we concluded that image transformation methods, namely PCA and TCA, contributed to improving the overall classification accuracy; the most dominant LULC classes in the study area were farms on sands and clay, while the less dominant class was natural water bodies; postclassification change detection methods show direct patterns of change in LULC classes, while the results of preclassification methods are contradictory to each other and give general indications of LULC changes; and the vegetation cover in NKS was negatively changed due to a number of socioeconomic factors.

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Chapter 16
Multi-model Approach for Spatial Evapotranspiration Mapping: Comparison of Models Performance for Different Ecosystems

Temesgen Enku, Christiaan van der Tol, Assefa M. Melesse, Semu A. Moges and A. Gieske

Abstract Accurate estimation of evapotranspiration (ET) is vital for water resource management. The FAO-56 Penman–Monteith (FAO-56 PM) is a standard method, but it requires numerous weather data. This challenges water resource managers to estimate ET in areas where there are no adequate meteorological data. Hence, simplified approaches that are less data intensive are the right alternatives. Here, ET was estimated using different approaches and their performances were evaluated in different ecosystems of Ethiopia. Surface Energy Balance Systems (SEBS) model was also used for spatio-temporal mapping of ET in the Fogera floodplain, Lake Tana Basin. The spatial average of actual ET (ETa) from remote-sensing (RS) data over the floodplain was less than the Penman–Monteith (PM) reference ET (ETo) in drier periods and larger in wet seasons. A sensitivity analysis of PM input variables at the Bahir Dar station showed that the incoming solar radiation and air temperature are most sensitive, and wind speed was found to be the least sensitive. The comparison of simple Enku (E) temperature method, Abtew (A) equation, modified Makkink

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(MM) method, and Priestley–Taylor (PT) method with the PM ETo in the different ecosystems of Ethiopia showed the MM method performed best in all the stations except Dire Dawa stations with coefficient of determination (R^2) of 0.94, Nash–Sutcliffe efficiency (NSE) of 0.88, root mean square error (RMSE) of 0.26 mm, and absolute mean error (AME) of 0.21 mm at Addis Ababa and Awassa stations. The performance of MM and PT methods in the dry and hot climate was poor. The E method performed consistently well in all the stations considered. While ET estimation from remotely sensed inputs has generally been improved, selection of the method of estimation is very important and should always be tested with observational data.

Keywords Evapotranspiration · MODIS · SEBS · Penman–Monteith · Ethiopia · Remote sensing · Modified Makkink · Priestley–Taylor · Abtew · Enku simple temperature method

16.1 Introduction

Population growth over the past decades and the economic growth in Ethiopia caused the demand for freshwater to increase. Water supply has to meet requirements not only for irrigation and agricultural production but also for domestic uses. Hence, well-planned and adequate water resources management is required at local and regional scales in East Africa. For such management, quantitative assessments need to be made for meteorological processes of precipitation and evapotranspiration (ET) that affect the water balance of the basins at large. ET and precipitation are the inputs to most hydrological models for studying water resource planning and management, assessment of irrigation efficiency of existing projects, evaluation of future drainage requirements, design of reservoirs and reservoir operations, water supply requirements of proposed irrigation projects, water supply requirements for domestic purposes, and preparation of river forecasts, to name but a few. There exist a multitude of methods, for estimation of ET. The availability of many methods for determining ET, with the wide range of data types needed, makes it difficult to select the most appropriate method from a group of methods for a given agro-climatic regions. There is, therefore, a need to analyze and compare the various existing ET models. Therefore, the objectives of this study are to (1) estimate actual ET (ETa) on the Fogera floodplain, Lake Tana basin, that probably is the most productive agricultural area in the Lake Tana basin, (2) estimate reference ET (ETo) using different empirical methods at different ecosystems and compare their performance with the more complete Penman–Monteith (PM) method, and (3) understand the most sensitive weather variable inputs to the PM ETo estimate in the area.

16.2 Study Area

Ethiopia is found in the horn of Africa; it lies between about 3°N to 15°N and 33°E to 48°E. The altitude in Ethiopia ranges from a lower elevation of about 116 m below sea level, in the Dallol depression of the Afar region, northeastern part of the country, to a highest elevation of about 4,620 m above sea level at Ras Dashen, in the Semien Mountains in the northern part of the country. Due to this high altitude difference, there is considerable spatial variability of temperature and climate, whereas seasonal variability is relatively low. Ethiopia is subdivided into five climatic regimes: moist, dry subhumid, semiarid, arid, and hyperarid regimes.

The Ethiopian National Meteorological Agency (ENMA) defines three seasons in Ethiopia: rainy season locally called *Kiremit* (usually from June to September), dry season locally called *Bega* (October to January), and short rainy season locally called *Belg* (February to May). Camberlin (1997) reported that the Indian monsoon activity is a major cause for summer rainfall variability in the East African highlands. The main rainfall season over the study area starts in June and ends in October. Majority of the study area receives rain during this summer season. The rest of the time it remains relatively dry and hot. The spatial variability of rainfall attributed to altitudinal differences is significant.

For this study, five "class I" stations with different climatic settings distributed over Ethiopia have been selected (Fig. 16.1). The rainfall distribution follows altitude; Dire Dawa has the lower elevations and very hot and dry climatic setting which receives the lowest mean annual rainfall of 661 mm with a standard deviation of 163.6 among the stations, whereas Debre Markos has the highest elevation and relatively cold climatic setting which receives higher annual rainfall of 1,476.8 mm with a standard deviation of 447.6 with extended unimodal type of rainfall. The Bahir Dar station receives the highest rainfall among the stations considered with medium altitude with unimodal rainfall characteristics. Awassa is located in the rift valley region of Ethiopia with bimodal rainfall characteristics, and Dire Dawa is representing lowlands and hot climatic settings. While the Addis Ababa station represents the central highlands, Debre Markos and the Bahir Dar stations represent north and northwest highlands of Ethiopia. The detailed characteristics of the stations are shown in Table 16.1. The Fogera floodplain is located in northwestern Ethiopia, about 625 km from the capital Addis Ababa along the shores of Lake Tana. The Ribb and Gumara rivers with catchment areas of 1,283 and 1,302 km^2, respectively (Abeyou 2008), pass through the plain and both drain into Lake Tana. Total annual rainfall in the floodplain ranges from about 1,100 to 1,530 mm. The mean monthly temperature of the area is about 19 °C. The floodplain is bounded by Lake Tana in the west, the Gumara River in south, the Ribb River in the north, and the Bahir Dar–Gondar road in the east. Its latitude ranges from 11°45′N to 12°03′N, while its longitude lies between 37°29′E and 37°49′E. It stretches about 15 km east–west and 34 km north–south, with an elevation of about 1,800 m above mean sea level (amsl), having an inundation area of about 490 km^2.

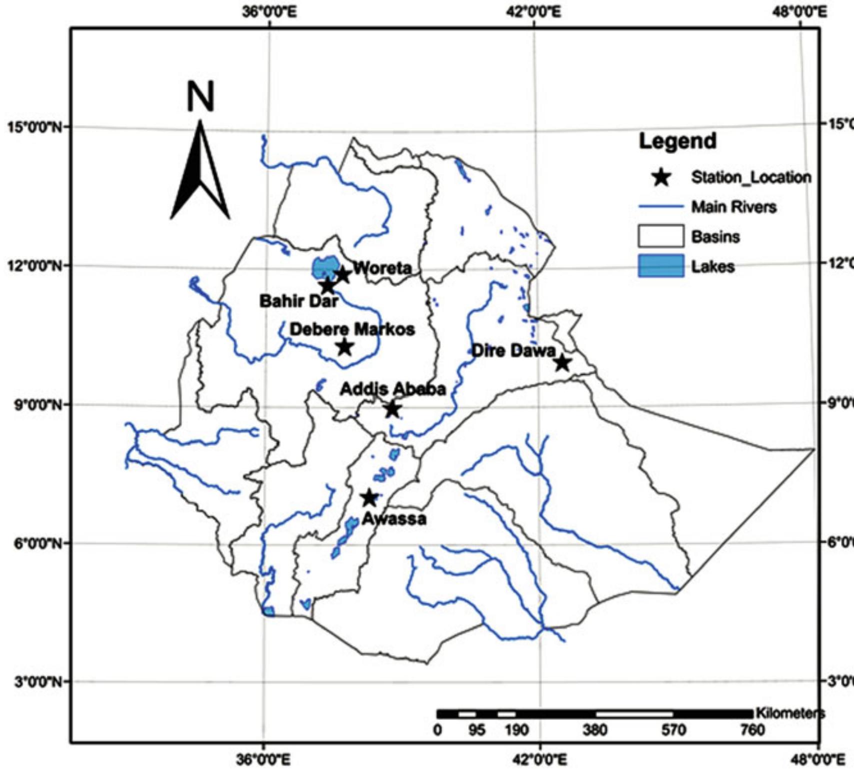

Fig. 16.1 Location map of study area

16.3 Materials and methods

16.3.1 Materials

16.3.1.1 Remote-Sensing Data

From Moderate Resolution Imaging Spectroradiometer (MODIS) onboard *Terra,* instantaneous images and composite products were used for the estimation of energy fluxes in the Fogera floodplain. The 8-day composites of reflectance (MOD09A1), leaf area index (MOD15A2), and the daily land surface temperature (MOD11A1) products were collected from MODIS collection 5. Instantaneous images (MOD021KM) and its respective geo-location files (MOD03) were acquired from Level 1 and Atmosphere Archive and Distribution System (LAADS). With respect to this, MODIS atmospheric products of aerosol optical depth, water vapor content, and ozone content were also collected.

Table 16.1 Station information and data statistics

Station name	Altitude (m)	Rainfall (mm)		Percentage of rainfall in		Type of rainfall	T_{max}		T_{min}		T_{mean}		Number of years
		Mean	Std. dev.	*Kiremit*	*Belg*		Mean	Std. dev.	Mean	Std dev	Mean	Std. dev.	
Addis Ababa	2,330	1,219.0	188.6	75.3	20	Bimodal	23.8	2.3	10.3	2.4	17.1	1.6	11
Awassa	1,750	996.2	128.4	44.5	31	Bimodal	27.4	2.5	12.9	2.7	20.1	1.4	11
Bahir Dar	1,800	1,526.9	156.6	93.4		Unimodal	27.2	2.5	12.5	3.2	19.8	2.1	14
Debre Markos	2,446	1,476.8	447.6	81.0		Extended Unimodal	22.9	2.8	10.6	1.9	16.8	1.7	10
Dire Dawa	1,180	661.0	163.6	52.4	34	Bimodal	32.4	2.8	19.1	3.3	25.7	2.8	11

16.3.1.2 Micrometeorology

A field campaign was arranged that installed eddy flux tower in the floodplain, from September 22 to 29, 2008; the eddy flux tower was mounted with: sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA), net radiometer (CNR1, Kipp & Zonen, Deft, The Netherlands), and humidity and temperature sensors. These sensors were connected to the Campbell Scientific data logger (CR5000). Wind speed in three directions and the sonic temperature were measured at 20 Hz with the CSAT3, the incoming and outgoing solar radiation, and longwave radiation were measured at 1/3 Hz with CNR1, and temperature and relative humidity data were collected from the CR5000 data logger. The 5-min net radiometer, relative humidity, and air temperature data were also recorded.

16.3.1.3 Meteorological Data

Long-term (10–15 years) daily meteorological data were collected from five "class I" stations from National Meteorological Agency of Ethiopia. Five minutes time resolution weather data were also collected from automatic recording weather station in the floodplain installed in June 2008. These stations were selected for their different ecosystems.

16.3.2 Methods

16.3.2.1 Remote-Sensing Methods

From MODIS onboard *Terra,* products were used for the estimation of ETa in the Fogera floodplain using the Surface Energy Balance Systems (SEBS) algorithms. MODIS detectors measure in 36 spectral bands between 0.405 and 14.385 μm and acquire data at three spatial resolutions of 250, 500, and 1,000 m. MODIS wide spectral resolution and viewing swaths, and atmospherically corrected products make measurements useful in a wide variety of earth system science disciplines. MODIS products of: the 8-day composite surface reflectance, the 8-day composite leaf area index, and daily land surface temperature, were acquired from collection 5. Fractional vegetation cover, broad band albedo, and emissivity were retrieved from SEBS algorithms.

Images Used in the Analysis During the growing season, two images per month were evaluated, and the rest of the year one image per month was considered. Table 16.2 shows the type, date, and Day of the Year (DOY) of the all images evaluated in this study.

Surface Energy Balance Systems (SEBS) Algorithm SEBS is one of the remote-sensing (RS) methods to estimate turbulent surface energy fluxes, developed by

Table 16.2 Date and type of images used in the analysis

Sr. no.	Date	Product name	DOY	Type of product
1	01 January 2008	MOD09A1 MOD15A2 MOD11A1	1	8-day composite 8-day composite daily
2	25 February 2008	MOD09A1 MOD15A2 MOD11A1	56	8-day composite 8-day composite daily
3	28 March 2008	MOD09A1 MOD15A2 MOD11A1	88	8-day composite 8-day composite daily
4	26 April 2008	MOD09A1 MOD15A2 MOD11A1	111	8-day composite 8-day composite daily
5	15 May 2008	MOD09A1 MOD15A2 MOD11A1	136	8-day composite 8-day composite daily
6	25 June 2008	MOD09A1 MOD15A2 MOD11A1	161	8-day composite 8-day composite daily
7	7 July 2008	MOD09A1 MOD15A2 MOD11A1	189	8-day composite 8-day composite daily
8	25 July 2008	MOD09A1 MOD15A2 MOD11A1	207	8-day composite 8-day composite daily
9	8 August 2008	MOD09A1 MOD15A2 MOD11A1	221	8-day composite 8-day composite daily
10	23 August 2008	MOD09A1 MOD15A2 MOD11A1	236	8-day composite 8-day composite daily
11	6 September 2008	MOD09A1 MOD15A2 MOD11A1	250	8-day composite 8-day composite daily
12	22 September 2008	MOD02 MOD03	266	Instant images
13	29 September 2008	MOD02 MOD03	273	Instant images
14	7 October 2008	MOD09A1 MOD15A2 MOD11A1	282	8-day composite 8-day composite daily
15	14 November 2008	MOD09A1 MOD15A2 MOD11A1	319	8-day composite 8-day composite daily
16	7 December 2007	MOD09A1 MOD15A2 MOD11A1	341	8-day composite 8-day composite daily

Su (2002). MODIS spectral products and meteorological data were used for the estimation of energy fluxes in SEBS. ETa is estimated as a residue of mass balance and energy balance equations in SEBS, which is written as

$$ETa = \frac{R_\mathrm{n} - G - H}{\lambda} \tag{16.1}$$

where ETa is the actual ET (mm/day), R_n is the net radiation (MJ/(m^2-day)), G is the soil heat flux (MJ/(m^2-day)), H is the sensible heat flux (MJ/(m^2-day)), and λ is the latent heat of evaporation (J/kg). Parameterizations of the inputs for the SEBS algorithm are explained in detail in Su (2002) and Enku (2009). SEBS uses spectral satellite observations and climatological data for the estimation of energy fluxes. The Woreta and the Bahir Dar weather station data were used. These are solar radiation, air temperature, wind speed, and computed specific humidity. The atmospheric pressure was assumed constant. The calculated instantaneous values were first extrapolated to daily values assuming that the evaporative fraction is constant during the day. Secondly, the daily values were extrapolated to monthly estimates, using the monthly PM estimates based on sunshine hours. All pixels of the floodplain are then averaged to obtain a single monthly ETa value.

16.3.2.2 Micrometeorology

During the field campaign, an eddy flux tower was installed in the floodplain and measurements were made with the sensors mounted on the flux tower. The sonic anemometer (CSAT3) measures at a frequency of 20 Hz and the net radiometer at a frequency of 1/3 Hz. Sensible heat flux and the friction velocity were calculated at half-hourly intervals from eddy covariance data.

Sensible Heat Flux and Friction Velocity From the eddy flux data, sensible heat flux (H), friction velocity (u_*), and the mean wind speed in the three orthogonal directions were calculated with an open source ECPACK software. From the sonic anemometer's wind speed and sonic temperature measurement, sensible heat flux was calculated as

$$H = \rho_\mathrm{a} c_p \overline{w'T'} \tag{16.2}$$

where H (W/m^2) is the sensible heat flux, ρ_a (kg/m^3) is the density of the air, c_p (J/kg K) is the specific heat capacity of the air, and $\overline{w'T'}$ is the covariance between the fluctuations of vertical wind speed and the sonic temperature. Friction velocity is a measure of the intensity of turbulence in the planetary boundary layer. This is calculated as

$$u_* = \left(-\overline{v'w'}\right)^{1/2} \tag{16.3}$$

where u_* (m/s) is the friction velocity, v' (m/s) is the horizontal instantaneous velocity fluctuation from the average, and w' (m/s) is the vertical instantaneous velocity fluctuation from the average.

Sensible heat flux was also calculated from ground measurements of vegetation height and radiometric surface temperature as

$$H = -\rho_{\mathrm{a}} c_p \frac{(T_{\mathrm{a}} - T_{\mathrm{s}})}{r_{\mathrm{ah}}} \tag{16.4}$$

where H is the sensible heat flux (W/m^2), T_{a} is the air temperature (K), T_{s} is the radiometric surface temperature (K), and r_{ah} is the aerodynamic resistance for heat transfer (s/m). The sensible heat flux from the eddy flux tower was also compared with the RS estimations. This is well explained in Enku (2009).

Evaporative Fraction Evaporative fraction is defined as the ratio of latent heat flux to the available energy.

$$\Lambda = \frac{\lambda E}{R_{\mathrm{n}} - G} \tag{16.5}$$

where Λ is the evaporative fraction, $\lambda E = (R_{\mathrm{n}} - G - H)$ is the latent heat flux (W/m^2), R_{n} is the net radiation (W/m^2), G is the soil heat flux (W/m^2), and H is the sensible heat flux (W/m^2) determined from equation. The CNR1 radiometer measures incoming and outgoing solar radiation, and longwave radiation, from which the net radiation was calculated.

Surface Albedo The measured incoming and outgoing solar radiation was used for the instantaneous albedo and daily albedo computations. The instantaneous albedo computed from SEBS routines during the satellite overpass was compared with the daily albedo observed CNR1 measurement. This comparison was based on pixel level at the eddy flux tower.

16.3.2.3 Conventional Methods

Information on ET, or consumptive use of water, is significant for water resources planning and management. In this study, different ET estimating models were evaluated with the standard PM method in different ecosystems of Ethiopia. The models were: simple Enku's (E) temperature method, simple Abtew (A) equation, modified Makkink (MM) method, and Priestley–Taylor (PT) method. The performance of these models in different ecosystems will be evaluated with the globally accepted standard PM method.

Penman–Monteith (PM) Method The PM equation (Monteith 1965; Penman 1948) is a physically based combination approach that incorporates energy and aerodynamic considerations. The PM equation produces direct estimates of ETa but requires knowledge of the PM canopy resistance (Sumner and Jacobs 2005). Generally PM equation gives acceptable ET estimates for practical applications in different climatic settings. The method requires inputs of net radiation, soil heat flux, air temperature, relative humidity, and wind speed. The calculation of the net radiation and assumption of soil heat flux were following the FAO-56 methodology. ETo is the potential ET from a hypothetical green grass of uniform height, 0.12 m, well watered, and a constant albedo of 0.23 with fixed surface resistance of 70 s/m (Allen 1998). PM is considered as a global standard method (Bois et al. 2008; Dingman 2002; Rana and Katerji 2000) and widely used globally. For the reference crop, after the aerodynamic resistance, $r_a = 208/u_2$ and the surface resistance $r_s = 70$ s/m are estimated; the general PM equation can be rewritten as

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{16.6}$$

where ETo is the reference ET (mm/day), R_n is the net radiation at the crop surface (MJ/m^2-day), G is the soil heat flux density (MJ/m^2-day), assumed to be zero, on a daily basis, T means the daily air temperature at 2 m height (°C), u_2 the wind speed at 2 m height (m/s), e_s the saturation vapor pressure (kPa), e_a the actual vapor pressure (kPa), e_s the e_a saturation vapor pressure deficit (kPa), Δ the slope of vapor pressure curve (kPa/°C), and γ the psychrometric constant (kPa/°C). The detailed computations of each input for ETo are found in the FAO-56 book. Sensitivity analysis of PM ETo to its input variables was also evaluated.

Enku Simple Temperature Method The Enku simple empirical temperature method (Enku and Melesse, 2013) estimates ETo from only maximum temperature data as

$$ET_o = \frac{(T_{\max})^n}{k} \tag{16.7}$$

where ETo is the reference ET (mm day^{-1}), $n = 2.5$ which can be calibrated for local conditions, $k =$ coefficient which can be calibrated for local conditions. The coefficient, k, could be approximated as $k = 48 * T_{mm} - 330$, where T_{mm} (°C) is the daily mean maximum temperature.

Abtew Simple Equation This method requires only solar radiation data for the estimation of ET. The method was tested in wetlands and open waters in different places and found to give a comparable result with complex methods (Abtew 1996; Melesse and Nangia 2005; Melesse et al. 2008). Abtew simple equation is defined as

$$ET = k\frac{R_s}{\lambda} \tag{16.8}$$

where ET is in mm/day and k is taken as 0.53 and could be adjusted according to the local situation (Abtew and Obeysekera 1995).

Modified Makkink Method The modified Makkink is a modified PT equation, which uses incoming solar radiation instead of net radiation (Brutsaert 2005). This method is one of the simplest radiation models: It requires only average air temperature and the incoming solar radiation. In the same way, this will be compared with the PM method in different climatic settings. The modified Makkink method is defined as (De Bruin 1981):

$$ET_{\text{o}} = 0.65\frac{\Delta}{\lambda(\Delta+\gamma)}R_{\text{s}} \tag{16.9}$$

where R_{s} is the incoming solar radiation MJ/(m^2-day).

Priestley–Taylor Method The Priestley–Taylor (PT) (1972) estimation in different ecosystems will be evaluated with the PM method. The PT equation requires net radiation, soil heat flux, and air temperature. It is expressed as

$$ET_{\text{o}} = \alpha\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{R_{\text{n}}-G}{\lambda}\right) \tag{16.10}$$

where the coefficient α varies in the range of 1.27–1.33; here, we took α as 1.3, ETo in mm/day, and input parameters as mentioned in Eq. (16.6).

16.3.2.4 Penman–Monteith Sensitivity Analysis

A sensitivity analysis is an important technique to improve understanding of the dominant climatic variables in the estimation of ETo in an area of interest. ETo is a measure of evaporative power of the atmosphere. It is independent of the crop type, the age of the vegetation, and management practices. This could be estimated from the meteorological data only. Sensitivity of ETo to the input variables varies with space and time (Gong et al. 2006). "In humid climate, ETo provides an upper limit for actual ET and in an arid climate it indicates the total available energy for actual ET" (Gong et al. 2006). Sensitivity analyses of PM ETo to the inputs—incoming solar radiation, air temperature, relative humidity, and wind speed—were made. Monthly averages of these weather variables were considered. These were increased and decreased by 10, 20, and 30 % from the average value of these variables for each run. To avoid nonsense computations in the sensitivity analysis, minimum and maximum temperature and relative humidity, the average air temperature and relative humidity, and their amplitudes were calculated (Bois et al. 2008). The minimum and the maximum values were taken under considerations while sensitivity for these variables was done. For the computations of net radiation, solar angles at the 15th day of each month were used. In this analysis, it was assumed that the maximum and minimum temperature and relative humidity increase and decrease simultaneously in the analysis of the respective variables.

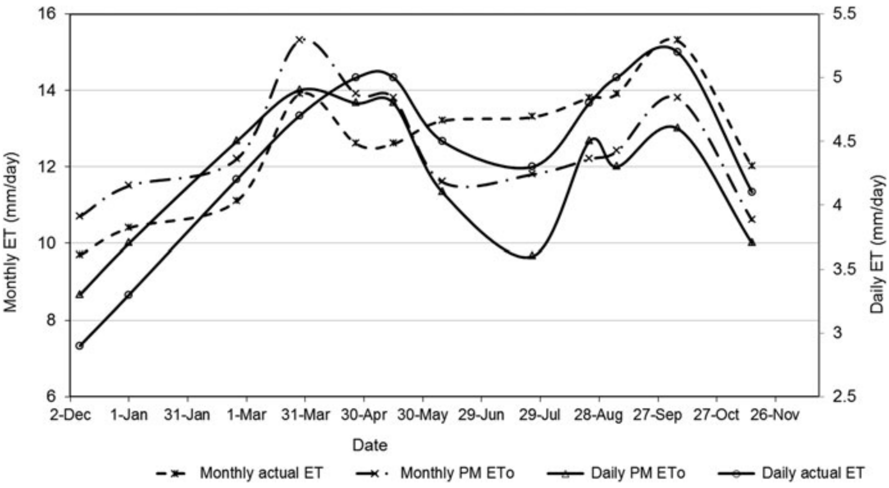

Fig. 16.2 Daily actual ET and PM ETo and monthly actual ET and PM ETo

16.4 Results and Discussion

16.4.1 Remote Sensing (RS)

16.4.1.1 Comparison of Actual ET to PM ETo

ETo is a climatologic variable characterizing the evaporative demand of the surface, whereas ETa represents the effects of soil moisture, land cover heterogeneity, and the variability of climatic conditions. Comparing ETa to ETo gives insight into the spatial variability of land cover and stress conditions. Differences between time series of ETa and ETo for specific crops indicate the seasonal cycle for the crop coefficient. It is noted that differences are also due to possible effects of water stress that is unaccounted for. We assume that water is sufficiently available not to constrain evapotranspiration. We note that ET estimations are for the wet season where rainfall commonly occurs in heavy daily showers. When comparing RS-based ETa with ground-based ETo, one should realize that ETo estimates are spatially limited and computed on a daily basis, whereas the RS technique estimates of ETa are spatially distributed, but they are only valid for the instantaneous time of the satellite overpass. Time series of ETo and ETa are shown in Fig. 16.2. One day per month was analyzed. The instantaneous RS ETa estimates were extrapolated to daily and monthly values.

The annual ETa estimated from this approach was 1,519 mm, while PM ETo was 1,498 mm in the year 2008. The mean annual rainfall over the past 5 years in the Fogera floodplain was 1,296 mm (Enku 2009). This indicates that the annual ETa was about 17 % higher than the mean annual rainfall over the area. This is probably due to the spate irrigation practices in the area during the dry seasons, which use

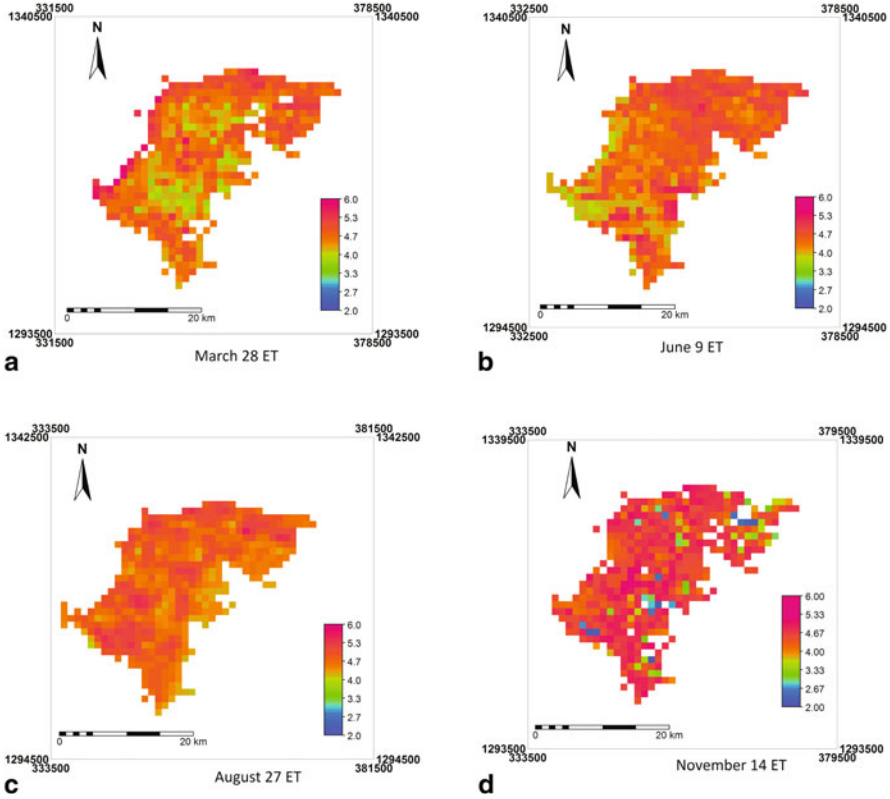

Fig. 16.3 Spatio-temporal distribution of ET over the Fogera floodplain in March (**a**), June (**b**), August (**c**), and November (**d**)

water from upstream areas. In Fig. 16.2, both the RS daily and monthly ETa and the PM ETo daily and monthly estimations follow a similar trend. In the wet season (July–September), the daily estimations from ETa were larger than the respective PM ETo, whereas in dry seasons, the PM ETo was larger than SEBS estimations. This could be explained by the drying out of the top soil layers leading to a reduction of moisture available for evapotranspiration. ETa was limited by the available net radiation during the rainy season.

16.4.1.2 Spatio-Temporal Distribution of ETa over the Floodplain

The spatio-temporal variation of ET in the Fogera floodplain was analyzed using four selected images. The spatial variation over the floodplain was more pronounced in the dry seasons than wet season. The spatial and temporal variations of ET are shown in Fig. 16.3 for selected months. On 27 August 2008 (Fig. 16.3c), the ETa over the floodplain ranges from a minimum value of 3.9 mm to a maximum of about

Table 16.3 Latent heat flux comparison with PM ETo

Date	Sensible heat flux MJ/(m^2-day)	Net radiation MJ/(m^2-day)	Latent heat flux (mm/day)	PM ETo (mm/day)	Kc
23 September 2008	2.045	15.0	5.29	4.58	1.15
24 September 2008	1.813	13.66	4.84	4.33	1.12
28 September 2008	2.831	15.74	5.27	4.81	1.10
Average	2.23	14.8	5.13	4.57	1.12

5.6 mm in forest and water bodies, with a mean value of 4.8 mm and a standard deviation of 0.5 mm. The lower standard deviation here clearly shows that the spatial variation in wet months is less pronounced. Similarly, on 14 November 2008, the spatial distribution of ET follows similar pattern as of 27 August 2008, except here more pixels become drier. Here, the minimum ET was as low as 2.09 mm and the maximum was 5.25 mm a day, with a mean of 4.12 mm and a standard deviation of 0.78 mm as shown Fig. 16.3d.

On 28 March 2008 (Fig. 16.3a), daily ET ranges from a minimum of 3.7 mm to a maximum of 6 mm with a mean value of 4.9 mm and a standard deviation of 0.7 mm. On 9 June 2008 (Fig. 16.3b), daily ET ranges from a minimum of 3.6 mm to a maximum of 5.3 mm with a mean value of 4.4 mm and a standard deviation of 0.5 mm.

16.4.2 Micrometeorology

Here sensible heat flux, latent heat flux, evaporative fraction, and broad band albedo computed from ground observations were compared with the RS derivations.

Sensible Heat Flux Sensible heat flux computed from the sonic anemometer was compared with the SEBS derived sensible heat flux estimations. The SEBS-derived sensible heat flux comparison was done, both with pixel value and averages of five pixels around the eddy flux tower. The average of the five pixels from SEBS estimation on 22 September 2008 was 119 W/m^2, while the eddy covariance sensible heat flux was 111 W/m^2. On the same day, a pixel value of SEBS sensible heat flux was 123 W/m^2. On 29 September 2008, the average was 107 W/$m^2$and the pixel value was 116 W/m^2, while the Eddy covariance sensible heat flux was 82 W/m^2.

Latent Heat Flux The daily latent heat flux was computed from the eddy flux tower observations. This was compared with the PM ETo. Table 16.3 shows that the PM ETo was less by about 12 %. This difference was comparable with the literature value of the rice crop coefficient during its mid-development stage (Allen 1998); as rice was the dominant crop around the eddy flux tower. Unfortunately, there were no good satellite images during these days and comparing with the RS estimations was not possible.

Evaporative Fraction The instantaneous evaporative fraction derived from RS technique was compared with evaporative fraction computed from the eddy flux

Table 16.4 Comparison of instantaneous and daily evaporative fraction

Date	Evaporative fraction			
	Instantaneous		Daily	Diff (%)
	From satellite data	Eddy flux data		
22 September 2008	0.75	0.76	–	–
23 September 2008	–	0.79	0.89	11.54
24 September 2008	–	0.79	0.88	10.38
28 September 2008	–	0.70	0.83	15.00
29 September 2008	0.77	0.71	–	–

Table 16.5 Instantaneous and daily albedo computed from the CNR1 observations

Date	Instant albedo at satellite overpass	Daily albedo	Percentage increase (%)
23 September 2008	0.13	0.15	15.4
24 September 2008	0.13	0.15	15.4
28 September 2008	0.13	0.15	15.4
Average	0.13	0.15	15.4

tower at the time of satellite overpass. The evaporative fraction from SEBS algorithm was found comparable with the eddy flux tower computation. These instant values were also compared with the daily average values computed from the eddy flux measurement. It was found that the instantaneous evaporative fraction was less by an average of about 12 %. The daily evaporative fraction was found constant except at the sunrise and sunset, where it was unstable. The detail is shown in Table 16.4.

Surface Albedo The instantaneous surface albedo during the satellite overpass computed from the eddy flux tower was compared with the daily average. It was found that the instantaneous albedo was about 15 % lower than the daily albedo. This was applied to adjust the instantaneous values to the daily estimates in the RS technique, which improves the RS ET estimations over the floodplain. The instantaneous and the daily computed albedo are shown in Table 16.5.

16.4.3 Conventional Methods

The ETo estimations of the different conventional methods were compared with the PM estimations, and the performances of these methods against the PM method were evaluated in different ecosystems. The performances of these methods were evaluated using four indices: coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), absolute mean error (AME), and root mean square error (RMSE) values. The detailed performances of the methods with different ecosystems are as shown in Table 16.6. The methods show different performances in different ecosystems. The MM method performs very well without local calibration of the model coefficient, in most objective functions set and in all stations except the Dire Dawa

Table 16.6 Comparison results of different methods with PM

Station and period	Methods	Performance when compared with PM				Percentage error
		R^2	NSE	AME	RMSE	
Addis Ababa (1995–2005)	*E*	0.61	0.52	0.40	0.51	2.5
	A	0.9	0.72	0.31	0.39	7.7
	MM	0.94	0.88	0.21	0.26	3.4
	PT	0.91	0.9	0.18	0.23	0.67
Awassa (1995–2005)	*E*	0.58	0.3	0.44	0.55	0.32
	A	0.89	0.64	0.31	0.39	7.11
	MM	0.93	0.88	0.18	0.23	1.22
	PT	0.89	0.89	0.17	0.22	1.31
Bahir Dar (1998–2011)	*E*	0.63	0.52	0.42	0.55	19
	A	0.7	0.58	0.41	0.51	13.8
	MM	0.79	0.79	0.27	0.36	18.6
	PT	0.76	0.72	0.30	0.42	22
Debre Markos (2002–2011)	*E*	0.7	0.69	0.5	0.6	3.5
	A	0.77	0.7	0.4	0.5	5.9
	MM	0.84	0.83	0.3	0.38	2.2
	PT	0.66	0.65	0.4	0.54	1
Dire Dawa (1995–2005)	*E*	0.67	0.66	0.54	0.70	0.1
	A	0.32	0.22	0.82	1.06	6.9
	MM	0.47	0.03	0.86	1.18	15.4
	PT	0.56	0.55	0.62	0.81	1.5

E Enku simple temperature, *A* Abtew simple equation, *MM* Modified Makkink, *PT* Priestley–Taylor

station. Dire Dawa has hot and dry climatic setting, where the performances of MM, A, and PT methods were poor. In this station, the E simple temperature method is performing well. Calibrating the coefficient of A equation improves the performance of the method in all the stations as shown in Table 16.6. Locally calibrated coefficient at the Dire Dawa station did not bring about significant performance improvement. Figure 16.4 shows the scatter plots of the different methods with the PM approach at Debre Makros station.

Enku Simple Temperature Method The estimation of ETo with this simple method was compared with the PM estimations, and the performance was evaluated. The method performed well in the majority of the stations with R^2, NSE, AME, and RMSE of 0.7, 0.69, 0.5, and 0.6 respectively, at Debre Markos station. The method also performs better than any other methods tested at the Dire Dawa climatic setting in all performance criteria used. The details are as shown in Table 16.6.

Abtew Simple Equation In the same way, the estimation of the method was also compared with the PM estimations and its performance in different ecosystems was evaluated. The method performs well after the coefficient was locally calibrated, in almost all the criteria set in all stations except the Dire Dawa station, where it fails to estimate ET properly as shown in Table 16.6.

Modified Makkink Method The MM method performs very well in all the performance evaluation criteria in all the stations except Dire Dawa station without

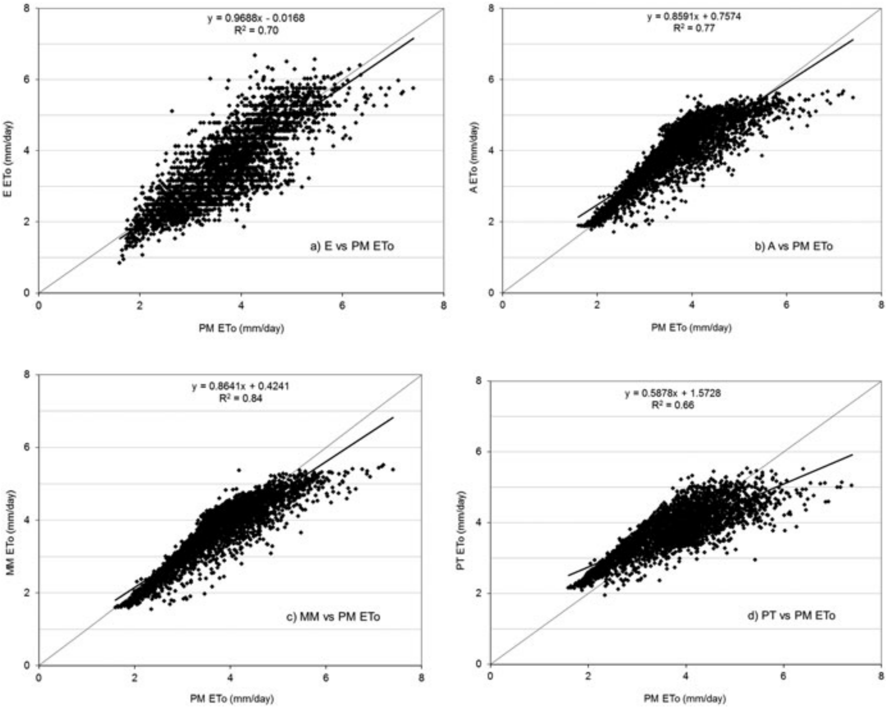

Fig. 16.4 Scatter plots of different methods with PM ETo at Debre Markos station

calibrating the coefficients. It performs very well, especially at the Addis Ababa station with R^2, NSE, AME, and RMSE of 0.94, 0.88, 0.21, and 0.26, respectively. MM was developed for wet surfaces; as a result, it will not be a surprise that the MM method is not performing well in dry and hot climatic setting like Dire Dawa as shown in Table 16.6.

Priestley–Taylor Method PT method is also performing well in most of the climatic settings, but it requires local calibration of the coefficient as low as 1.1 in most stations that brought about significant performance improvement at Addis Ababa, Awassa, and Bahir Dar stations. Locally calibrated coefficient at the Dire Dawa station did not bring about significant performance improvement.

16.4.4 Sensitivity Analysis

Sensitivity analysis of the PM ETo for its input variables was done in the year 2007 at Bahir Dar station. The result of sensitivity analysis showed that solar radiation was found the most sensitive weather variable almost independent of the seasons of the year. PM ETo was also comparably sensitive to air temperature as solar radiation.

Table 16.7 Weather variables statistics at Bahir Dar station

	T_{max}(°C)	T_{min} (°C)	T_{mean} (°C)	RH (%)	SS (h)	Rs (MJ/m^2-day)	WS (m/s)
Mean	27.2	12.5	19.8	57.9	8.0	20.5	0.9
Std. dev.	2.4	3.2	2.1	15.6	2.8	3.8	0.4

T_{max} maximum temperature, T_{min} minimum temperature, T_{mean} mean temperature, *RH* relative humidity, *SS* sunshine hours, *Rs* incoming solar radiation, *WS* wind speed

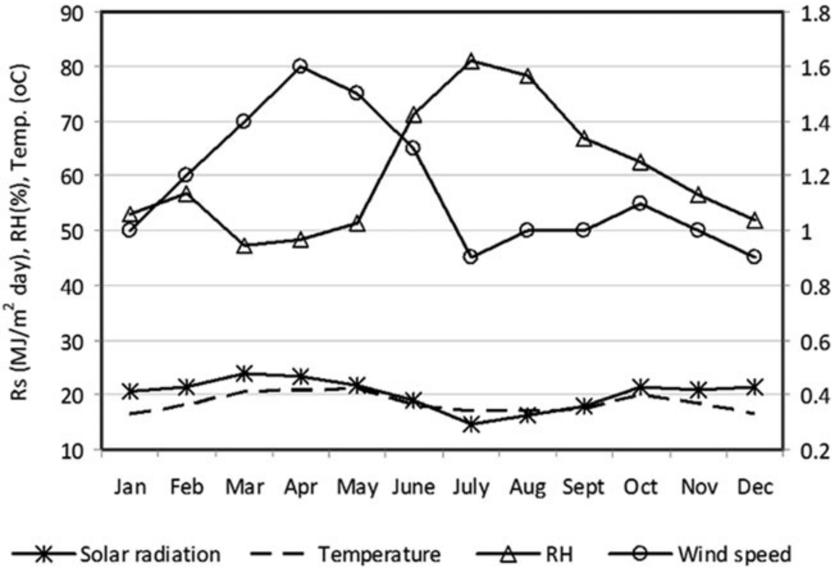

Fig. 16.5 Monthly average weather variables at the Bahir Dar station (2007)

Wind speed was found least sensitive. Relative humidity influences ETo negatively and high relative humidity values have more influence on ETo than smaller values. Gong et al. (2006) explained sensitivity of ETo to the input variables varies with seasons. But here sensitivity result does not change with the change of seasons. This is because the variation of weather variables for more than a year is a minimum in the area. For example, the long-term mean wind speed in the area was 0.9 m/s with a standard deviation of 0.4 m/s. The long-term (14 years) mean and standard deviation of the weather variables at Bahir Dar station are shown in Table 16.7.

During the sensitivity analysis, long-term weather data were evaluated. The daily maximum and minimum solar radiation was 27.53 MJ/(m^2-day) and 8.9 MJ/(m^2-day) in April and October, respectively. The daily maximum and minimum temperature was 33.8 °C in April and December 0 °C, respectively. The relative humidity ranges from a minimum of 21 % to a maximum of 94 %. Minimum was in April and maximum was in July, August, and September. The monthly average weather variables at Bahir Dar station is shown in Fig. 16.5.

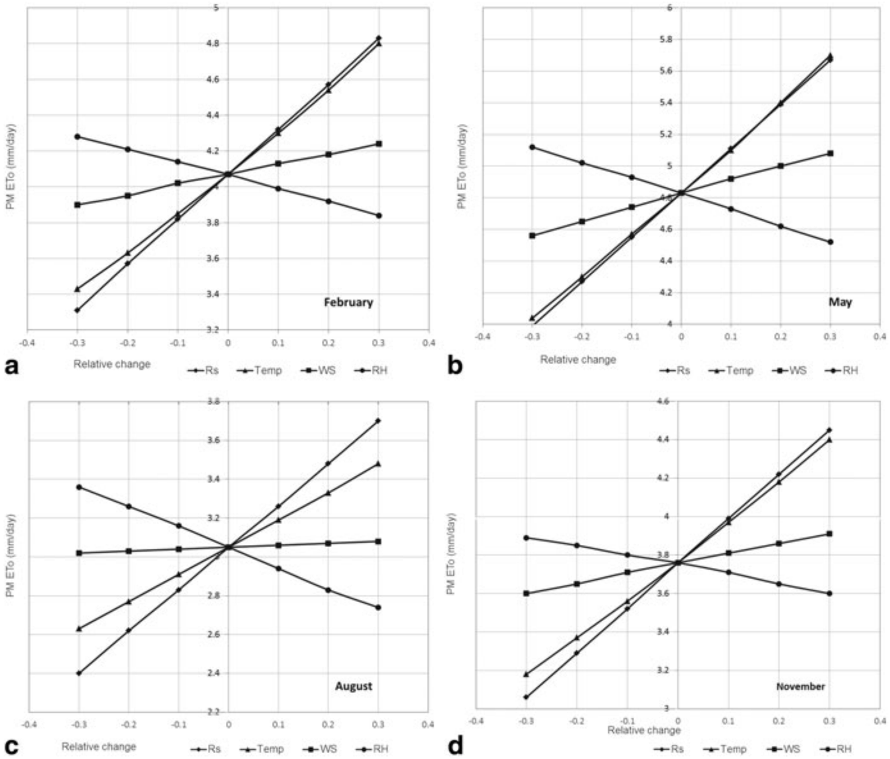

Fig. 16.6 Sensitivity analysis results of ETo to input variables in February (**a**), May (**b**), August (**c**), and November (**d**)

A simple but practical way of presenting a sensitivity analysis is to plot relative changes of weather variables against changes in PM ETo as a curve. The sensitivity analysis result at Bahir Dar station for some months in the year 2007 representing different seasons is shown in Fig. 16.6.

16.5 Conclusions and Recommendations

The spatial average of ETa estimated from RS over the floodplain was smaller than the PM ETo in relatively drier periods, but greater in wet seasons. This is because the increased biomass in the wet season evapo-transpire at a potential rate and the available soil moisture. The annual ETa over the plain was found to be about 1,519 mm, whereas the annual PM ETo was 1,498 mm. In wet seasons, the spatial variation of ETa was less pronounced, whereas in relatively dry months the spatial variation was clearly pronounced. ET estimation from remote-sensed inputs have generally been improved.

Ground Ground-based estimations of ETo for the long-term time series data were done using different methods at five different ecosystems distributed over Ethiopia. The different empirical methods were compared to the standard PM ETo. From the different conventional methods used, the MM method was the only method which does not require local calibration of the coefficient to perform best in all the stations except Dire Dawa station where its performance was poor. This method performed the best among the models tested, with an R^2 of 0.94, NSE of 0.88, RMSE of 0.26 mm, and AME of 0.21 mm at Addis Ababa and Awassa stations. The PT method overestimated ETo when the a priori coefficient, $\alpha = 1.3$, was used. Estimates were improved well when the coefficient α was reduced to 1.1 in most of the stations considered. The simple Abtew equation also performed well in the area. However, it proved necessary to calibrate the coefficient.

Radiation and temperature were found almost equally sensitive inputs to the PM ETo almost irrespective of the seasons. That was why Enku's simple temperature method was performing well in the stations used in this study consistently. This method performs well, even at the Dire Dawa station where other methods failed. This method is recommended for the area where there is insufficient data to use other methods, especially for annual ET estimations for hydrological studies. The results obtained with the MM and A methods appear to be promising. However, calibration of the a priori coefficients is required before these simple methods can be routinely applied in the area. Application of these simple methods in dry and hot ecosystems in the area should be seen in cautiously.

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Chapter 17
Modeling Rainfall Erosivity From Daily Rainfall Events, Upper Blue Nile Basin, Ethiopia

Tewodros Assefa Nigussie, Abebe Fanta, Assefa M. Melesse and Shoeb Quraishi

Abstract The upper Blue Nile River basin is one of the most degraded basins in Ethiopia. Soil erosion hazard assessment is of paramount importance in order to reduce soil erosion. Presently, the most commonly used empirical models, in Ethiopia, for annual soil loss assessments are the Universal Soil Loss Equation (USLE) and its revised version, RUSLE. The rainfall erosivity factor (*R*) is an important factor used in computation of soil erosion by the USLE, the Revised and Modified USLEs. And, therefore, the value of *R* for the upper Blue Nile River basin was computed using autographical data of 6–10 years from 12 meteorological stations scattered all over the basin based on the method suggested by Wischmeier and Smith (*Predicting Rainfall Erosion Losses: A Guide to Conservation Planning*,1978). Accordingly, higher rainfall erosivity values were recorded in the basin, the highest and the lowest being 7,208.91 and 1,737.97 MJ-mm/ha·h·year, respectively. Rainfall erosivity peaks were observed in the months of July and August throughout the basin. Various models were developed to predict rainfall erosivity for areas where self-recording rain gauges are not available. The validity test of the monthly rainfall erosivity equations, developed for the two rainfall zones, revealed model efficiencies of 0.73 and 0.82 for Zone A and Zone B, respectively. Nevertheless, the model efficiency of the monthly rainfall erosivity prediction equation for the entire basin is 0.85. The validity test of the annual erosivity models resulted in model efficiencies of 0.89 for Zone A, 0.65 for Zone B, and 0.80 for the entire basin. Using the developed annual rainfall erosivity prediction model at basin level, annual rainfall erosivity values of 72 stations equipped with non-recording rain gauges were predicted so that it would help all stakeholders to make proper planning and implement effective measures to reduce the problem. However, further research is needed to investigate the variability of erosivity under changing climate by taking different factors into consideration.

Keywords Erosivity · Soil erosion · Blue Nile basin · Modeling · USLE · RUSLE

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17.1 Introduction

17.1.1 *Background and Justification*

Soil erosion is one of the major problems in Ethiopia. Deforestation and poor land management practices expose the soil surface to rain and wind leading to an increased surface runoff, thus enhancing soil erosion (Birru 2002). The removal of the top fertile soil from the land, in turn, creates unfavorable conditions for vegetation/crop to establish and this resulted in accelerated soil loss.

Considerable numbers of studies were conducted in Ethiopia regarding land degradation at national level. Some of these studies include the Ethiopian Highland Reclamation Study (EHRS) (FAO 1986), the National Conservation Strategy Studies (Sutcliffe 1993), the Ethiopian Forestry Action (1993), and the study by Keyzer and Sonnevled (2001). Findings of these studies vary considerably. The EHRS indicated that water erosion (sheet and rill) was the most important process of land degradation. It was noted that in the mid-1980s, 27 million ha (almost 50 % of the highland area) was considerably eroded, 14 million ha was seriously eroded, and more than 2 million ha had been eroded beyond reclamation. Erosion rates were estimated to be 130 t/ha-year for cropland and 35 t/ha-year on average for all land in the highlands. Sutcliffe (1993) indicated the rate of soil erosion to be lower than that reported by EHRS though he emphasized the importance and magnitude of nutrient loss. Hurni (1988) estimated that average erosion rates on the then unproductive croplands and croplands planted with annual crops were 70 and 42 t/ha-year, respectively, while it averaged 8 t/ha-year on land planted with perennial crops and 5 t/ha-year or less for all other land-cover types. Results obtained from test plots at the Andit Tid (North Shewa) Soil Conservation Research Project (SCRP) site indicated that soil loss under traditional soil management techniques averaged 152 t/ha-year (Birru 2002).

The upper Blue Nile River basin is the most degraded basin due to rapid population growth, poverty, poor watershed management, poor or absence of effective water-use policy, and frequent natural disasters (Melesse et al. 2011). According to Woodward et al. (2007), 72 % of the total suspended sediment load of the Nile (120×10^6 t year$-^1$) is contributed by this basin. Soil loss in the areas cultivated through traditional practices amount to 122–128 t per hectare per year in the highlands of the upper Blue Nile River basin (World Bank 2008).

To rectify the problem associated with total soil and nutrient losses, non-governmental organizations (NGOs) and the government along with people of Ethiopia launched massive reforestation and soil conservation schemes in the country during the past three decades. However, these programs suffered major setbacks during the implementation phase owing to shortcomings in the approaches adopted and improper design of structural measures (Hurni 1988). The shortcomings included:

- Overemphasis on structural measures and uniform application of measures regardless of variations in agroecological situations

- Failure to consult and involve peasants in the planning process, i.e., top-to-down approach was followed, and as a result lack of ownership to the constructed structures
- Lack of clear policy, especially concerning ownership, control, and utilization of afforested areas and closed hillsides

Despite these severe implications and different estimates of the rates of erosion in the country and in the upper Blue Nile basin, there is a lack of qualitative and quantitative data on current rate of erosion for most of the watersheds, which helps in better understanding of the process of soil erosion, designing soil and water conservation measures, and quantifying the major parameters that affect soil erosion. At present, the most commonly used method for predicting the average rate of soil loss due to water erosion from agricultural land is Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978) and its successor Revised USLE (RUSLE; Renard et al. 1997). In Ethiopia, there are few evaluated and validated soil loss estimation models throughout the country; the USLE has been adopted in Ethiopia, often with good results, at least from the practitioners' perspective (Carruci 2000). The equation represents the major factors affecting erosion (Hudson 1977), and transferring it to locations throughout the world required only the determination of appropriate values for the different factors (Foster and Mayer 1977).

In USLE, the climatic influence on soil erosion is represented by rainfall factor, known as *R* factor, and it is the most precise single estimate of rainfall erosion potential (Wischmeier 1959). There are annual variations in the value of erosivity as a result of variations in the rainfall characteristics. These variations of erosivity by rainfall contain important information, in addition to the total erosivity, for designing of soil conservation practices (Clark et al. 2000). Wischmeier and Smith (1958) noted that the erosivity explains about 80 % of the variation in soil loss. Its annual and monthly values serve as a main guide for designing soil conservation practices in many countries (Babu et al. 1978; Renard et al. 1997). Hudson (1977) indicated that in addition to the above-mentioned applications, assessing the erosive power of rainfall numerically helps improve the design of conservation works in practical soil conservation exercises, and in research it helps increase the knowledge and understanding of erosion.

In many developing countries, including Ethiopia, where the upper Blue Nile basin is located, spatial and temporal coverage of pluviograph data is limited. Whenever available, pluviograph data are often incomplete, and the record period is very short. In contrast, daily rainfall data are most widely available for longer periods. It is, therefore, desirable to be able to estimate the erosivity (*R*) factor and its monthly distribution, which is needed for using USLE\RUSLE to predict soil erosion from daily rainfall amounts. In addition to this, in areas where long-term pluviograph data are not available, the R factor may be estimated using mean annual rainfall (Yu et al. 2001). Information on the seasonal distribution of rainfall erosivity is also needed to calculate annual cover and management factor in the USLE\RUSLE (Renard et al. 1997). Moreover, seasonal distribution of rainfall erosivity is essential to assess erosion hazards.

17.1.2 Objectives

The main goal of this study was to develop equations for the estimation of the *R* factor and generate rainfall erosivity information for the upper Blue Nile River basin that will help all stakeholders involved in soil conservation works.

Specific Objectives The specific objectives of this study are to

- Estimate daily, monthly, seasonal, and annual rainfall erosivity factor (*R*) for the upper Blue Nile River basin, and
- Develop monthly and annual rainfall erosivity models from daily rainfall amount for the upper Blue Nile basin by developing a relationship of rainfall and erosivity values

17.2 Materials and Methods

17.2.1 Description of the Study Area

17.2.1.1 Geography

The upper Blue Nile River basin is geographically located between 34°16′31″ and 39°49′38″ east longitudes and between 7°42′9″ and 12°45′19″ north longitudes. The basin is bounded west by the Sudan, north by the Tekeze basin, east by Awash, and south by Baro–Akobo and Omo–Ghibe basins. The Blue Nile River originates from the highlands of Amhara Region in northern Ethiopia and flows about 800 km (UNESCO-WWAP 2007) in the western direction. The basin covers about 200,000 km^2 of the three regional states of Amhara, Oromiya, and Benishangul Gumuz (Fig. 17.1).

17.2.1.2 Population

The upper Blue Nile River basin is home to more than 18.4 million of Ethiopia's 81 million people as projected by Central Statistical Agency (CSA 2005) for 2010 (Awulachew et al. 2007) based on the 1994 population census. The upper Blue Nile River basin, which contributes 86 % runoff to the Nile, is the most populous and the fifth most densely populated basin in Ethiopia (Table 17.1).

17.2.1.3 Climate

The upper Blue Nile River basin has a mean annual rainfall of 1,451 mm based on the data of Bahir Dar station for the period between 1960 and 1992 (Kebede et al. 2006) and with a minimum of 794 mm and a maximum of 2,049 mm (Abtew

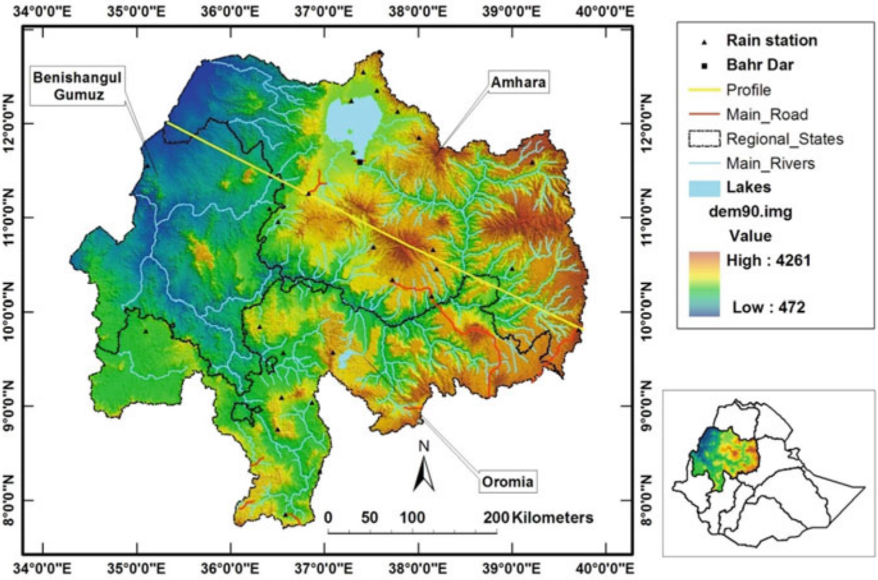


Fig. 17.1 The upper Blue Nile River basin and its topography

Table 17.1 Population by region as projected in the 1994 population census for upper Blue Nile River basin (Abay basin) based on the regional population data of Awulachew et al. (2005) and CSA (2005)

Region name in the basin	Unit	Amhara	Oromia	Ben. Gumuz	Total
Area	km^2	92,638	62,933	44,474	200,045
	%	46.31	31.46	22.23	100.00
Counted in 2006	Population	11,392,784	5,134,964	568,572	17,096,320
	Density (per km^2)	123	82	13	85
Projected for 2010	Population	12,310,897	5,494,788	617,841	18,423,525
	Density (per km^2)	133	87	14	92
Projected for 2015	Population	13,874,675	6,201,139	695,360	20,771,174
	Density (per km^2)	150	99	16	104

et al. 2009). The mean annual evapotranspiration of the basin is 1,300 mm (Engida 1999). Annual rainfall over the basin decreases from the southwest (> 2,000 mm) to the northeast (around 1,000 mm), with about 70 % occurring between June and September (Conway 2000). The basin's annual air temperature ranges between 11.5 and 25.5 °C (UNESCO-WWAP 2007).

17.2.1.4 Geomorphology and Soils

The upper Blue Nile River basin has an extremely varied topography, and its landscape is characterized by highland complex of mountains and dissected plateau

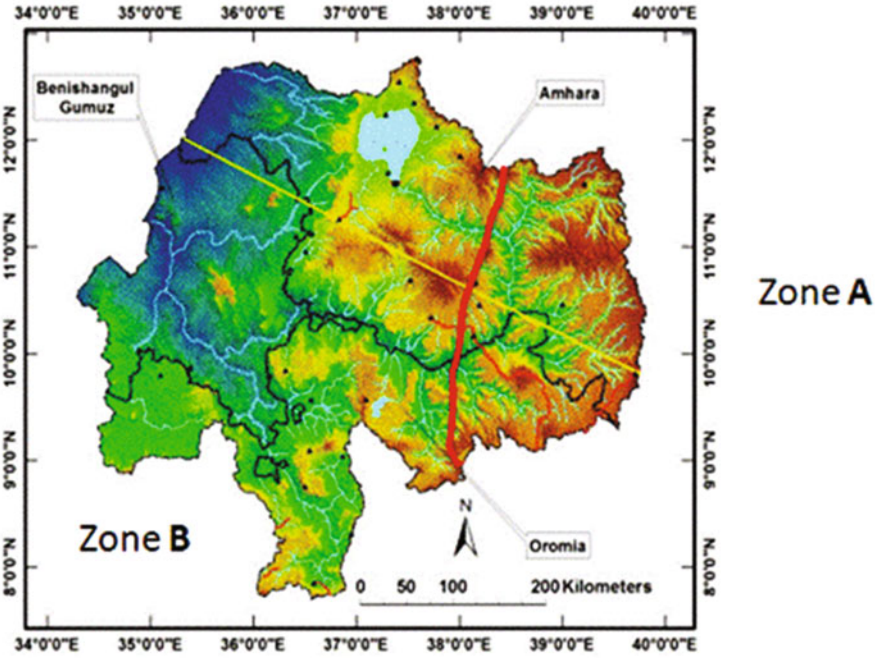


Fig. 17.2 Rainfall pattern zones in the Blue Nile River basin

(Fig. 17.1). The basin lies between 472 and 4,261 m.a.s.l. and has an average elevation of 2,358 m (± 1,084 m).

The basin is formed on a wide range of geologic formations. Based on the soil map of Ethiopia (based on the soil map by woody biomass study), 16 major soil units were identified. Nitisols are the most dominant soils in the area. The next most dominant major soil units are Cambisols and Vertisols with coverage of 23.63 and 16.51 %, respectively. The upper Blue Nile River basin has a varied land use/land cover with a proportion of 37.2 % for agriculture, 30.3 % for grassland and bushland, and 1.96 % for water bodies (Melesse et al. 2011).

17.2.2 Rainfall Zones in the Basin

Based on the classification given by the National Meteorological Service Agency (NMSA 1996; Fig. 17.2), the basin is divided into two rainfall pattern zones: Zone A (the eastern half with a bimodal rainfall pattern) and Zone B (the western half with a unimodal rainfall pattern). This classification was found to be superior over FAO's (1984) classification as it was more recent and there were not many variations in the rainfall pattern zones for the basin given by both studies made by the respective organizations.

Table 17.2 Geographical description of the study sites. (Source: National Meteorological Service Agency and SCRP)

No.	Station	Rainfall zone	Lat. (N) (°′)	Long. (E) (°′)	Altitude (m.a.s.l.)	# of years of data used
1	Alem Ketema	A	10 02	39 02	2,280	8
2	Andit Tid	A	09 48	39 43	3,060	6
3	Debre Birhan	A	09 38	39 35	2,750	10
4	Maybar	A	11 00	39 33	2,530	6
5	Nefas Mewcha	A	11 44	38 27	3,000	9
6	Sirinka	A	11 33	39 37	1,874	10
7	Bahir Dar	B	11 36	37 25	1,770	8
8	Dangila	B	11 07	36 25	2,128	6
9	Debre Markos	B	10 20	37 40	2,515	8
10	Gonder	B	12 33	37 25	1,967	8

17.2.3 Experimental Materials and Data Collection

Autographic rainfall data for eight stations in the basin were obtained from NMSA. Additional autographic data from two research stations were obtained from the former SCRP Office. The raw data were collected from the two stations located at research stations believed to represent the highland areas of the basin. The eight principal meteorological stations, out of the 31 principal stations, equipped with self-recording rain gauges were selected for the analysis based on availability of data and distribution over the basin. Due to non-availability of long period record for all the stations within the study area, it was decided to use a 10-year record for the computation of erosivity values; however, less than 10 years' data were used for some of the stations where autographic rainfall data was available for less than 10 years. In some cases, the 5-year moving average method was used to estimate the missing monthly rainfall data for the stations. A brief geographical description of the study sites is given in Table 17.2.

17.2.4 Homogeneity Test

The rainfall data were tested for homogeneity using Bartlett's test (Zar 1999), and the same method was used to evaluate the homogeneity of the variance for the data that were obtained from different meteorological stations. The test statistics for this analysis for samples having unequal degrees of freedom was used. The formula given by Gomez (1984) was used for this test:

$$X^2 = \frac{2.3026\ [(A)(\log {s_p}^2) - C]}{1 + \left[\frac{1}{3(k-1)(D-\frac{1}{A})}\right]}, \tag{17.1}$$

where $A=\sum_{i=1}^{k} f_i$, $B=\sum_{i=1}^{k} (f_i)(s_i^2)$, $C=\sum_{i=1}^{k} (f_f)(\log s_i^2)$, $D=\sum_{i=1}^{k} \frac{1}{f_i}$, s_p^2 is pooled variance given by $s_p^2 = \frac{B}{A}$, f_i = degree of freedom for each variance, K = the number of samples (isolates) in the analysis, and s_i^2 is the variance in each isolate.

17.2.5 Data Analysis

The original numerical data converted from the graphical data obtained from NMSA and SCRP were encoded and fed into the computer. The preliminary data arrangements and the necessary calculations for the computation of rainfall energy and erosivity values were also carried out using Excel.

In addition to the above, prediction of the rainfall erosivity using the daily, monthly, seasonal, and annual rainfall amounts obtained from the selected stations was done. Moreover, annual rainfall amounts obtained from stations with non-recording type of rain gauges were used to predict annual erosivity so as to see the distribution of erosivity throughout the basin. Regression analysis was done and linear, logarithmic, quadratic, power, and exponential regression models were employed, and the best-fitting relations with the highest R^2 values were selected.

17.2.5.1 Computation of Erosivity (R) Factor

The erosivity factor is the sum of all individual storm erosivity values over a given period of time (Eqs. 17.2 and 17.3). Storms of less than 12.5 mm rainfall amount, separated from other rain periods by more than 6 h, were not included in the computation, unless as much as 6.35 mm of rain falls in 15 min (Wischmeier and Smith 1978):

$$R = \sum_{j=1}^{n} (EI)j. \tag{17.2}$$

The following relation gives the equation for the storm energy (E):

$$E = \sum_{0}^{d} e.i.dt, \tag{17.3}$$

where e is for rainfall energy per unit of rainfall, i is the rainfall intensity for that time dt, and d is the rainfall duration for the given storm.

In computing the erosivity of an erosive rainfall event, the slopes of rainfall lines that are different at different time intervals were identified from the pluviographical data, and this information was then transferred to a tabular form taking the starting and ending time of each slope class with the corresponding rainfall amounts. Then, the rainfall intensity (I, mm/h) was calculated as a ratio of a particular increment of rainfall amount (mm) to that particular duration of the increment (h).

The unit kinetic energy (e) of the duration storm was calculated using Eq. 17.4, and the total energy of a storm (E) was calculated by summing the unit kinetic energy (e) values in a rainfall event (Eq. 17.3):

$$e = 0.29(1 - .596\exp(-.04I))(\mathrm{J/m^2} \times \mathrm{m}) \quad I \leq 76\ \mathrm{mm/h} \tag{17.4}$$

$$e = 0.283\ (\mathrm{J/m^2} \times \mathrm{m}) \quad I > 76\ \mathrm{mm/h}. \tag{17.5}$$

The event erosivity factor was then determined by the relationship given in Eq. (17.6):

$$R = E \times I_{30}, \tag{17.6}$$

where I_{30} is maximum 30-min intensity.

The maximum 30-min intensity (I_{30}, in mm/h), which is defined as twice the greatest amount of rain falling in any 30-min period of a rainstorm, was obtained by breaking the rainfall hyetograph into periods of constant intensity (Wischmeier and Smith 1978) and as a maximum summation of rainfall during any consecutive 30 min. When the duration of the erosive storm is less than 30 min, I_{30} was taken as twice the amount of rain (Krauer 1988). In order to obtain daily, monthly, and yearly erosivity index (EI) values, the storm EI values for that length of period were added. In times when a storm begins on the last day of a month and terminates on the second, the EI_{30} value for the storm was divided into individual months in proportion to the amount of rainfall in that month (Yu 1998). Similarly, the same approach was used to obtain EI values in a day.

17.2.5.2 Erosivity Modeling

As stated by Mikhailova et al. (1997), regression equation may not be appropriate for estimating the erosivity factor (R) values for those stations with different monthly rainfall distribution. Therefore, rainfall pattern zones of the region were identified according to NMSA (1996) in order to get a more accurate relation for the estimation of the R factor.

To establish a relationship between rainfall and erosivity, annual, seasonal, monthly, and daily erosivity indexes (EI_{30} values) were plotted against annual, seasonal, monthly, and daily rainfall amounts, respectively, for the selected stations in the study area using MS Excel. Linear ($Y = ax + b$), quadratic ($Y = a + bx + cx^2$), logarithmic ($Y = a + b\ln x$), exponential ($Y = ae^{bx}$), and power ($Y = ax^b$) curve fitting relations were considered as candidate models as indicated by Taffa (2003), and the best-fitting curve was selected based on the highest coefficient of determination (R^2), the smaller standard error of estimates (SE), and residual mean squares (RMS). Then, based on the type of regression equation selected, the values of constants "*a*," "*b*," and "*c*" were estimated for the equation relating erosivity and rainfall. In doing these, the intensity was processed to give rainfall amount and erosivity, and then 4–8-year data for the 12 stations were used to develop the relation. The types of relationship between variables were observed, and regression analysis was performed to develop the equations.

17.2.5.3 Model Validation

The remaining 2-year data of each rainfall station, other than the data used for the model development, were used for validation by comparing the predicted value

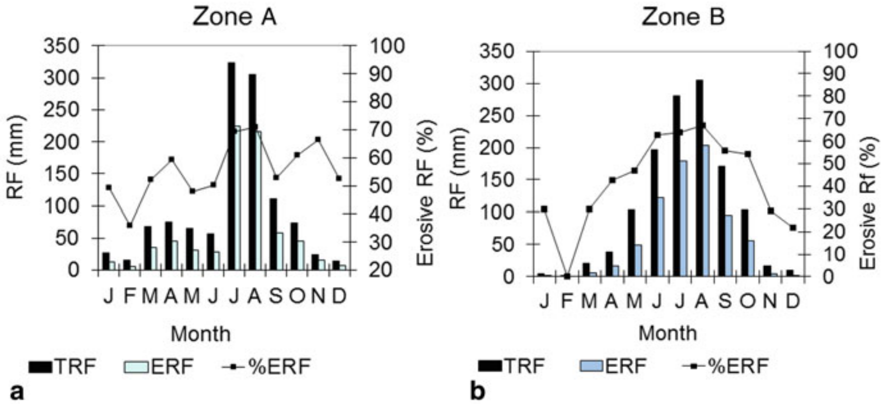


Fig. 17.3 Total monthly rainfall (*TRF,* mm), erosive rainfall (*ERF,* mm), and % of erosive rainfall for the two rainfall zones. **a** Zone A. **b** Zone B

of the erosivity and the computed value of erosivity, by using R^2 (coefficient of determination) and model efficiency (ME). The ME, according to Nash and Sutcliffe (1971), was calculated using the equation:

$$\text{For the model efficiency, ME} = \frac{\sum_{i=1}^{N}(R_i - R_a)^2 - \sum_{i=1}^{N}(S_i - R_i)^2}{\sum_{i=1}^{N}(R_i - R_a)^2}, \tag{17.7}$$

where R_i is the ith item in the recorded (measured, in this case, computed) value, S_i is the ith item in the simulated (predicted or estimated) value, and R_a is the mean of recorded values for number of data points, N.

17.3 Result and Discussion

17.3.1 Rainfall Zones and Homogeneity Test

The eastern part of the basin (Zone A) is represented by Alem Ketema, Andit Tid, Debre Birhan, Maybar, Nefas Mewcha, and Sirinka meteorological stations and has two rainy periods (from June to September/November and from February/March to May), while having the dry period to occur in the rest of the months. The western part of the basin (Zone B) is represented by Bahir Dar, Dangila, Debre Markos, and Gonder meteorological stations and is known to have one peak rainy season, the length decreasing towards the north and eastern parts of the zone, and the rainy period ranged from February/March to November (Figs. 17.3 and 17.4). The values

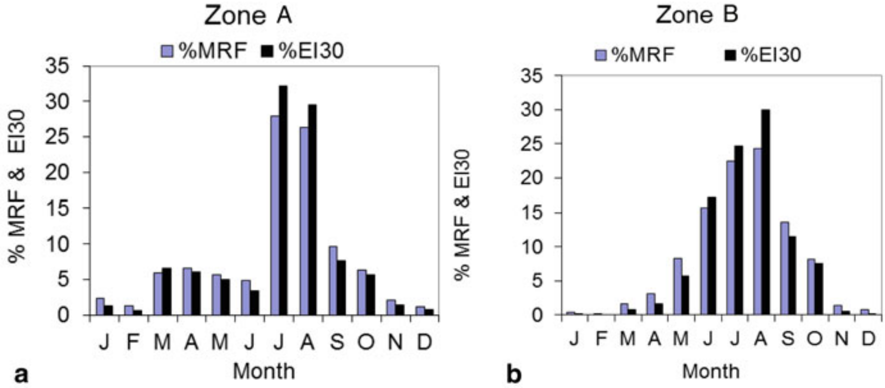


Fig. 17.4 Distribution of monthly rainfall (*MRF*) and rainfall erosivity for the rainfall zones. **a** Zone A. **b** Zone B

Table 17.3 Seasonal distributions of rainfall and erosive rainfall for the rainfall zones

Season	% Rainfall		% Erosive rainfall	
	Zone A	Zone B	Zone A	Zone B
Kiremt (June to Sept.)	68.68	76.08	72.65	81.58
Bega (Oct. to Jan.)	11.92	10.73	11.19	8.70
Belg (Feb. to May)	19.40	13.19	16.16	9.72
Total	*100*	*100*	*100*	*100*

of χ^2 for homogeneity of variances for annual rainfall amounts of the two rainfall zones were calculated. As a result, these values were 8.22 and 8.21 for zones A and B, respectively, where both values were found to be significant at 5 % probability level. From the values of the homogeneity test, it could be concluded that the data from each station represented their respective pattern zones.

Figure 17.3 also shows the monthly distribution of total and erosive rainfall for the two rainfall zones of the basin constructed using 6–10 years of data series. Under both conditions, July and August are found to be the best contributors to the total annual rainfall. It was also observed that the amount of the erosive rainfall increased with increasing percentage to the total monthly rainfall with the exceptions of the months of October and November for Zone A and January in the case of Zone B. This variation could be the result of high intensity of the rainfall in these particular months.

Taking the different seasons into consideration, *Kiremt* (June to September) rainfalls, in both rainfall zones, contributed the highest amount to the total annual rainfall and erosive rainfall (Table 17.3). *Kiremt* rainfall contributed 72.65 and 81.58 % of the total erosive rainfall in Zone A and Zone B, respectively. In Zone A, a considerable percentage of the total erosive rainfall occurs in *Belg*, as well.

17.3.2 Rainfall Erosivity Values

17.3.2.1 Monthly, Seasonal, and Annual Erosivity Values

In order to compute erosivity values of any timescale, storm erosivity values were computed, and daily, monthly, seasonal, and annual erosivity values were obtained by summing up storm (event) erosivity value within the day, month, season, and year. It is not possible to present daily rainfall erosivity values for the stations under study due to the volume of the information and, therefore, Table 17.4 summarizes monthly, seasonal, and annual erosivity values for the 12 meteorological stations within the study area. It was observed during the analysis and computation that daily rainfall erosivity was highly variable in the basin that as high as 2,288.91 MJ-mm/ha·h·day of erosivity value from 76.4 mm of rainfall, but a value of 234.8 MJ-mm/ha·h·day from a daily rainfall amount of 102.1 mm and as high as 234.78 MJ-mm/ha·h·day of erosivity value from 10.6 mm of rainfall, but a value of 3.9 MJ-mm/ha·h·day from a daily rainfall amount of 16.5 mm were recorded.

Considering the distribution of monthly rainfall erosivity, the total rainfall for July and August contributed the highest erosivity in addition to the highest contribution to the total rainfall (Table 17.4). According to the classification of rainfall zones given by NMSA (1996), in Zone A, where the smaller rains in *Belg* (February to May) and major rains in *Kiremt* took place, less than 24.19 % of the total rainfall occurred during *Belg* and more than 62.83 % of the total mean annual rainfall erosivity occurred during the *Kiremt* season. In Zone B, there was only one rainy season whose length decreased from the southwest part of the study area to the north and to the east, and more than 75.35 % of the total mean annual rainfall erosivity occurred during the *Kiremt* (June to September) season. It could be observed from Table 17.3 that the mean annual erosivity varied considerably across the study area. Accordingly, the highest mean annual rainfall erosivity value of 7,209 MJ-mm/ha·h·year was computed at Andit Tid (Zone A). The lowest mean annual rainfall erosivity value of 1,738 MJ-mm/ha·h·year was estimated at Debre Birhan in the same rainfall zone of the study area. In Zone B, the maximum rainfall erosivity value of 4,115 MJ-mm/ha·h·year was estimated for Dangila, and the lowest mean rainfall erosivity value of 1,783 MJ-mm/ha·h·year was recorded at Metema.

Figure 17.4 illustrates the distribution and pattern of mean monthly rainfall and rainfall erosivity for the two rainfall zones in the Amhara Region, and it can be observed from the figure that the value of rainfall erosivity increased with the amount of rainfall.

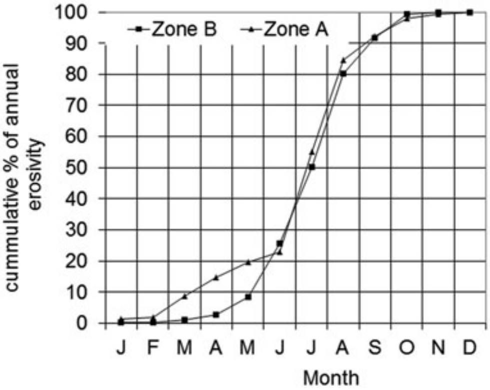
17.3.2.2 Monthly Erosion-Index Distribution Curves

The annual erosion index values do not completely describe the differences in rainfall erosion potential during different months of the year. The mean monthly erosion index values were expressed as percentage of average of annual values and plotted cumulatively against time. The distribution curves for the various stations in rainfall

Table 17.4 Mean monthly, seasonal, and annual rainfall erosivity (MJ-mm/ha·h·year) of the two rainfall zones in the basin

Month	Zone A						Zone B			
	Alem Ketema	Andit Tid	Debre Birhan	Maybar	Nefas Mewcha	Sirinka	Bahir Dar	Dangila	Debre Markos	Gonder
Jan	4.89	10.38	3.42	198.18	7.56	48.81	0	0	37.67	0
Feb	32.32	10.52	0	41.46	2.64	20.03	0	0	0	0
Mar	77.31	375.77	72.59	724.7	85.79	242.87	26.96	30.41	50.83	5.46
Apr	304.3	181.31	86.23	196.1	141.23	211	52.9	48.15	131.92	29.43
May	143.9	41.90	23.3	338.71	75.1	60.46	32.09	267.2	266.75	192.05
June	228.4	208.17	73.38	142.24	118.76	49.5	777.68	630.9	369.55	611.12
July	564.9	2,154.6	806.1	1,807.82	1,138.4	602.12	1,076.48	787.8	580	1,372.17
Aug	923.7	2,300.80	482.5	1,236.3	845.6	810.47	386.46	256.76	941.27	1,114.6
Sep	289.8	727.28	116.64	258.9	161.5	161.7	393.11	622.79	399.25	236.34
Oct	59.75	637.32	45.41	270.1	118.3	238.18	210.89	435.73	205.41	341.9
Nov	12.63	138.42	28.41	47.08	35.42	55.92	16.45	35.29	29.18	2.7
Dec	0	22.47	0	59.29	2.82	83.42	0	0	27.44	4.3
Annual	*2,641.9*	*7,208.91*	*1,737.9*	*5,320.9*	*2,733.1*	*2,584.48*	*4,073.02*	*4,115.03*	*3,039.27*	*3,910.16*
Kiremt	2,006.8	5,390.82	1,478.6	3,445.3	2,264.25	623.79	3,633.73	3,298.25	2,290.07	3,334.23
% total	*75.96*	*74.78*	*85.08*	*64.75*	*82.84*	*62.83*	*89.21*	*80.15*	*75.35*	*85.27*
Bega	77.27	808.59	77.24	574.69	164.12	426.33	227.34	471.02	299.7	348.9
% total	*2.9*	*11.22*	*4.44*	*10.80*	*6.00*	*16.49*	*5.58*	*11.45*	*9.86*	*8.93*
Belg	557.8	1,009.50	182.2	962.3	304.7	534.3	211.9	345.76	449.5	226.9
% total	*21.11*	*14.00*	*10.48*	*18.08*	*11.20*	*20.68*	*5.20*	*8.40*	*14.79*	*5.80*

Fig. 17.5 Mean monthly rainfall erosion index distribution curve for the rainfall zones



Zone A exhibited that there was some amount of rainfall erosivity during shorter rainy season (*Belg*) and, therefore, had little difference from the distribution curves for the stations in Zone B. This difference in the pattern of the distribution curves for the rainfall zones is shown in Fig. 17.5.

17.3.3 Relationship Between Rainfall and Erosivity for Selected Meteorological Stations

17.3.3.1 Daily Rainfall and Erosivity

The regression equations developed for the meteorological stations under study on a daily basis were compared, and the best fitting curve was selected based on the highest coefficient of determination (R^2), the smaller standard error of estimates (SE), and RMS. The selected equations for the corresponding stations are summarized in Table 17.5. The lowest coefficient of determination (0.51) was noted at Nefas Mewcha, and the value of highest coefficient of determination (0.67) was recorded

Table 17.5 Summary of daily erosivity prediction equations for the selected stations

Station	Equation	R^2	SE	RMS
Alem Ketema	$R_d = 0.0468\,(P_d)^2 + 4.68\,P_d - 32.68$	0.58	46.79	2,989.82
Andit Tid	$R_d = 0.7013\,(P_d)^{1.5592}$	0.65	0.52	0.27
Bahir Dar	$R_d = 0.104\,(P_d)^2 + 0.589\,P_d + 22.76$	0.60	69.78	4,869.58
Dangila	$R_d = 0.039\,(P_d)^2 + 5.3\,P_d - 33.203$	0.58	48.23	2,383.96
Debre Birhan	$R_d = 0.0087\,(P_d)^2 + 0.53\,P_d + 12.39$	0.59	35.72	1,275.69
Debre Markos	$R_d = 11.64\,P_d - 144.87$	0.67	97.24	9,554.9
Gonder	$R_d = 23.97e^{0.0501\mathrm{Pd}}$	0.58	0.63	0.39
Maybar	$R_d = 0.51\,(P_d)^{1.648}$	0.57	0.63	0.40
Nefas Mewcha	$R_d = 0.556\,(P_d)^{1.5863}$	0.51	0.62	0.38
Sirinka	$R_d = 0.00363\,(P_d)^2 + 8.754\,P_d - 76.2$	0.59	58.78	3,431.45

R_d daily rainfall erosivity (MJ-mm/ha·h·day), P_d daily rainfall amount (mm)

Table 17.6 Summary of monthly rainfall erosivity prediction equations for the selected meteorological stations

Station	Equation	R^2	SE	RMS
Alem Ketema	$R_m = 2.6072\, P_m - 39.517$	0.74	139.55	9,468.33
Andit Tid	$R_m = 0.1485\,(P_m)^{1.5763}$	0.92	0.45	0.20
Bahir Dar	$R_m = 0.0061\,(P_m)^2 + 0.673\, P_m + 52.72$	0.89	180.20	32,473.00
Dangila	$R_m = 0.0022\,(P_m)^2 + 2.46\, P_m - 60.26$	0.78	193.85	37,578.40
Debre Birhan	$R_m = 0.0047\,(P_m)^2 + 1.12\, P_m + 15.37$	0.90	111.59	12,451.30
Debre Markos	$R_m = 0.0067\,(P_m)^2 + 0.9734\, \mathrm{P_m} - 0.5023$	0.83	156.55	24,495.62
Gonder	$R_m = 0.0061\,(P_m)^2 + 0.73\, P_m + 38.7$	0.87	135.59	18,383.26
Maybar	$R_m = 0.0044\,(P_m)^2 + 2.76\, P_m + 43.84$	0.88	312.73	97,800.74
Nefas Mewcha	$R_m = 0.308\,(P_m)^{1.384}$	0.85	0.51	0.26
Sirinka	$R_m = 0.0018\,(P_m)^2 + 2.68\, P_m - 47.42$	0.84	135.64	18,388.32

R_m monthly rainfall erosivity (MJ-mm/ha·h·month) $\mathrm{P_m}$ monthly rainfall amount (mm), *RMS* root mean square, *SE* standard error

at Debre Markos. These values were considered to be lower, when compared to the values of R^2 (0.63–0.70) obtained from six stations in the Southern Nations, Nationalities, and Peoples' Region (SNNPRS) by Habtu (2004), Elsenber et al. (1993) with R^2 value of 0.71, and Mannerts and Gabriels (2000) with R^2 value of 0.90. Krauer (1988) also showed that there was poor relationship between daily rainstorm and the corresponding amount of daily erosivity (R^2 ranging from 0.42 at Hundelafto (Hararge) to 0.55 at Andit Tid) using 4 years of data from former SCRP stations at the national scale. Generally, the values of R^2 for this study showed the existence of a poor relationship between daily rainfall amount and the corresponding daily erosivity. This could be as a result of the very erratic nature of the rainfall event in the basin.

17.3.3.2 Monthly Rainfall and Erosivity

Various regression equations were developed for the prediction of monthly rainfall erosivity from monthly rainfall amounts. Then, the best fitting curve was selected following the same method described earlier. The lowest coefficient of determination ($R^2 = 0.74$) was recorded for the station at Alem Ketema, whereas for the other stations under study, the coefficients of determinations were found to be more than 0.78 (Table 17.6). Most of these R^2 values were found to be higher than those obtained by Habtu (2004) (0.65–0.80) for different stations in SNNPRS and close to that of Zelalem (2007) (0.71–0.90) for different stations in the Oromiya Region. Quadratic-type rainfall erosivity predictive equations were selected for all the stations except Andit Tid and Nefas Mewcha where power-type equations were selected and Alem Ketema where linear type of equation was selected.

17.3.3.3 Annual Rainfall and Erosivity

Using the collected and manipulated data, various regression equations were developed to relate annual rainfall amount with annual rainfall erosivity, and the best

Table 17.7 Summary of annual rainfall-predicting equations for the selected meteorological stations

Station	Equation	R^2	SE	RMS
Alem Ketema	$R_a = 119.74e^{0.003\mathrm{P}}$	0.88	0.14	0.02
Andit Tid	$R_a = 0.0003\,(P_a)^{2.2799}$	0.90	0.09	0.01
Bahir Dar	$R_a = 151.61e^{0.0023\mathrm{P}}$	0.91	0.12	0.01
Dangila	$R_a = 251.8e^{0.0019Pa}$	0.97	0.13	0.02
Debre Birhan	$R_a = 92.68\,e^{0.0035Pa}$	0.89	0.14	0.02
Debre Markos	$R_a = -0.0058\,(P_a)^2 + 19.86\,P_a - 12{,}501$	0.94	335.29	112,422.98
Gonder	$R_a = 0.001\,(P_a)^2 + 0.964\,P_a - 23.512$	0.92	465.35	216,549.02
Maybar	$R_a = 5.809\,(P_a)^{0.9561}$	0.98	0.12	0.01
Nefas Mewcha	$R_a = 0.0077\mathrm{p}^2 - 11.69\,P_a + 6{,}137.4$	0.83	400.43	160,340.25
Sirinka	$R_a = 3{,}240.1\,\ln(P_a) - 19{,}877$	0.66	236.59	55,974.32

R_a annual rainfall erosivity (MJ-mm/ha·h·year) P_a annual rainfall amount (mm), RMS root mean square, SE standard error

models were selected using the already established criteria. Table 17.7 shows the summary of the selected equations. Higher R^2 values (> 0.82) were computed for all the stations except Sirinka ($R^2 = 0.66$). Most of the R^2values followed the same range of R^2 values, i.e., 0.71–0.99 obtained by Krauer (1988) at national scale and 0.64–0.99 for different stations in the Oromiya Region by Zelalem (2007). The R^2 values for the stations in Zone A were found to be relatively smaller as a result of the erratic and variable nature of the rainfall in this zone. Exponential-type relations were selected for Alem Ketema, Bahir Dar, Dangila, and Debre Birhan stations; logarithmic-type equation was selected for Sirinka station, quadratic-type equations were selected for Debre Markos, Gonder, and Nefas Mewcha stations, whereas power type of equations were selected for Andit Tid and Maybar stations. The regression equations developed for predicting the annual erosivity at each station varied considerably, and this showed that there was a variation in annual rainfall erosivity at different locations.

From the earlier discussions, it can be generalized that rainfall erosivity can be explained by annual regression equations better than monthly and daily regression equations, taking the values of the coefficient of determination of daily, monthly, and annual regression equations into consideration. This could be because the values of monthly rainfall and the corresponding erosivity values were added to give annual values, which may decrease the variability.

The time difference in the data used for the computation of erosivity at these timescales could contribute to the variation in the values of the coefficient of determination. In other words, R^2 values showed an increase with the timescale because, as the number of observation used in the analysis was decreased to lesser number of observations by summing the values at a shorter timescale, the variability between the observations decrease that resulted in a stronger association between the values of annual rainfall and annual rainfall erosivity.

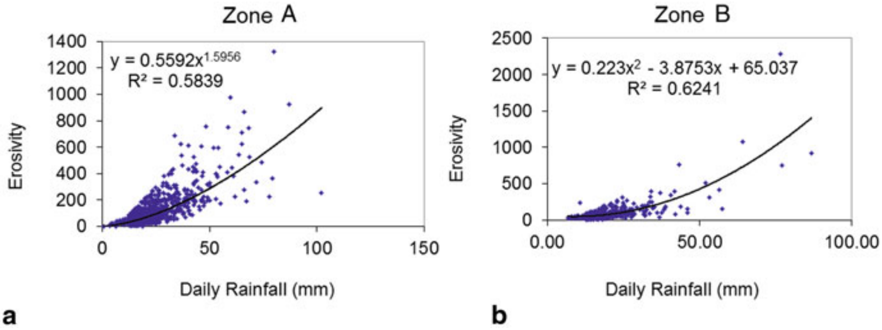


Fig. 17.6 Regression equations for predicting daily rainfall erosivity for the rainfall zones. **a** Zone A. **b** Zone B

17.3.4 Relationship Between Rainfall and Erosivity for the Rainfall Zones

17.3.4.1 Daily Rainfall and Erosivity

After testing the various regression equations based on the value of the coefficient of determination, the best equations relating daily rainfall amount and daily erosivity for the rainfall zones were selected. Scatter diagrams and the selected regression equations for this analysis are presented in Fig. 17.6 along with the best-fit lines. Power relationship for Zone A and quadratic relationship for Zone B were selected, but R^2 values for both of the rainfall zones show a poor relationship between daily rainfall amount and erosivity. Therefore, these equations cannot be used for erosivity prediction at this scale.

17.3.4.2 Monthly Rainfall and Erosivity

Various regression equations were developed for each rainfall pattern zone, and the best models were selected by comparing the R^2 values. Scatter diagrams and the selected regression equations of monthly rainfall verses the corresponding rainfall erosivity for the rainfall zones are presented in Fig. 17.7 along with the best-fit lines. Quadratic regression equations, for both zones, were established to predict the erosivity from the mean monthly rainfall. It was also observed that the models explain 83.55 and 85.81 % of rainfall erosivity in the rainfall zones A and B, respectively. These values were found to be very close to the corresponding values obtained for the Oromiya Region, which explained 75–90 % (Zelalem 2007). The R^2 values show that there exists a good relationship between mean monthly rainfall and its erosivity index for different rainfall zones of the upper Blue Nile River basin, and, therefore,

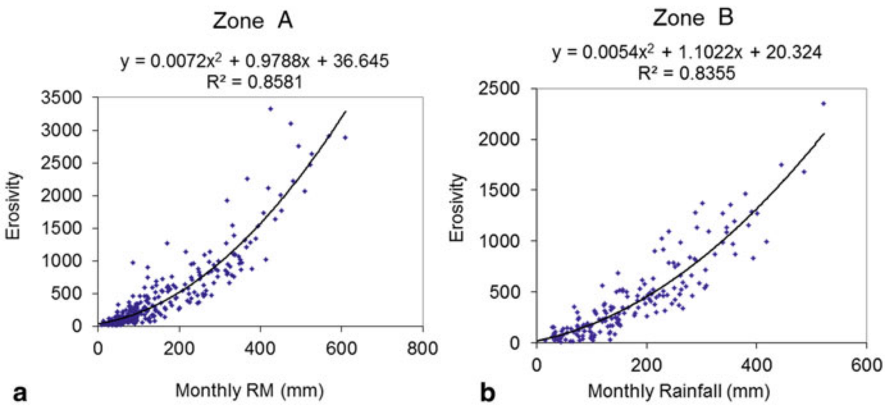


Fig. 17.7 Regression equations for predicting monthly rainfall erosivity for the two rainfall zones. **a** Zone A. **b** Zone B

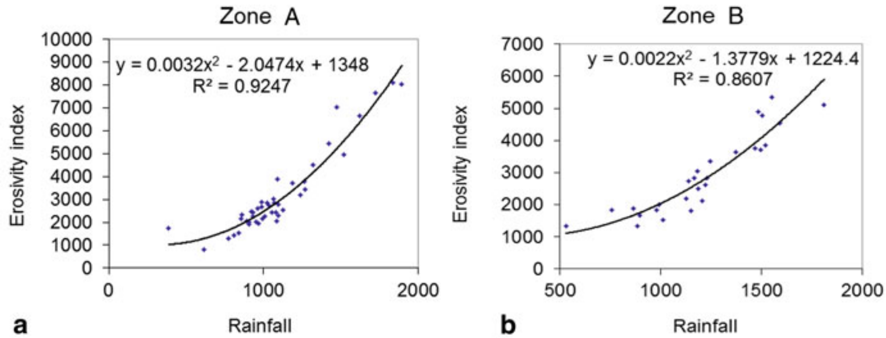


Fig. 17.8 Regression equations for predicting annual rainfall erosivity for the rainfall zones. **a)** Zone A. **b)** Zone B

these models could be used as good predictors or decision support tools in designing future soil conservation strategies.

17.3.4.3 Annual Rainfall and Erosivity

Various regression equations were developed based on the values of annual rainfall and erosivity for the two rainfall zones, and the best models were selected based on the values of already established criteria. Figure 17.8 exhibits the selected regression equations, scatter diagrams of the annual rainfall amounts against the corresponding erosivity values for the two zones along with the best-fit line.

Quadratic regression equations were established for both of the zones to predict the annual rainfall erosivity from the mean annual rainfall. It was noted that the models explained 92.47 and 86.07 % of the rainfall erosivity values for the zones A and B, respectively. These values were found to be very close to the values (90 and 87 %) obtained for the corresponding rainfall zones in the Oromiya Region (Zelalem 2007). From the regression analysis, there exists a very good relationship between mean annual rainfall and its erosivity indexes for the two rainfall zones. Therefore, these regression models may be considered to be good prediction tools for annual rainfall erosivity in each of the rainfall zones.

Here again, it can be noted that the regression equations developed for predicting erosivity values at different timescales for the rainfall zones varied considerably. Taking the values of the coefficient of determination of daily, monthly, and annual regression equations into consideration, one can conclude that rainfall erosivity can be explained by annual regression equations. This could be because the values of monthly rainfall and the corresponding erosivity values were added to give annual values, which may decrease the variability. Generally, the time difference in the data used for the computation of erosivity at these timescales could contribute to the variation in the values of the coefficient of determination. In other words, R^2 values showed an increase with the timescale because, as the number of observations used in the analysis was decreased to lesser number by summing the values at a shorter timescale, the variability between the observations was found in a decreasing trend that resulted in a stronger association between the values of annual rainfall and annual rainfall erosivity.

17.3.5 Relationship Between Rainfall and Erosivity at Basin Scale

The result of the regression analysis for the basin as a whole showed a good relationship between rainfall and erosivity for the monthly and annual relationships but showed a very poor relationship at a daily scale with R^2 value of 0.55 which was expressed by a quadratic relationship. The functional relationships between the combined (aggregated) monthly and annual rainfall and their erosivity values for the whole basin were noted to be of quadratic type with R^2 values of 0.84 in both of the cases (Fig. 17.9). These values were found to be higher than the monthly and annual R^2 values obtained for SNNPRS (0.60 and 0.72, respectively) as reported by Habtu (2004) and for the Oromiya Region (0.78 and 0.82, respectively) as reported by Zelalem (2007). Moreover, the R^2 value of the relationship between annual rainfall and erosivity obtained for the basin was also found to be higher than the value reported by Krauer (1988) (0.79). From these R^2 values, one can say that there exists a very good relationship between mean monthly and annual rainfall and their erosivity values for the basin as a whole. Hence, these regression equations can be considered as reasonable prediction tools of rainfall erosivity values of the basin as they were selected by having higher R^2 values than other forms of regression equations.

Fig. 17.9 Relationship between daily, monthly, and annual rainfall amounts (mm) and their erosivity for the upper Blue Nile River basin. **a** Daily. **b** Monthly. **c** Annual

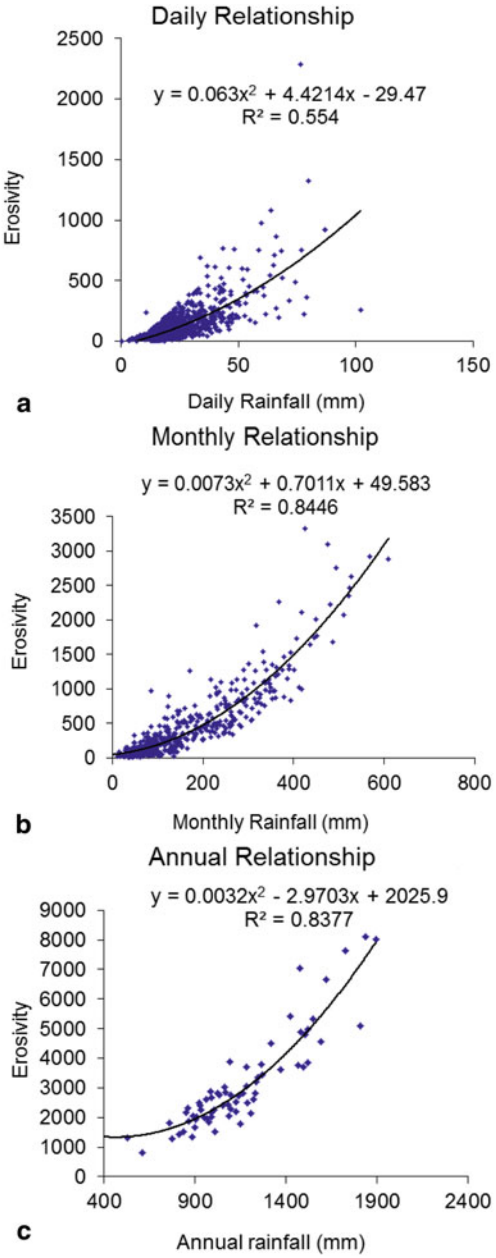


Table 17.8 Validation results of monthly rainfall erosivity equations for the selected stations

Rainfall zone	Station	*n*	*r*	ME
A	Alem Ketema	15	0.91	0.76
	Andit Tid	19	0.92	0.83
	Debre Birhan	14	0.92	0.70
	Maybar	18	0.75	0.56
	Nefas Mewcha	14	0.97	0.93
	Sirinka	15	0.77	0.56
B	Bahir Dar	14	0.98	0.90
	Dangila	14	0.89	0.64
	Debre Markos	14	0.94	0.84
	Gonder	13	0.95	0.77

n the number of observations used for the purpose of validation

17.3.6 Model Validation for the Selected Stations

17.3.6.1 Monthly Rainfall Erosivity Prediction Models

Two-year data not used for the model development were employed for model validation. The correlation coefficients calculated between computed and predicted monthly rainfall erosivity values ranged from 0.73 to 0.98 for all stations (Table 17.8). This indicates that there is a strong and linear association between the computed and estimated values of rainfall erosivity. But, despite the higher values of *r*, the MEs, particularly for Maybar and Sirinka, were found to be less than 60 %. For the other stations, the ME varied from 64 to 97 %, and this implies that the models are efficient in predicting rainfall erosivity for the particular stations under consideration, as ME is the important measure of the ability of a model than the *r* value.

17.3.6.2 Annual Rainfall Erosivity Prediction Models

Maximum deviation between the computed and predicted annual rainfall erosivity values estimated using the predicting equation for the stations are presented in Table 17.9. As presented in the same table, underestimation of rainfall erosivities varied from 538 to 3,240 MJ-mm/ha·h·year (8–47 %), and the overestimation ranged from 275 to 1,693 MJ-mm/ha·h·year (8–45 %).

17.3.7 Model Validation for the Rainfall Zones and the Basin as a Whole

17.3.7.1 Monthly Rainfall Erosivity Prediction Model Validation for the Zones

The correlation coefficients between computed and predicted monthly erosivities for the rainfall zones were estimated to be 0.72 and 0.95 for Zone A and Zone B,

Table 17.9 Summary of maximum deviation between computed and predicted erosivity using regression equations developed for the selected meteorological stations

Stations	Underestimation	Underestimation (%)	Overestimation	Overestimation (%)
Alem Ketema	–	–	1,692.59	43.50
Andit Tid	1,932.94	27.80	–	–
Debre Birhan	–	–	294.24	21.80
Maybar	538.15	7.50	1,567.18	40.20
Nefas Mewcha	619.04	20.10	284.57	13.70
Sirinka	681.53	24.60	310.16	14.30
Bahir Dar	1,591.53	25.20	992.21	21.80
Dangila	–	–	1,349.98	17.10
Debre Markos	–	–	704.94	22.90
Gonder	3,240.27	46.50	–	–
Min	*538.15*	*7.50*	*274.82*	*8.30*
Max	*3,240.27*	*46.50*	*1,692.59*	*43.50*
Mean	*1,307.03*	*25.21*	*778.25*	*22.34*

Table 17.10 Validation results of monthly rainfall erosivity prediction models for the rainfall zones and the basin as a whole

Rainfall zone	*n*	*r*	ME
A	112	0.72	0.73
B	66	0.95	0.82
Basin-wide	178	0.90	0.85

respectively (Table 17.10). Both the *r* and ME values showed that these regression models could be used satisfactorily for the prediction of monthly rainfall erosivities for respective rainfall pattern zones. Moreover, the distribution pattern of predicted erosivity in relation to computed erosivity is shown in Fig 17.10. From the figure, it can be seen that under both of the rainfall zones, the predicted and the computed erosivity are clustered close to the one-to-one line and in both of the conditions, but more underpredicted and scattered values were observed for erosivity values greater than about 1,500 MJ-mm/ha·h·month.

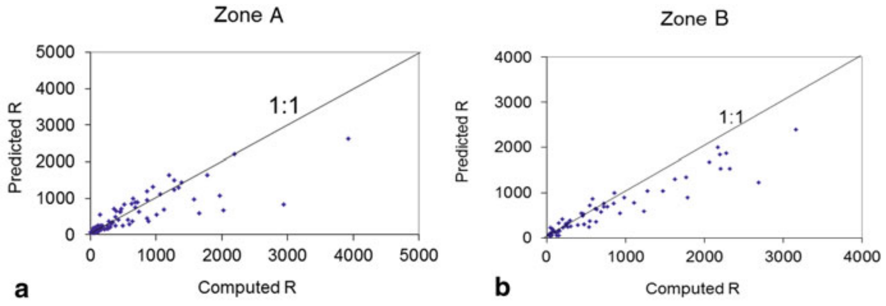


Fig. 17.10 Distribution pattern of the monthly predicted rainfall erosivity to the computed rainfall erosivity for the rainfall zones. **a** Zone A. **b** Zone B

Table 17.11 Validation results of annual rainfall erosivity prediction models for the rainfall zones and the basin

Rainfall zone	*n*	*r*	ME
A	14	0.97	0.89
B	10	0.89	0.65
Basin-wide	24	0.91	0.80

17.3.7.2 Monthly Rainfall Erosivity Prediction Model Validation for the Basin

As presented in Table 17.10, the correlation between the computed and predicted erosivity values is 0.90 for the whole basin, and this shows a strong association between the computed and predicted values of rainfall erosivity. The ME value of 0.85 computed at the basin scale was also found to be higher than the MEs for the rainfall zones A and B.

17.3.7.3 Annual Rainfall Erosivity Prediction Model Validation for the Zones

The results of the correlation analyses between the computed and predicted annual rainfall erosivity for the rainfall zones were found to be 0.97 and 0.89 with the corresponding MEs of 0.89 and 0.65 for Zone A and Zone B, respectively (Table 17.11). The correlation between the computed and predicted annual erosivity values is 0.91, and it shows a strong association between the computed and predicted values of annual rainfall erosivity.

17.3.7.4 Annual Rainfall Erosivity Prediction Model Validation for the Basin

As presented in Table 17.11, the ME for the study area as a whole (0.80) was also found to be higher than the ME for rainfall Zone B (0.65) but lower than the ME for rainfall Zone A (0.89).

17.3.8 Distribution Patterns of Mean Monthly Rainfall Erosivity Values for the Rainfall Zones and the Basin

Figure 17.11 illustrates the mean monthly computed and predicted rainfall erosivity for the rainfall zones and for the basin as a whole. In all of the cases, the mean monthly predicted rainfall erosivity matches the mean monthly computed rainfall erosivity values. Moreover, the annual regression equation developed to predict annual rainfall erosivity for the basin as a whole was compared with the regression equations given by Krauer (1988), Habtu (2004), Zelalem (2007), and the computed

Table 17.12 Values of predicted mean annual rainfall erosivity and computed mean annual erosivity values. (Wischmeier and Smith 1978)

Station	Mean annual rainfall (mm)	Mean annual erosivity (MJ-mm/ha·h·year)				
		Wischmeier and Smith	Krauer	Habtu	Zelalem	Tewodros
Alem Ketema	1,038.93	2,637.51	3,771.10	4,073.67	2,439.04	2,393.97
Andit Tid	1,694.47	7,208.93	6,936.05	8,112.90	3,985.46	6,180.75
Bahir Dar	1,410.06	4,071.79	5,562.92	6,263.24	3,314.54	4,200.06
Dangila	1,435.48	4,115.01	5,685.65	6,422.84	3,374.50	4,356.02
Debre Birhan	828.27	1,733.82	2,754.04	2,960.67	1,942.09	1,760.99
Debre Markos	1,299.65	3,155.97	5,029.86	5,583.80	3,054.08	3,570.64
Gonder	1,327.67	3,910.18	5,165.14	5,754.08	3,120.18	3,722.99
Maybar	1,295.27	5,320.98	5,008.71	5,557.31	3,043.75	3,547.28
Nefas Mewcha	1,086.49	2,577.55	4,000.72	4,338.73	2,551.23	2,576.17
Sirinka	1,015.63	2,590.27	3,658.61	3,945.60	2,384.05	2,309.99

erosivity value according to Wischmeier and Smith (1978). Table 17.12 shows the computed (Wischmeier and Smith 1978) and predicted mean annual rainfall erosivity values using regression equations developed for this study (referred to as Tewodros in Table 17.12 and Fig. 17.10), for SNNPRS and Oromiya regions and for the country as a whole (Krauer's equation).

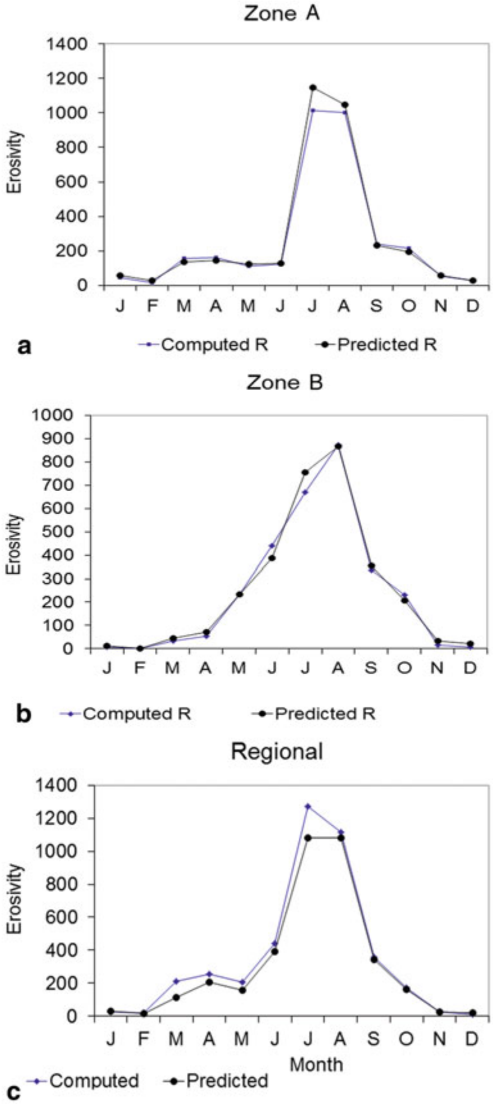
Erosivity values predicted using the Krauer (1988) and Habtu (2004) equations were found to be higher than values predicted using the equation developed for the upper Blue Nile River basin (Fig. 17.12). This could be because Krauer developed the regression equations for Ethiopia based on the data from only seven stations scattered all over the country, which may result in a less efficient model, and Habtu (2004) developed the regression equation based on the data from SNNPRS, which is located in the southwestern part of the country and known to have different rainfall pattern and amount than the upper Blue Nile River basin. In many cases, as can be seen in Fig. 17.12, erosivity values predicted using the developed equation in this study and by Zelalem were found to be close to the computed values of erosivity using the method suggested by Wischmeier and Smith.

17.4 Summary

This study investigated the rainfall erosivity in the upper Blue Nile basin. The data from the selected meteorological stations were grouped into two rainfall pattern zones according to the classification by NMSA (1996), and regression equations were developed and they analyzed rainfall erosivity for rainfall zones and for the basin as a whole.

The main objective of the study was to generate information on rainfall erosivity that will help planning and implementation of practical soil and water conservation activities and to establish rainfall erosivity prediction equations that can be used

Fig. 17.11 Distribution pattern of mean monthly predicted against mean monthly computed rainfall erosivity values about the 1:1 line. **a** Zone A. **b** Zone B. **c** Zone C



within the basin's environmental conditions. For the development of these predictive equations, graphical data (1993–2002) from the NMSA for eight of the selected stations were collected, and processed data (1996–2004) for two of the former SCRP research stations were used in this study. The *Kiremt* season (June to September) is the main rainy season in both of the rainfall zones of the basin although rainfall Zone A gets some amount of *Belg* rains with varying amount from location to location.

The method suggested by Wischmeier and Smith (1978) for computing rainfall erosivity was used to determine the erosivity for the selected meteorological stations.

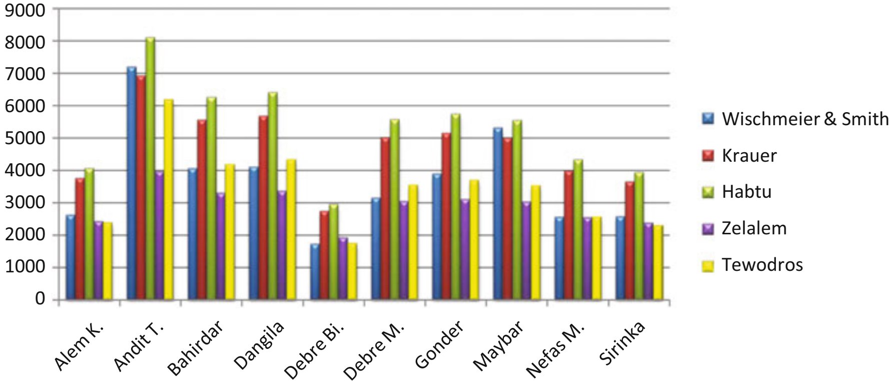


Fig. 17.12 Comparison of predicted mean annual rainfall erosivity using different regression equations and computed mean annual erosivity values. (Wischmeier and Smith 1978)

These computed values of rainfall erosivity were analyzed both statistically and graphically and were also examined spatially and temporally. Higher rainfall erosivity values were recorded in rainfall Zone B even though the highest (7,208.91 MJ-mm/ha·h·year) and the lowest (1,737.97 MJ-mm/ha·h·year) were recorded at rainfall Zone A. It was also observed that the highest rainfall erosivity values were observed in the months of July and August for both of the rainfall zones. The months of April and May were found to be with values of high erosivity during the *Belg* season in rainfall Zone A.

Various rainfall erosivity prediction equations were developed at different scales based on monthly and annual rainfall amounts to predict monthly and annual erosivity for areas, which were not equipped with self-recording type of rain gauge, and the best model was selected by considering R^2, SE, and RMS values. As a result, two regression equations, i.e., monthly and annual, were developed relating rainfall and its erosivity at monthly and annual timescales. The validity test of the monthly rainfall erosivity equations developed for the two rainfall zones revealed that the model performed well with ME being 0.73 and 0.82 for Zone A and Zone B, respectively, although the ME value of 0.85 at basin level performed reasonably well for the monthly model. The validity test of the annual erosivity models showed that the MEs are 0.89 for Zone A, 0.65 for Zone B, and 0.80 at basin level. Recommended equations found in this study for predicting rainfall erosivity values are given as follows:

Rainfall Zone A:

$$R_{\mathrm{m}} = 0.0072(P_{\mathrm{m}})^2 + 0.9788P_{\mathrm{m}} + 36.645 \quad R^2 = 0.86 \tag{17.8}$$

$$R_{\mathrm{a}} = 0.0032(P_{\mathrm{a}})^2 - 2.0474P_{\mathrm{a}} + 1{,}348 \quad R^2 = 0.92 \tag{17.9}$$

Rainfall Zone B:

$$R_{\mathrm{m}} = 0.0054(P_{\mathrm{m}})^2 + 1.1022P_{\mathrm{m}} + 20.324 \quad R^2 = 0.84 \tag{17.10}$$

$$R_{\mathrm{a}} = 0.0022(P_{\mathrm{a}})^2 - 1.3779P_{\mathrm{a}} + 1{,}224.4 \quad R^2 = 0.86 \tag{17.11}$$

For the basin as a whole:

$$R_{\mathrm{m}} = 0.0073(P_{\mathrm{m}})^2 + 0.7011P_{\mathrm{m}} + 49.583 \quad R^2 = 0.84 \tag{17.12}$$

$$R_{\mathrm{a}} = 0.0032(P_{\mathrm{a}})^2 - 2.7903P_{\mathrm{a}} - 2{,}025.9 \quad R^2 = 0.84, \tag{17.13}$$

where R_m and R_a are monthly and annual erosivity values (MJ-mm/ha·h), respectively, and P_m and P_a are the corresponding rainfall amounts (mm).

17.5 Conclusion and Recommendation

Monthly and annual erosivity prediction models developed for both rainfall pattern zones and at basin scale were simple and efficient, except that the validity test of the annual erosivity model for rainfall pattern Zone A showed ME to be 0.65, which is considered to be low. Therefore, except the annual erosivity model developed for the rainfall pattern Zone A, the models developed in this study could be used as important tools to predict monthly and annual rainfall erosivity in different parts of the upper Nile basin and/or may be used in the planning and designing of soil and water conservation works. Moreover, the models can be used to predict rainfall erosivity to be used as an important factor in soil loss assessment models like USLE and RUSLE.

Iso-erodent and erosion (erosivity) hazard maps can be developed by using geographic information system (GIS) techniques and can be used as a tool to identify areas subjected to high rainfall erosivity risk, and values can be taken or interpolated from the iso-erodent lines that will help in planning, design, and implementation of various development and research activities related to soil and water conservation. In addition, these maps can be used as an important tool for decision making related to identification and prioritization of high-risk areas and proper allocation of budget, taking other factors affecting water erosion into consideration.

Generally, as this is the first attempt to develop regression relationships between rainfall and the corresponding rainfall erosivity at different timescales with limited data, attempts should be made to enrich and update this information, both spatially and temporally. In order to do this accurately, the quality and quantity of the graphical data should be improved by reducing the timescale the data are being recorded, replacing the existing rain gauges with modern apparatus, and improving the database management at all levels. It should be noted that the data used in this study were collected from stations found in the Amhara Region part of the upper Blue Nile River basin because of absence of stations equipped with self-recording rain gauges in the Oromia and Benishalgul Gumuz parts of the basin.

Natural rainfall erosivity is a very complex process with many factors involved, especially in mountainous areas like the upper Blue Nile basin. Mikhailova et al. (1997) noted that elevation and temperature also have an impact on rainfall erosivity in addition to the rainfall characteristics. Therefore, in order to improve the information on rainfall erosivity, more parameters have to be taken into account and further research work should focus on the interaction of a number of factors with rainfall erosivity, taking the issue of climate change into consideration.

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Part IV
Climate Change and Water Resources

Chapter 18
Climate Change Impacts and Development-Based Adaptation Pathway to the Nile River Basin

Semu A. Moges and Mekonnen Gebremichael

Abstract Nile River basin is a complex hydrological system which consists of distinct hydrological regimes at the different reaches of the river system. The runoff response of the system to the change in future climate is greatly associated to the variation in the behavior of the hydrological regimes of the river system. Developing an appropriate basin, wide adaptation strategies that promote water development in the basin requires an understanding of the sensitivity of the different hydrological regimes of the basin to climate change.

From the experimental sensitivity study and existing information in the Nile basin, four distinct hydrological regimes are broadly distinguished: the water source regime, water accumulation regime (energy source regime), water-losing ecosystem regime, and the water use regime. The water source and energy source regimes are both highly sensitive to climate change. It has high stored potential energy due to the flow accumulation and elevation advantage towards the exit from the source regime.

The water-losing regime consists of the extended swamps in southern Sudan and the southwestern part of Ethiopia. Building multi-year storage schemes upstream of the swamps provides flexible means of water use, maintenance of ecosystem services, and management of disruptive floods or water losses. This regime is highly vulnerable to unsustainable water abstraction than it is to climate change. If development is carefully and scientifically planned and implemented, not only water availability is improved but also the economic and physical freedom of people living around the swamps may be enhanced. Furthermore, adaptive options can be leveraged from water-saving activities through modernizing irrigation schemes and enhancing the efficiency and productivity of currently existing large-scale irrigation schemes in

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Sudan and Egypt. Using less water and improving allocative efficiency add up to the list of upstream adaptive measures.

We conclude that there is scientific means and strong justification to adapt to climate change in the Nile basin without undermining the development needs of the riparian countries. It must, however, be underlined that without basin-wide integrated planning and management framework, the transferability of the suboptimal regime-based adaptive measures to basin-wide benefit will remain constrained. Effective basin-wide planning and management requires high-level scientific and political cooperation, institutional mechanism, and legal instruments, which currently do not exist. Integrated basin-wide climate change adaptation must be seen as an opportunity for cooperative engagement in the basin.

Keywords Climate change · Nile River basin · Hydrologic regimes of the Nile basin · Climate adaptation · Blue Nile · White Nile · Nubian sandstone aquifer

18.1 Background and Introduction

The Nile is the world's longest river, stretching 6,700 km in length and covering an area of about 3 million km^3 (Shahin 1985). The river consists of the Ethiopian Nile and the equatorial Nile originating from two distinct geographical zones. The source of the equatorial Nile is in the equatorial lakes region. Its catchment area includes the riparian states of Burundi, Democratic Republic of Congo (DRC), Kenya, Rwanda, Tanzania, and Uganda. The Ethiopian Nile originates in the highlands of the western part of Ethiopia.

The equatorial Nile and Ethiopian Nile have dramatically different flow patterns. The flow from the equatorial Nile (known as White Nile flow) is tempered by the natural perennial storage of the Great Lakes, of which the Lake Victoria is the most important. Consequently, it is characterized by a relatively steady flow pattern. Although the annual rainfall input in the equatorial region can reach 580 billion cubic meters (BCM) (FAO 2011), the annual flow at Mongolla before entering the Sudd swamp reaches 36 BCM and more than half of this flow (19.9 BCM) is lost in the Sudd swamps (Sutcliffe and Park 1999; FAO 2011).

The Ethiopian Nile (the Blue Nile, Sobat, and the Atbara) originating from Ethiopian highlands is subjected to heavy seasonal flow fluctuations in contrast to the White Nile. Between the months of June and September, flow increases dramatically due to seasonal heavy rains occurring between June and September. Though the total annual rainfall volume reported is over 430 BCM, the total flow generated through these river systems is in the order of 73 BCM (FAO 2011). Contrasting the flow contribution of the White Nile and Ethiopian Nile, much of the flow generated from Ethiopian highlands arrives to the Main Nile with negligible loss while White Nile joins the main Nile with significant water loss on the way.

Climate change projection studies in the Nile basin offer a glimpse of uncertainty and high level of sensitivity of flows to changes in the climate. A recent review by Di Baldassarre et al. (2011) showed the large diversity and uncertainty in the outputs of climate change impact studies in the Nile River system, opposite trends and contradicting recommendations provides daunting challenge to planners in the basin. Moreover, demographically and economically induced growth in demand for water is expected to outweigh climate-driven changes. Adaptation in the water sector should focus on building-adaptive capacity and no-regret-type activities in response to multiple factors. Climate change adaption recommendation must combine the projection uncertainty as well as the growing demand which is a nonclimate factor. In effect, Nile basin needs a development-based adaptation approach that builds the resilience capacity and the need for economic growth of the Nile basin society.

This chapter dwells on demonstrating development-based adaption measures as a recipe to climate change as well as cooperation in the Nile basin. The study undertakes sensitivity analysis to climate on selected watersheds and reaches of the Nile basin and deduces a possible pathway to adaptation to climate change in the basin. As demonstrated by many review research papers (e.g., Di Baldassarre et al. 2011; Xu 1999), a considerable number of research works have been undertaken to investigate the impact of climate change on the water resource systems over the past several years. There is, however, little research work on how to integrate the climate change impact adaptation to development requirements of the basin. Addressing the regional water development issues requires understanding the distinct hydrological, climate, and other dominant features of the basin.

18.2 Hydrology of the Nile and Salient Features

The Nile is the world's longest river, traversing more than 6,700 km and covers 11 African countries. It extends for more than 3 million km^2 stretching from equatorial to Mediterranean regions of Africa (Fig. 18.1). Nile is one of the world's basins shared by 11 countries: Burundi, DRC, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Tanzania, South Sudan, Sudan, and Uganda.

The Nile obtains its flow from three sources: (a) the basin of the equatorial lakes plateau, (b) the Ethiopian highland plateau, and (c) the Bahr el Ghazal basin. Almost 85 % of the annual flow that reaches Egypt's Aswan Dam originates from the Ethiopian highlands and reaches the main Nile through Sobat, the Blue Nile, and the Atbara rivers (Fig. 18.1). The remaining 15 % comes from the equatorial lakes through the White Nile. The contribution of Bahr el Ghazal is almost negligible (Fig. 18.1).

The first important characteristic of the Nile is its extreme hydrological variability within the subbasins and the main Nile River system. The total annual flow volume of the Nile at the border between Sudan and Egypt has historically been taken (before any significant abstraction) as 84 km^3 (1901–1959). However, the Nile flow over the past 100 years (1870–2000) has also exhibited higher variability, with annual flow

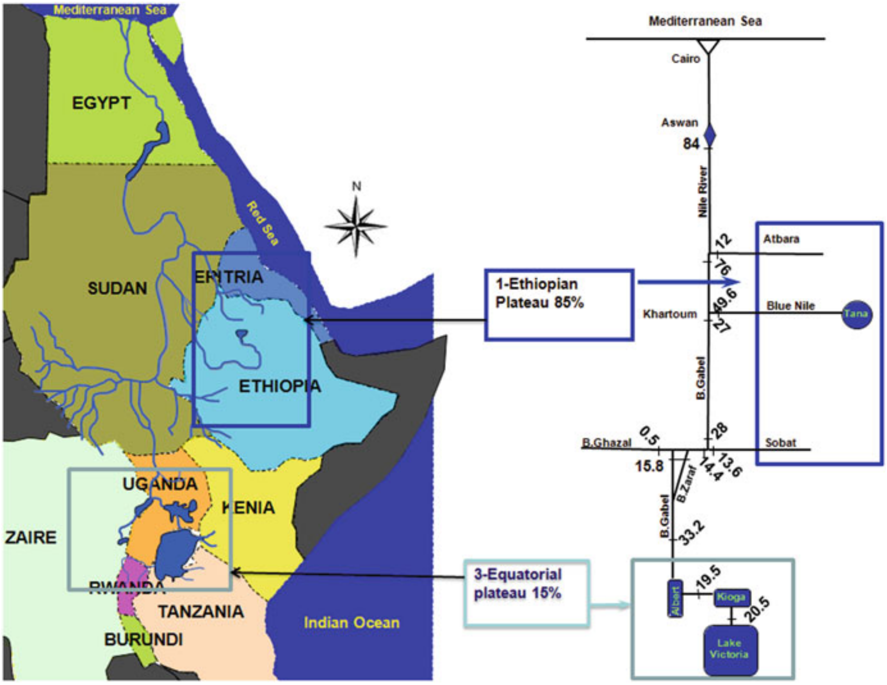

Fig. 18.1 The Nile basin

fluctuating between 40 and 150 BCM. In terms of water yield, the Nile has the lowest specific discharge (0.98 L/s/km^2) of all world rivers having a basin area exceeding 1 million km^2. This is almost one tenth of the estimated specific discharge of the Congo basin, which is geographically the closest to the Nile basin (Shahin 1985).

Other important salient characteristics of the Nile hydrology today are its high evaporation and conveyance losses. Blackmore and Whittington (2008) summarized the main water losses: (1) about 19 BCM are lost annually from man-made reservoirs, e.g., at High Aswan Dam (HAD) in Egypt; (2) the annual conveyance losses directly from the channel total approximately 20–30 BCM; (3) significant losses occur from irrigation systems operated throughout the Nile basin; and (4) water evaporation from flood plains is often referred to as “losses”; this water can potentially provide increased flow through proper management and regulated flow. Furthermore, the pattern of evaporation rates is related to the topographic differences in the basin. Potential evaporation is relatively low in the mountains around the equatorial lakes and in Ethiopia where rainfall is highest, but it gradually increases as one move northwards along the river. Low levels of humidity and long hours of sunshine in the northern desert areas produce very high open water evaporation rates of up to 3,000 mm per year.

Thirdly, only about 25 % of the total basin located in Ethiopian highlands and the mountainous part of the equatorial lakes region contributes almost the entire Nile

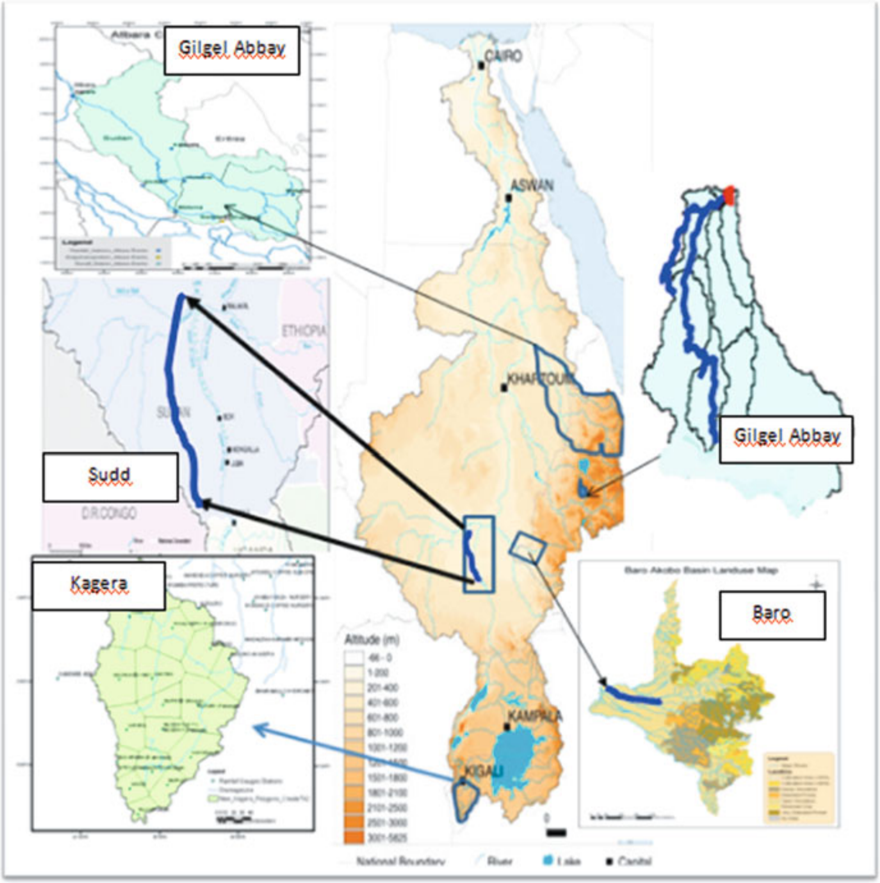

Fig. 18.2 The representative study reaches and watershed of the Nile basin

flow (Fig. 18.2). These regions receive a mean annual rainfall amount greater than 1,000 mm. As one moves northwards through southern Sudan, rainfall gradually declines, reaching about 200 mm per year at the junction of the Blue and White Niles in Khartoum. North from there, desert conditions prevail, and rainfall drops to practically zero in northern Sudan and most of Egypt. In terms of rainfall distribution, the upper riparian countries are characterized by seasonal rainfall variability while the arid regions of the lower riparian countries are characterized as the absolute water scarce part of the basin. The hydrology of the Nile clearly shows the heavy dependency of lower riparian countries on the water of the Nile while the upper riparian countries continued scrambling on rainfall variability for so long.

The fourth feature of the Nile is the two major sources areas of the Nile water are highly degraded and produce enormous sediments that flow into the Nile. The sediments produced from the equatorial Nile basin are usually absorbed by the series of lakes and swamps along the path, while sediments produced from Ethiopian highlands directly affect the Nile reach up to the HAD. According to El Monshid et al. (1997), the estimated sediment load of the Blue Nile at the Sudan border with Ethiopia reaches 140 million tons per year, while at HAD it reaches 160 million tons (including Atbara and other contributions). Betrie et al. (2011) also showed a similar magnitude of sediments is generated from the Blue Nile alone.

The fifth and hydro-politically active feature of the Nile is its water use. Perhaps it may be the only transboundary water basin where the upstream water suppliers of upper riparian countries use insignificant amount of water and the lower riparian water recipients of the Nile use almost 100 % of the total Nile flow and defend their hydro-hegemonic rights from the grounds of historical and acquired rights. Ongoing uncooperative development in the basin will further complicate the water security issue in the basin. This chapter presents the major future challenges of the basin.

18.3 Selected Watershed and River Reach Study Areas

The study consists of three representative watersheds of different size and location and two other swamp reaches located in Baro-Akobo subbasin in Ethiopia and White Nile reach in South Sudan. The watersheds included the Gilgel Abbay, 1,664 km^2, located in the Lake Tana subbasin (Blue Nile, Ethiopia), and Atbara, 43,600 km^2 the main Atbara subbasin flow in Sudan and Kagera (Area = 58,349 km^2), located in the equatorial Nile basin (Lake Victoria subbasin catchment) (Fig. 18.2).

The lower Baro reach is located between Gambella and Burebeiy in Ethiopia and occupies the river reach of 200 km that encompasses flat low land areas of Baro River system between 8.25 N and 34.58 E (Gambella) and 8.42 N and 33.23°E (Burebiey). The Sudd reach consists of the area between Mongolla and Malakal (South Sudan), and the distance between these reaches is approximately about 500 km (measured from Google Earth). This reach is known for its significant water loss and relatively constant outflow from the swamp with little seasonal fluctuation.

18.4 Sensitivity Analysis and Implication to Climate Change Adaptation

18.4.1 The Watershed Regimes

The Hydrologiska Byråns Vattenbalansavdelning (HBV) model used for sensitivity analysis was calibrated and verified on the three selected watersheds of Gilgel Abbay, Kagera, and Atbara based on Nash–Sutcliffe efficiency coefficient (Elshamy et al. 2009). The calibrated model was used to understand the sensitivity of the response of the watersheds (in this case runoff). This is done by hypothetical delta changes of rainfall and evaporation (i.e., changing one variable while fixing the other) by ± 5,

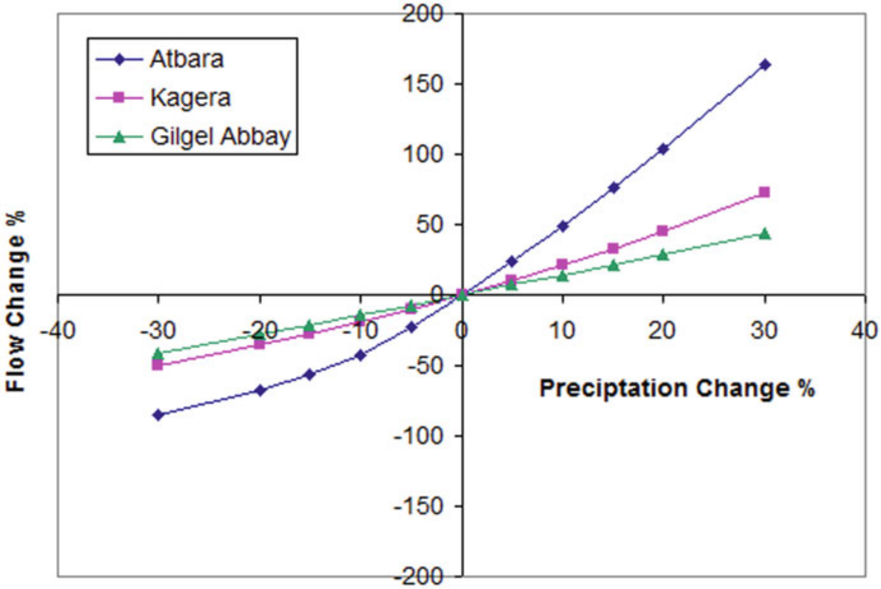

Fig. 18.3 Sensitivity of different catchments to changes in climatic conditions. (Source: Elshamy et al. 2009)

10, 15, 20, 25, and 30 % and monitoring the change in average discharge. From this study, we summarized the following findings: (1) flow is more sensitive to changes in rainfall than to changes in potential evapotranspiration (PET); (2) positive changes in rainfall are amplified in flow changes to a larger degree than negative changes, e.g., a rainfall increase of 10 % yields flow increases of 49, 29, and 14 % for the Atbara, Kagera, and Gilgel Abbay, respectively, while a 10 % reduction yields flow reductions of 42, 19, and 14 % for the three basins respectively; (3) in general, the delta change in the hydro-meteorological variables of precipitation and PET changes in the watershed is highly sensitive regardless of the sizes and locations of the catchments. Figure 18.3 shows the sensitivity of the three basin flows to changes in climate.

Socioeconomic activities located in highly sensitive hydrological regimes are generally vulnerable to small changes in the climate change as witnessed from the extremely vulnerability of rain-fed agriculture in the Ethiopian highlands. Retarding runoff and enhancing infiltration capacity of the soil improve the hydrological condition for socioeconomic activity in largely vulnerable areas of rain-fed agriculture. Arresting runoff through distributed small-scale water harvesting structures improves resilience capacity of rain-fed agriculture to climate change.

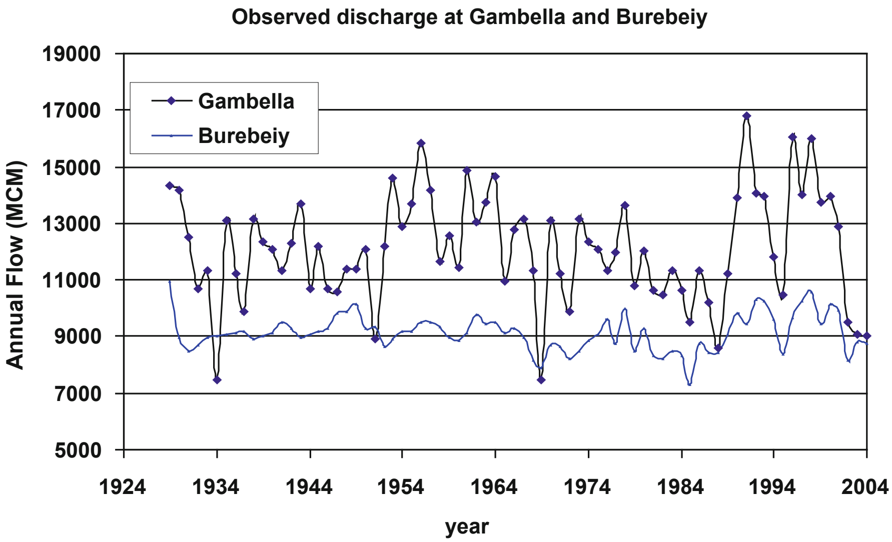

Fig. 18.4 The inflow and outflow runoff of Baro at the Gambella reach

18.4.2 The Lower Baro and the Sudd Reach

18.4.2.1 Lower Baro Reach

A flow-to-flow relationship was established between the inflow and outflow in the lower Baro and Sudd reaches to understand the sensitivity of the impact of the climate change. Inflow–outflow relationship has been developed to describe the relationship between the inflow at Gambella and outflow at Burebeiy (border to South Sudan). The developed relationship was validated and used for sensitivity analysis. As shown in Fig. 18.4, the inflow at Gambella is larger than the outflow at Burebeiy (border to Sudan) except during few dry years and months where the flow is contained within the channel (e.g., years 1934 and 1968). Based on monthly flow relationship between the two sites, empirical equation was developed to describe the flow regime phenomena between these two reach:

$$Q_{B(t)} = Q_{G(t)} - 0.1904^{*} Q_{G(t)} + 6892.1^{*} \frac{Q_{B(t-1)}}{Q_{B\text{mean}}} \tag{18.1}$$

where Q is the annual flow (in MCM), t is the time step, B_{mean} is the long-term mean at Burebeiy (Sudan border to Ethiopia), B and G are Baro flow at stations Burebeiy and Gambella, respectively.

As shown in Fig. 18.5, the equation represents the relationship between the upstream and downstream reaches of lower Baro reasonably well. This equation was used to undertake the sensitivity of the lower reach Baro River. Based on Delta change of − 5, − 10, − 20, and − 30 % in upstream reach inflow, the change in the

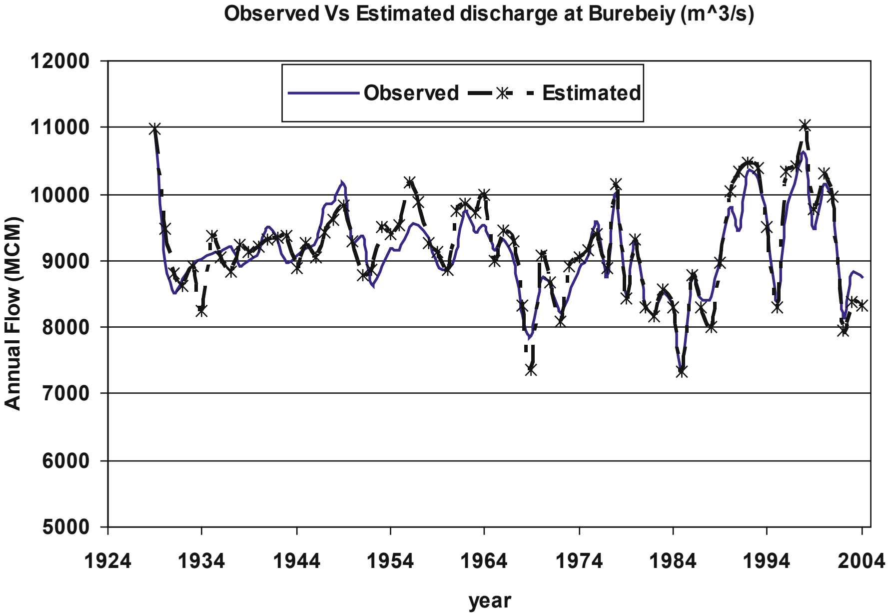

Fig. 18.5 The observed and modeled estimates of lower Baro at Burbeiy (Sudan border)

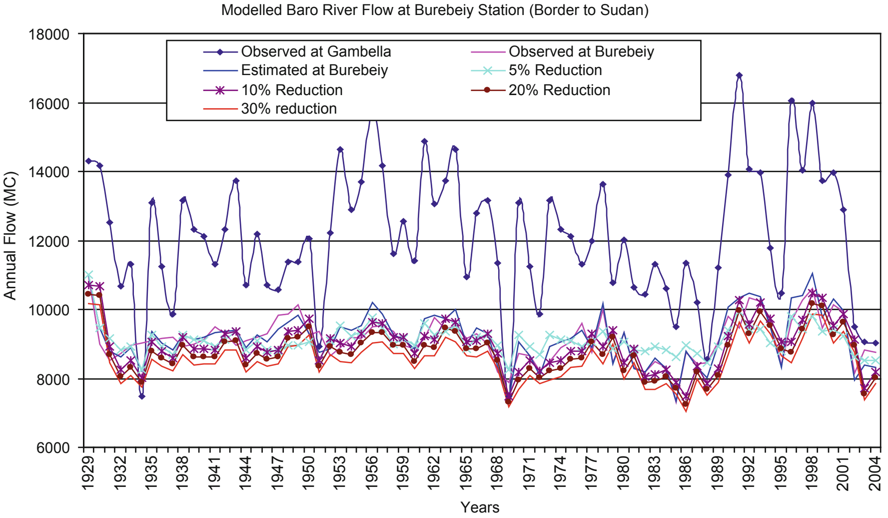

Fig. 18.6 Sensitivity outputs of Baro reach: Gambella–Burebeiy

downstream outflow at Sudan border (Burebeiy) is only reduction in flows of 1.03, 2.27, 4.77, and 7.28 %, respectively (Fig. 18.6). This reduction in flow from the hypothetical change in upstream inflow can be considered as highly less sensitive.

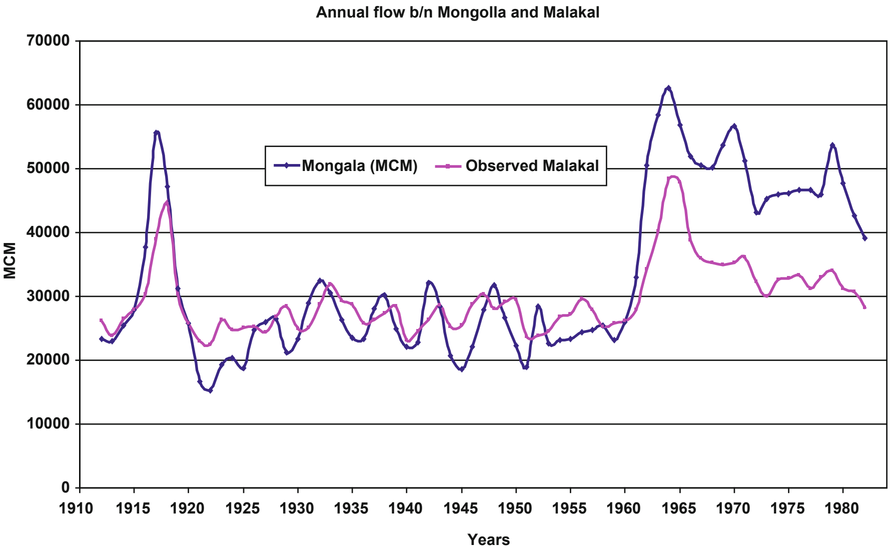

Fig. 18.7 The inflow and outflow characteristics of the Sudd reach

18.4.2.2 The Sudd Reach

Similarly, inflow–outflow relationship was established to the Sudd reach between the inflow at Mongolla and outflow measured at the outflow of Sudd in Malakal to understand the sensitivity of the impact of the climate change (Eq. 18.2). Inflow–outflow relationship was similarly validated and used for sensitivity analysis. As shown in Fig. 18.7, the inflow at Mongolla is larger than the outflow at Malakal during the flood season. This reach constitutes the flow contribution from the equatorial Nile lakes (measured at Mongolla), the Sobbat (from Ethiopian highlands), and Bahr el Ghazal (western Sudan). The monthly inflow and outflow water balance in the reach can be described by

$$Q_{\text{mal}} = 0.694^{*} Q_{\text{sob}} + 0.310^{*} Q_{\text{mon}} + 9894.7 \qquad (18.2)$$

where Q is the annual flow (MCM) and the subscripts mal, sob, and mon symbolize reaches at Malkal, Sobbat (before Malakal junction), and Mongolla respectively.

As shown in Fig. 18.8, with the exception of the extraordinary peaks of 1918 and 1964, the model can properly capture the relationship between the two reaches. This relationship was used to test the sensitivity of climate change impacts. Based on Delta change of − 5, − 10, − 20, and − 30 % (Table 18.1) in upstream reach Mongolla inflow, the change in the downstream outflow at Malakal is only reduction in flows of 2.8, 5.6, 11.1, and 16.7 %, respectively (Fig. 18.9). This reduction in flow from the hypothetical change in upstream inflow can be considered as less sensitive compared to the catchment sensitivities.

Socioeconomic activities located in or downstream areas are generally resilient to small or moderate changes in flows as witnessed from steady flow conditions of Baro

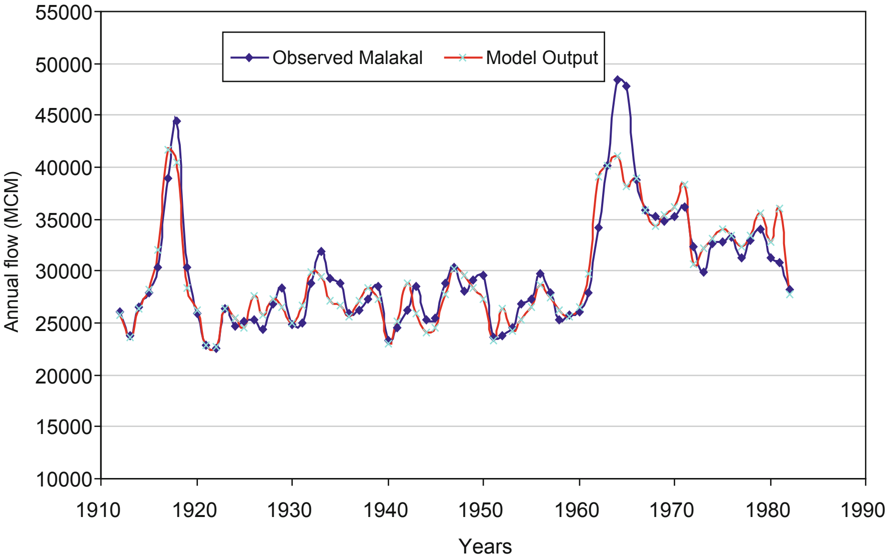

Fig. 18.8 The observed and modeled flow estimates of Sudd at the lower reach of Malakal

Table 18.1 Sensitivity-selected reaches of Nile basin to hypothetical % reduction in rainfall

Reach/catchment	5 %	10 %	20 %	30 %	Remark
Gambella–Burebeiy	1.03	2.27	4.77	7.28	Less
Mongolla–Malakal	2.8	5.6	11.1	16.7	Less
Gilgel Abbay	6.0	11.0	22.0	33.0	More
Kagera	7.0	14.0	26.0	36.0	More
Atbara	12.0	30	54*	???	Extreme

* extremely sensitive with reduction reaching 90% for some months

River or the White Nile downstream of the swampy reaches. However, larger positive increase in the inflow due to enhanced rainfall to these reaches increases catastrophic flood events and usually disrupts socioeconomic activities of the area. Scientifically, arresting the multi-year flooding events of catastrophic nature and controlled release of inflows to such swampy reaches enhance socioeconomic activities and water availability without reducing the sustainability of the established ecosystem.

18.5 Development-based Adaptation to Climate Change in the Nile Basin

On the basis of the above study and long years of experiences over the Nile basin, we broadly divide the Nile into four hydrological regimes: the water source or the high-rainfall regime (region A), the energy source regime or the transition regime (region B), the water-losing ecosystem regime (region C), and the water use regime (region D) (Fig. 18.10). Generally, the outflow from the water source (region A)

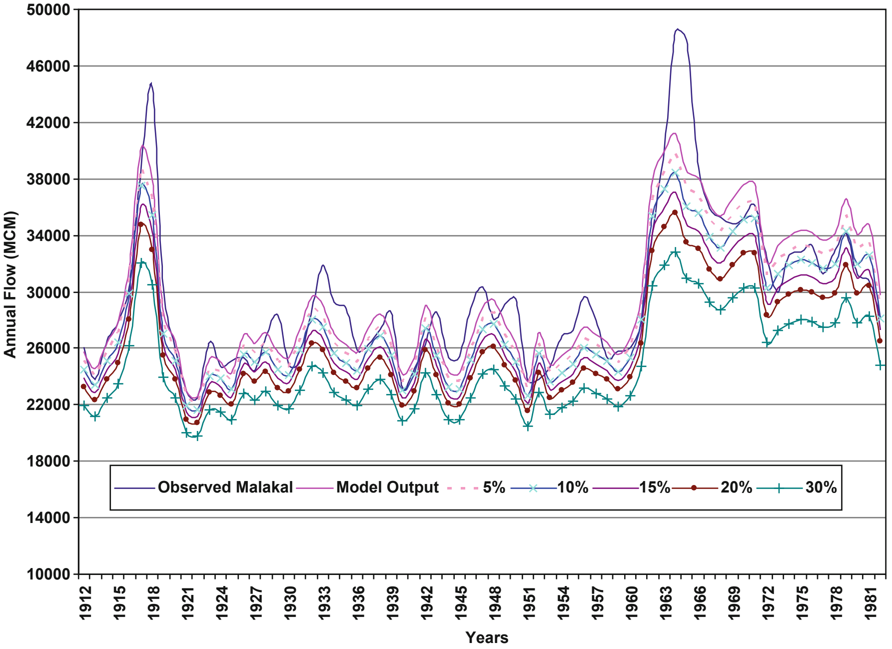

Fig. 18.9 Sensitivity outputs of Sudd reach

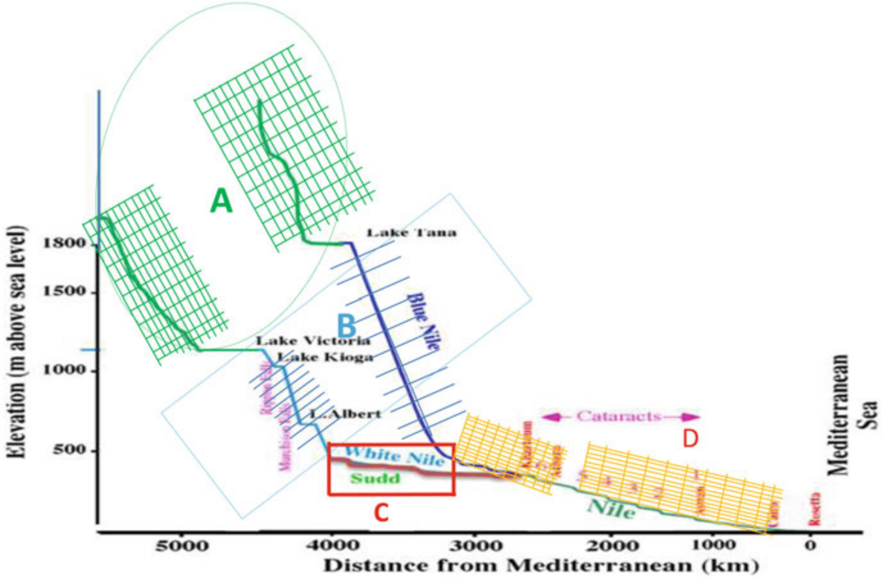

Fig. 18.10 The major hydrological regimes of the Nile

and energy source (region B) regimes is highly sensitive to climate change, while the outflow from the water-losing ecosystems (region C) is less sensitive to climate change effects. The water use regimes (region D) are usually located downstream of the large storage dams and are less sensitive to climate change impacts. Generally, it is argued that storage-based development on highly climate change-sensitive hydrological regimes provides a dual benefit to both upstream and downstream water users. It provides the needed development in the upstream riparian countries and enhancing subsequent water-saving options to decrease the impacts of climate change on water availability. Subsequent sections provide development-based approaches to adapt the future impacts of climate change in line with this understanding.

18.5.1 Region-Specific Development-based Adaptation Pathways

18.5.1.1 Water Source Regime (Region A)

The water source regime consists of the highland parts of the upper riparian countries (Burundi, DRC, Ethiopia, Kenya, Rwanda, South Sudan, Tanzania, and Uganda). This regime is largely based on subsistence rain-fed agriculture. Rainfall in many of these upstream riparian countries exceeds 1,000 mm per annum. FAO (2011) estimate shows that the total rainfall in the regime may reach 2,000 BCM—Sudan (51 %), Ethiopia (23 %), and Uganda (13 %). In the FAO (2011) study, Sudan refers to Sudan before separation into South Sudan and Sudan. Though the study indicates the rainfall amount to be in Sudan, from our knowledge of the basin large part of the rainfall is attributed to South Sudan. Despite the grossly enormous annual precipitation, the regime socioeconomic economic activity suffers from seasonal and annual rainfall variability that occurs at unprecedented scale. The rainfall variability usually occurs in the form of wrong timing, variable onset and cession of rainfall, disruptive amount and intensity falling in short duration of time, dry spells, and unpredictable frequency of occurrence. Due to climate change, it is anticipated that variability of rainfall and increasing tendency of temperature are likely to affect the socioeconomy of the water source regime (Boko et al. 2007). It is also shown that (Moges and Gebregiorgis 2013) increased population pressure and land degradation put additional pressure on the regime water availability. Studies show that the productivity of rain-fed agriculture remains one of the lowest in the world with resultant food insecurity in the basin (e.g., FAO 2000). Reducing the effect of variability of rainfall and enhancing the productivity of rainfall over the vast rain-fed agriculture area of upstream riparian countries are critical to abate the likely impact of future climate change. Technologies and innovations that enhance soil water storage by reducing the effects of rainfall variability are important majors to be considered specifically:

- *Improving at site water infiltration through improved tillage, agronomy and watershed rehabilitation, afforestation and zero grazing approach*

- *Reducing nonproductive evaporation water through converting into evapotranspiration (green water)*
- *Improving water availability through supplementary irrigation on the basis of efficient and effective water harvesting and watershed rehabilitation technologies*

Implementation of water and soil conservation management at the farmers' field over the past 50 years has not reduced the risk of dry spell (CA 2007). Development, transfer, and implementation of new technology to manage and use the available precipitation for more productive and stable agriculture are a complex task (Kampen 1982). For instance, several years of intervention of soil and water conservation (SWC)-based rainfall productivity enhancement in Ethiopia has not been successful. Thus as much as it holds promise for adaptation to climate change in rain-fed agriculture, improving rain-fed agriculture in smallholder farming in a diverse culture and highly impoverished community is anticipated to be daunting. Such methods as transforming the agrarian animal-driven farming system into machinery-based farming in a wider scale brings significant change to rain-fed agriculture productivity. It can improve depth of penetration of plowing allowing more infiltration, facilitate efficient agronomic practices throughout cropping season, and, furthermore, it gives farmers more time and opportunity to engage in other livelihood-earning activities. There is no simple solution to the challenge, but integrated long-term practices in the wider area may improve the rainfall productivity and water availability. Some suggestions to vitalize implementation and effectiveness of technologies and innovations include:

- *Sustained and wide area investment in rain-fed productivity innovations and technology and outreach programs. One such typical wide area technological implement is transforming the agrarian farming system into tractor-driven farming system.*
- *Sustained capacity building of professionals, development agents, and farmers in research and development of technologies and implementation.*
- *Rainfall productivity-targeted policy instruments, enforcement mechanisms, and commitment from decision makers in the basin.*
- *Cooperative basin-wide effort to jointly garner financial and technical support from global partners and donors for sustained long-term investment in rainfall technologies.*

18.5.1.2 The Energy Source Regime

This regime is located in the lower reaches of the water source area between the highland (high-rainfall regime) and lowland (low-rainfall regime). It is a transitional region located largely in the lower reaches of the main tributaries of the Nile. The lower reaches of Blue Nile, Tekeze (Atbara in Sudan), Baro, Kagera in Rwanda, and other tributaries flow into the Lake Victoria. Like the water source regime, the energy source regime is highly sensitive to climate change (Fig. 18.10). It possesses huge potential-stored energy attributed to high elevation difference and concentrated flow. It is located just before the water-losing reaches of the swamps and marshes located in highly evaporation zone (Fig. 18.9). Development and management of hydropower-based multipurpose large-scale storage schemes in these reaches offer multipurpose benefits as well as buffer the effect of climate change and climate variability. It produces large amount of stable green energy pool to the regional market as well as the upstream countries of the water source. It also provides the capacity to reduce the sensitivity of flow and buffers the impacts of climate change on the lower riparian countries.

The importance of the grand storage schemes has fascinated past generation engineers working in the Nile (e.g., *Century Storage Scheme* proposed by Hurst et al. 1946). However, comprehensive storage scheme development as a vision to the Nile was, in many ways, shaped after Whittington's Nile Vision paper (Whittington 2004) that addressed the series of large dams in Blue Nile basin in addition to the *Century Storage Scheme* proposed by Hurst et al. (1946) (in Whittington 2004). Hydro-economic modeling approaches have also underlined the viability of developing grand water storage scheme in these reaches of the Nile basin (Whittington et al. 2005; Wu and Whittington 2006; Blackmore and Whittington 2008; Block and Strzepek 2010; Goor et al. 2010). Furthermore, energy storage regulations provide flexibility to sustainably manage the sensitive ecosystems of large swamps of the Sudd, reducing the currently observed disruptive characteristics of the swamps particularly when wetter years prevail.

In this study, the focus is on the highly sensitive subbasins of the upper Nile—the Blue Nile and Tekeze (Atbara) subbasins from Ethiopian highlands and Kagera subbasin from the equatorial. The purpose of the storage facilities in these subbasins is mainly enhancing resilience to climate change while generating enormous energy to the riparian countries. The Blue Nile, as a major energy source in the regime, is presented in more detail. The Blue Nile has potential for more than 15,000 MW of energy (Desalegn et al. 2011). It has long been touted as one of the opportunities for production of regional energy requirement while enhancing cooperation in the Nile basin. Recent independent studies commissioned by World Bank (Blackmore and Wittington 2008) indicate that construction of more cascaded large storage dams in upper Blue Nile (Abbay) provides more economic benefit as well as enhances water availability in the system. As the study shows, a single reservoir at Blue Nile (Karadobi dam) enhances energy from 3,400 to 10,000 GWh/year while slightly increasing system evaporation from 16.6 to 16.9 BCM. In another scenario, four cascaded reservoirs in the upper Blue Nile provided energy generation of the magnitude of 28,300 GWh/year and system evaporation loss reduction from 16.6 to 15.5 BCM. Therefore, more water storage in the Blue Nile provides higher economic benefit as well as adaptive capacity towards climate change impacts on lower riparian countries.

18.5.2 The Water-losing Ecosystem Regime and Water Conservation Schemes

The major flows from southwestern Ethiopia, the Baro-Akobo basin (or Sobbat as it is called in Sudan), the White Nile in South Sudan as it emerges from Uganda, and the *Bahr el Ghazal* rivers are the major rivers joining the vast swampy flat areas of the Sudd and Machar in South Sudan. As much as 50 % of the Nile flow is estimated to be lost in these extensive swamp systems. While maintenance of the swamp system is a vital ecosystem resource to the region, controlling the upstream flows to benefit the region is formulated. It is particularly important to consider controlling multi-year floods that disrupt socioeconomic activities and stock human life for development of the region as well as expand infrastructure in the region. Three major development options in these reaches are identified.

Baro River Storage Schemes The development of storage facilities and operational management of Baro River for multipurpose uses (hydropower, irrigation, and flood protection upstream of Gambella) will have an insignificant effect on the socioeconomic activities and ecosystem services of downstream riparian in a climate change scenario. As it was shown earlier (Fig. 18.6 and Table 18.1), Baro in Sudan is not sensitive to upstream hydrological regime change and has the capacity of buffering the anticipated changes in climate and increased socioeconomic activity in upstream riparian reaches. It is, however, important to carry out a proper scientific analysis to balance the requirements of ecosystem services and downstream socioeconomic activities on an annual as well as multi-year basis to benefit from rare flood events and compensate for rare drought events. Some of the planned storage facilities in Ethiopia on the Baro River must accommodate multi-year planning and management of the system without a significant effect on the downstream services and requirements.

Integrated Lake Albert and Cascaded weirs The Lake Albert storage scheme was initially included as part of the *Century Storage Scheme* (Hurst 1946) and elaborated in the *Century Storage Plus* (Whittington 2004) studies as a necessary dam for a over-year storage reservoir. The cascaded lakes of equatorial Nile have the capacity to absorb climate change shock. Further regulation of the Lake provides socioeconomic benefits such as hydropower to Uganda and flood storage capacity for South Sudan and downstream release at later dry season. It has an advantage of reducing disruptive flood events regularly havocking South Sudan; it reduces unnecessary losses in the downstream swamp in the Sudd to a manageable level and enhances water availability.

Developing regulation at the Lake Albert can provide an opportunity to develop run-of-the-river cascaded hydropower plants between the Lake to Mongolla in South Sudan before White Nile enters the Sudd. The Lake storage is operated in a multi-year operation basis rather than annual to maintain the balance of the sensitive ecosystems downstream in the Sudd at the same time providing higher dry season flow. Controlled outflow from the Lake Albert will also facilitate controlled flood plain inundation and controlled recession agriculture in South Sudan avoiding disruption. As shown from sensitivity study earlier (Fig. 18.9 and Table 18.1), the effect of water use on inundation for agriculture in South Sudan is negligible as the effort is to convert the uncontrolled evaporation into controlled evapotranspiration (green water). Ultimate utilization of the Lake Albert storage and cascaded run-of-the-river hydropower development must be dictated by multi-year management and operation of the reservoirs without significantly affecting the ecosystem services and requirements in the Sudd swamp.

Bahr el Ghazal Dams and Bypass Canals Bahr el Ghazal loses a significant amount of the water generated in that subbasin when it joins White Nile at Malakal (Sutcliffe and Park 1999). It loses approximately 11.3 BCM of annual volume of flow out of the nearly 12 BCM of annual flow generated from the tributaries in the subbasin. Only about 0.6 BCM outflow is contributed to the White Nile. As sensitivity studies in similar swampy reaches indicate, outflow from such reaches is not significantly affected by the impacts of climate change. There are potential storage possibilities in the upper reaches of the Bahr el Ghazal for generating hydropower to South Sudan and facilitating enhanced regulated flow during the dry season to the White Nile without affecting the swamps' behavior. Shahin (1985) also indicated the varying storage sizes of the building ranging from 0.5 to 2 km^3 in the upper tributaries of the Bahr el Ghazal that provide dual benefit.

Beyond enhancing dry flow conditions to the White Nile, the possibility of a bypass canal to reduce excessive and disruptive wetter year floods is essential both to the community and to enhance flow to the White Nile. It also reduces excessive loss of water through evaporation. Shahin (1985) also reported the necessity of bypass canals to regain wetter year floods. Any canal system or combined storage and canal network in the Bahr el Ghazal must be designed and operated to carry only excessive floods beyond the prescribed threshold. However, part of the seasonal swamps may be converted to green water (evapotranspiration) agriculture through which evaporation is converted into evapotranspiration. Proper planning and management of Bahr el Ghazal will have enhanced flow availability to offset the impacts of climate change on other sensitive watersheds in the basin while providing benefits to the riparian countries.

18.5.3 Water Use Regime: Improving Water Use Efficiency and Water Productivity in Agriculture

Generally, it is recognized that the total water use efficiency in low-lying large-scale irrigation schemes offers large water saving that can buffer the impacts of climate change. Though water use efficiency varies depending on the location, crop type, and season, the total water use efficiency in Egypt is about 51 % (CEDARE 2011). Likewise, studies show that water use efficiency of large-scale irrigation in Sudan is about 22 %, which is much lower compared to Egypt (Mohamed et al. 2011). There is a wider scope and opportunity to improve system efficiency and regain the lost water in the large-scale irrigation schemes in lower riparian countries. Even without change in existing irrigation technologies, studies indicate that proper allocation of water among crops, seasons, and locations in Egypt potentially increases national farm income by about 28 % per year (Gohar and Ward 2011). Though it is a daunting task to improve the efficiency of the system, putting institutional and legal framework that rewards individual farmers or water use associations with improved water use efficiency may encourage towards overall system improvement and eventual water saving in the system. Improving overall efficiency of irrigation schemes in the Nile basin may unlock tremendous amount of water from the Nile. The largest agricultural water users of Egypt and Sudan work towards improving water use efficiency by at least 20 %, which means accessing 5 BCM more water from the system. FAO (2000) has suggested two approaches for water saving in the large-scale irrigation schemes in the Nile basin: improved end-use efficiency and improved allocation efficiency.

The improved end-use efficiency is the principle of producing more crops with less water through demand management. Improve irrigation efficiency in low-lying irrigation schemes of Egypt and Sudan through continuous and long-term implementation of water management practice by reducing irrigation canal and field-level irrigation losses. Proper leveling, regular maintenance and monitoring of canal losses, and precision irrigation practices such as drip and sprinkler irrigation systems with better integrated field moisture control system are some of the technical requirements to improve irrigation efficiency. However, the technical efforts must be supplemented by better institutional and regulatory frameworks that have real enforcing power.

Improved allocation efficiency is a principle that can be implemented on a basin-wide scale. The principle is to shift high water-consuming crops to less evapotranspiration areas and season while implementing agricultural production of higher economic value in a small area and using less water in high evapotranspiration areas. Trade-offs can be made within the riparian countries such that the less evaporative demand countries can produce high water-consuming crops and the high evaporative demand countries produces less water-consuming crops. In this way, the total green water flow can be enhanced. Adjustments can also be made within the high evaporative countries to produce high water-demanding crops during winter where water consumption is lesser.

18.5.4 Integrated Basin-Wide Management and Operational Control

Integration of activities, operations, and management in the different water regimes of the Nile basin is pivotal for sustainable development and adaptation pathway to the future of the Nile. The suboptimal operation and activities in the different hydrological regimes must be integrated into optimal basin-wide operation and management of the water under one operational control system. Coordination and communication of strategies to centralized institutional arrangements is crucial for sustainable adaptation path in the basin.

It also provides possibilities to implement dynamical adaptive procedures in the basin based on feedback and real time operation control. However, integrated basin-wide management and control operation require basin-wide cooperative agreement, permanent institutional arrangement, and legal facilities. Figure 18.11 indicates integrated basin-wide Nile basin management under one banner.

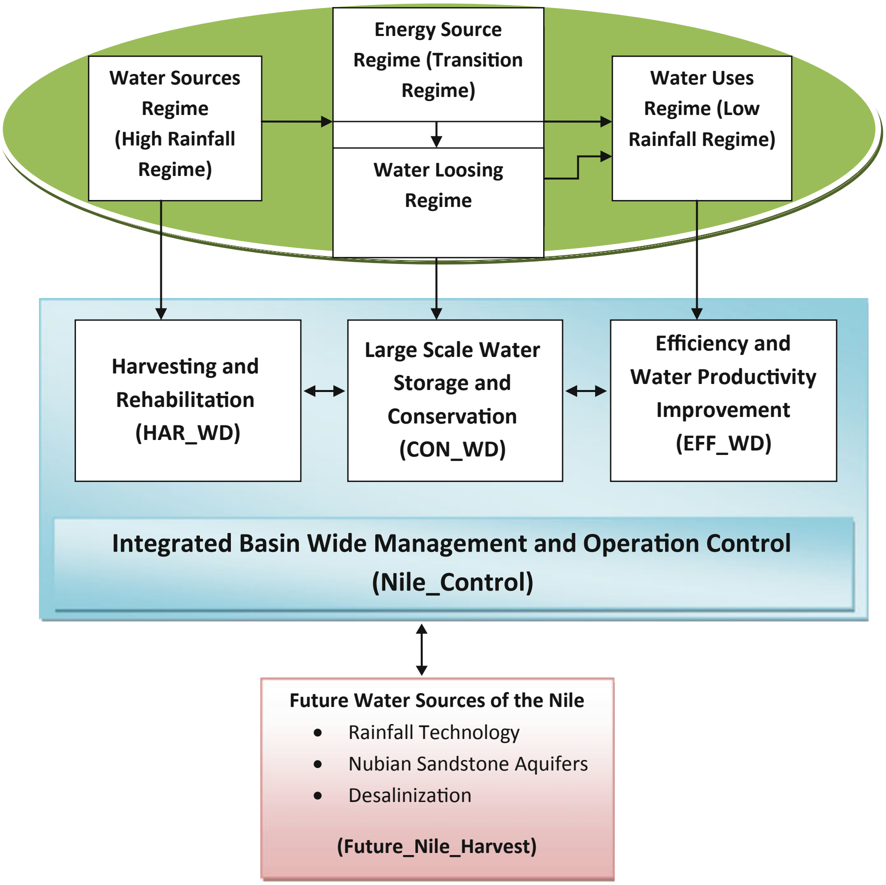

Fig. 18.11 Integrated basin-wide management and operational control system

18.5.5 *Sourcing Additional Water to the Future of the Nile*

Not only the climate change impacts but also other drivers such as overcrowding, economic growth, and land degradation affect the future ability of the Nile to furnish vital benefits and services to the Nile basin sustainably. Under genuine cooperative framework, exploring complementary water sources and alternative technologies is very essential to the basin. As shown in Fig. 18.11, complementary sources can be part of the integrated management components of the basin. They may be useful to augment the Nile flow to lower riparian countries during multi-year droughts, offsetting the part of the growing demand in the basin. This study provides examples of such new water source potentials to the future of the Nile: groundwater from Nubian sandstone aquifers and large-scale desalinization processes.

Table 18.2 Potential groundwater in the Nubian sandstone aquifers

No.	Stored GW (Km^3)	Author	Remark
1	15,000	Ambroggi (1966)	
2	542,180	Salem (2002)	
3	373,000	-do-	NSA (41.5 %—Egypt, 36.6 %—Libya, 9 %—Sudan, and 12.8 %—Chad
4	84,600	-do-	PNA (46 %—Egypt, 54 %—Libya)
5	14,818	Abu Zeid (2003)	Recoverable
6	543,500	-do-	Storage volume
7	372,950	Bakhbakhi (2011)	Total fresh GW
8	14,459	Bakhbakhi (2011)	Total recoverable fresh GW

NSA Nubian sandstone aquifer, *PNA* post-Nubian aquifer

18.6 Deep Aquifer Water Utilization

The amount of stored groundwater in the Nubian aquifers has fascinated scientists over the past half a century (Table 18.2). The estimated stored amount varies greatly from 14,818 to 543,000 km^3. Preliminary analysis was performed to support the importance of the utilization of this groundwater as part of alleviating future water scarcity based on conservative lower estimate.

Considering the two lowest conservative estimates of the recoverable volume of groundwater of 14,500 and 60,000 km^3 and extraction scenario 10 km^3/year for each country of Sudan and Egypt, the water can be used to supplement the two countries for over a thousand year. If this stored groundwater is used in the right time and right quantity, it offers a great flexibility and benefit to the lower riparian countries of Sudan and Egypt. Though Egypt currently utilizes significant amount of this water, a possibility of enlarging the water base as a supplementary to the Nile for its expanding population is not remote. The cost-effective deep-drilling technologies are as important as the water sources and are instrumental for the success of future deep water drilling.

18.6.1 Positive Prospects of Large-Scale Desalinization

Many countries of the world have started using desalinization technologies to extract potable water from saline seawater since the 1950s. Currently, the discouraging cost of desalinization and environmental issues are rapidly changing in favor of implementation of desalinization. Over the span of 40 years, it has been shown that the unit cost has been reduced by a factor of 10 (Reddy and Ghaffour 2007). According to the review by the Water Reuse Association (2012), the unit cost of production in 2010 has reached a minimum of US$/cumecs 0.65 and is expected to decline further. In terms of size, the largest plant found in Israel produces 127 MCM/year at a cost of US$/cumecs 0.57 (IDE Technology 2012).

This obviously is an indication of an enormous opportunity for the future generation of countries located at the ocean and sea frontiers. It is in the interest of Nile countries living at the coastline, particularly Egypt, Sudan, and Eritrea, to develop a long-term strategy for developing large-scale desalinization plants while, in the medium term, expanding the existing desalinization plants in the country.

18.7 Summary and Conclusion

The Nile River basin is a complex hydrological system which consists of distinct hydrological regimes at the different reaches of the river system. The runoff response of the system to the change in the future climate is greatly associated to the variation in the behavior of the hydrological regimes of the river system. Developing an appropriate basin-wide adaptation strategies that promote water development in the basin requires an understanding of the sensitivity of the hydrological elements of the basin to climate change at the different reaches and tributaries of the basin.

Generally, flows from the mountainous highland subbasins are highly sensitive to climate change scenario than flows in the swampy hydrological regimes. Flows emanating from highland watersheds in Ethiopia are more than twice sensitive for a delta change in the rainfall pattern. Flow from the Tekeze River subbasin is found to be the most sensitive (four times) followed by Gilgel Abbay. The flow from the swampy reaches of lower Baro and Sudd is far less sensitive to climate change relative to the highland regimes.

From this study, basin-wide conceptual framework to development-based adaptation approach to climate change was formulated. The water source regimes of the upper reaches of Ethiopian and equatorial Nile receive highly variable rainfall, and the flows are highly sensitive to changes in the climate. Reducing the effects of rainfall variability and enhancing rainfall productivity through sustained investment in farming technologies and agronomic innovation are essential. Capacity building, rainfall-targeted policy instrumentation, and basin-wide cooperation to garner long-term financial resources to improve rained agriculture productivity are vital to reduce the impacts of climate change. Furthermore, supplementary irrigation, combined with improved agronomic practice, enhances carbon sequestration, buffers hydrological variability, and shall be promoted through carbon markets and carbon financing as part of developmental activity.

The energy source regime is where there is high-stored potential energy due to the flow accumulation and elevation advantage. It is generally a transition zone between the water source and the flat swampy water-losing regimes. This regime is highly sensitive to climate change, and storage-based hydropower development provides sustainable energy as well as buffers the impact of climate change. Particularly large-scale or cascaded storage reservoirs may provide additional storage capabilities for storing multi-year flood events of disruptive nature that are usually spilled over the swamps and affect socioeconomic activities in southern Sudan.

Water losing regime of the Nile is part of the reach that exhibits high annual runoff lose in the the floodpains of the South Sudan and Ethiopia. As much as 50 % of the Nile flow is anticipated to be lost in these extensive swamp systems. Without lossing focus into the larger picture of sustainability of swamp ecosystems, controlling multi-year floods that are usually disruptive to socioeconomic activities and stocks human life help to improve the livelyhood of the community in one hand and enhances water availablity in the other hand. As the ecosystem service is part of the swamp water demand in the regime, thoughtful scientific analysis and study should be in place before implementing upstream control structures.

Additional water can be saved from modernizing irrigation schemes and enhancing the efficiency and productivity of currently existing irrigation water in water user areas of Sudan and Egypt. Using less water and improving allocative efficiency add up to the list of downstream adaptive measures.

In conclusion, there is scientific means to adapt to climate change without undermining the development needs of the riparian countries. However, it must be underlined that without basin-wide integrated planning and management strategy, the transferability of the suboptimal regime adaptive measures to basin-wide benefit will remain constrained. Effective basin-wide planning and management requires high-level cooperation, institutional mechanism, and legal instruments which currently are stalled. it is hoped that the ongoing construction of the great renaissance dam in Ethiopia and similar projects will have significant catalytic role in bringing the Nile basin riparian countries back to cooperative framework. Integrated basin-wide climate change adaptation must be seen as an opportunity for cooperative engagement in the basin.

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Chapter 19

Climate Change Projections in the Upper Gilgel Abay River Catchment, Blue Nile Basin Ethiopia

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Abstract According to future projections, precipitation and temperature will increase over Eastern Africa in the coming century. This chapter presents basin-level impact of climate change over the Upper Gilgel Abay River catchment, Blue Nile basin, Ethiopia, by downscaling the Hadley Centre Coupled Model, version 3 (HadCM3) global climate model using the statistical downscaling model (SDSM). The baseline period (1961–1990) recommended by the Intergovernmental Panel on Climate Change (IPCC) was considered for analysis of the baseline scenario. For future scenario analysis, the time periods of the 2020s, 2050s, and 2080s were applied. Mean annual rainfall will be expected to increase by 2.21, 2.23, and 1.89 % for A2 scenario and by 2.06, 1.85, and 0.36 % for B2 scenario by the 2020s, 2050s, and 2080s, respectively. The projected average temperature increases by 0.43, 1.05, and 1.92 °C for A2 scenario and by 0.47, 0.87, and 1.38 °C for B2 scenario in the three time periods. In the study area, the minimum temperature increases by 0.55, 1.06, and 1.83 °C for A2 scenario and 0.50, 0.87, and 1.29 °C for B2 scenario in the 2020s, 2050s and 2080s, respectively.

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Keywords Blue Nile · Gilgel Abay · Climate change · Statistical downscaling · GCM · SDSM

19.1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC 1992) defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.” A steady-state increase in the global annual mean surface air temperature associated with a given global mean radiative forcing is referred to as climate sensitivity, and radiative forcing (climate forcing) is the perturbation of the energy balance of the surface–troposphere system, after allowing the stratosphere to readjust to a state of global mean radiative equilibrium (Harvey et al. 1997).

Almost all scientists agree with global warming as an influence which contributes to climate change. Greenhouse effect is the reason why the global temperature has risen by 0.76 °C (0.57–0.95 °C) from 1850–1899 to 2001–2005 and this temperature rise has resulted in warming of the oceans and melting of glaciers, which caused the total twentieth-century sea level rise, estimated to be 0.17 m (0.12–0.22 m; Solomon 2007). This situation seriously affects coastal areas and densely populated countries.

Warming in Africa is very likely to be larger than the global annual mean warming throughout the continent and in all seasons, with drier subtropical regions warming more than the moister tropics, and there is likely to be an increase in annual mean rainfall in East Africa (Christensen et al. 2007). Seasonally, in parts of equatorial East Africa, rainfall is predicted to increase in December–February and decrease in June–August (McCarthy et al. 2001).

For the Intergovernmental Panel on Climate Change (IPCC) mid-range (A1B) emission scenario, the mean annual temperature will increase in the range of 0.9–1.1 °C by 2030, in the range of 1.7–2.1 °C by 2050, and in the range of 2.7–3.4 °C by 2080 over Ethiopia compared to the 1961–1990 normal (NMA 2007). The major adverse impacts of climate variability in Ethiopia include (NMA 2007): (1) food insecurity arising from occurrences of droughts and floods; (2) outbreak of diseases, such as malaria, dengue fever, and water-borne diseases (e.g., cholera, dysentery) associated with floods, and respiratory diseases associated with droughts; (3) land degradation due to heavy rainfall; and (4) damage to communication, road, and other infrastructure by floods.

The study by Abdo et al. (2009) showed that the average annual minimum temperature is expected to increase by 1 °C in the 2020s while in the 2050s the minimum temperature is expected to increase by 2.2 and 1.7 °C for A2 and B2 scenarios, respectively. The average annual minimum temperature is projected to increase by 3.7 and 2.7 °C for A2 and B2 scenarios, respectively, in the period of the 2080s. The study also showed in 2020s, the maximum temperature is projected to increase by 0.6 °C while in 2050s the maximum temperature is expected to increase by 1.4 and 1.1 °C for A2 and B2 scenarios, respectively. In the 2080s, the annual

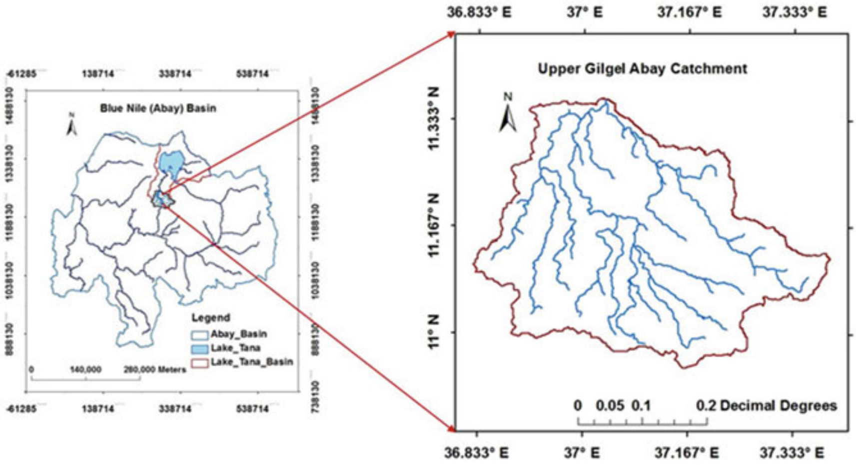

Fig. 19.1 Location of the study area

maximum temperature is expected to increase by 2.5 and 1.8 °C for A2 and B2 scenarios, respectively. Bekele (2009) showed that the rainfall experiences a mean annual increase by 0.82, 0.85, and 1.6 % for A2 scenario in the 2020s, 2050s, and 2080, respectively. In case of B2 scenario, rainfall exhibits a mean annual decrease in amount by 0.5 and 1.0 % in the 2020s and 2050s and increase by 0.54 % in the 2080s. Abdo et al. (2009) also indicate that the variation in mean annual rainfall is lesser than the variation in the monthly rainfall.

The objective of this chapter is to investigate future changes in local-scale climatic variables in the Upper Gilgel Abay catchment. Large-scale general circulation models (GCMs) climate variables, such as rainfall and temperature, were downscaled by using local-scale baseline climate variables (predictands) for this objective using statistical downscaling model (SDSM).

19.2 Materials and Methods

19.2.1 Study Area

The Gilgel Abay River is the largest tributary of the Lake Tana subbasin and originates from the highland spring of Gish-Abay town. Traditionally, people believe that the origin of Blue Nile River is this spring. The catchment covers the area of 1,654.3 km^2 of the Lake Tana basin and the longest flow path extends to 80.6 km.

Location Geographically, the Upper Gilgel Abay River catchment is found north of the Upper Blue Nile basin, which is the southern part of Lake Tana subbasin with the latitudes and longitudes between 10°56′ 53″ to 11°21′ 58″N and 36°49′ 29″ to 37°23′ 34″E, respectively (Fig. 19.1).

Topography The elevation of the Upper Gilgel Abay catchment ranges from 1,891 to 3,524 m above mean sea level (amsl). The highest elevation of the catchment is

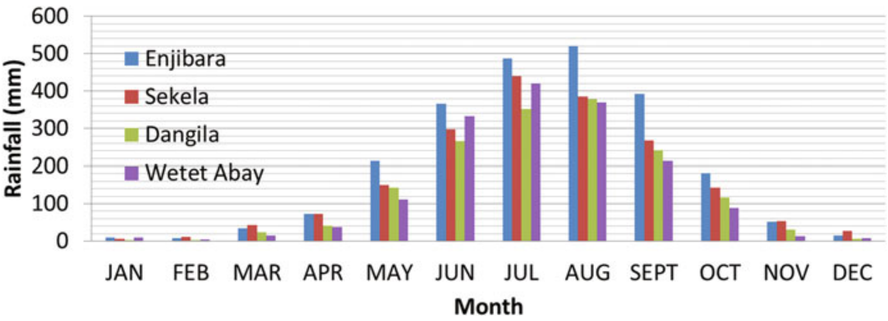

Fig. 19.2 Mean monthly rainfall (1994–2008) distribution of the Upper Gilgel Abay catchment

located on the southeastern tip. Nearly half of the catchment has an elevation that ranges from 1,891 to 2,190 m amsl which extends from the center to the north tip (the outlet of the river).

Climate Mean monthly rainfall (1994–2008) plot of Enjibara, Sekela, Dangila, and Wetet Abay meteorological stations indicates that the study area has one peak per year (Fig. 19.2). Therefore, the Upper Gilgel Abay catchment lies in monomodal climate class according to Ethiopian climate classification (Tadege 2001) with respect to rainfall regimes. The main rainfall season of the study area is from June to September and accounts for 70–90 % of the annual rainfall (Abdo et al. 2009).

According to the traditional climate classifications of the country (Tadege 2001), most of the area of the catchment is found in the *woina dega* climate (warm climate; 1,500–2,500 m amsl).

Mean annual areal rainfall (1994–2008) of the study area was computed using inverse distance weighted (IDW) interpolation technique (Fig. 19.3) by accounting the selected ten meteorological stations. As shown in the map, the mean annual areal rainfall of the study area varies from 1,624 to 2,349 mm. Majority of the study areas have a mean annual rainfall between 1,842 and 1,986 mm.

The temperature of the study area is highly affected by elevation change where the temperature decreases with increasing elevation (Fig. 19.4). For instance, mean monthly maximum temperature of Wetet Abay (1994–2008) at an elevation of 1,915 m amsl varies from 24.3 to 31.3 °C and of Gundil at an elevation of 2,574 m amsl varies from 18.3 to 24.9 °C. Generally, daily variation between maximum and minimum temperature is high as compared to the seasonal variation of temperature in the study area.

19.2.2 Available Data

Predictands (historical climate variables) and daily predictor variables for past and future projections were available to investigate future changes in local-scale climatic variables in the catchment.

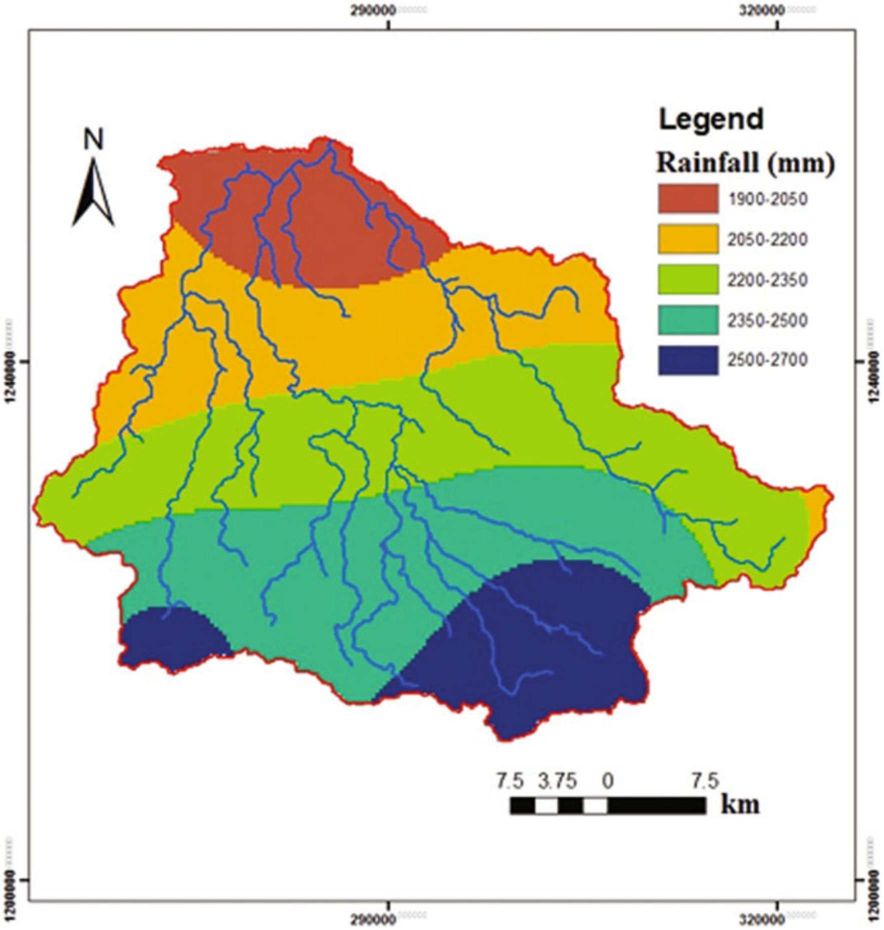

Fig. 19.3 Mean annual areal rainfall of the Upper Gilgel Abay catchment

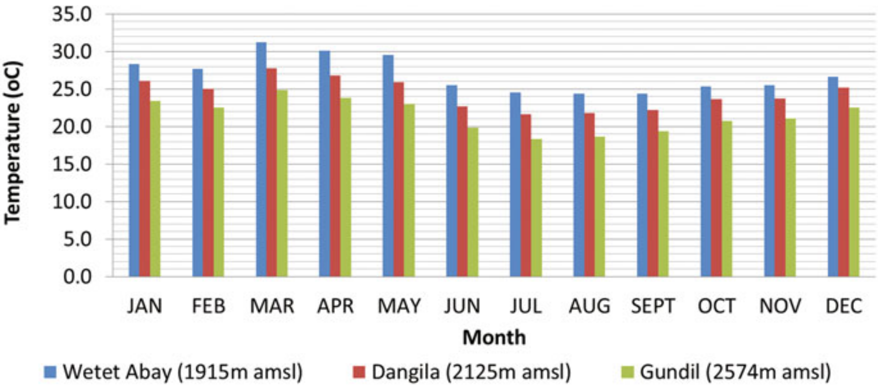

Fig. 19.4 Mean monthly (1994–2008) temperature of stations with elevation difference

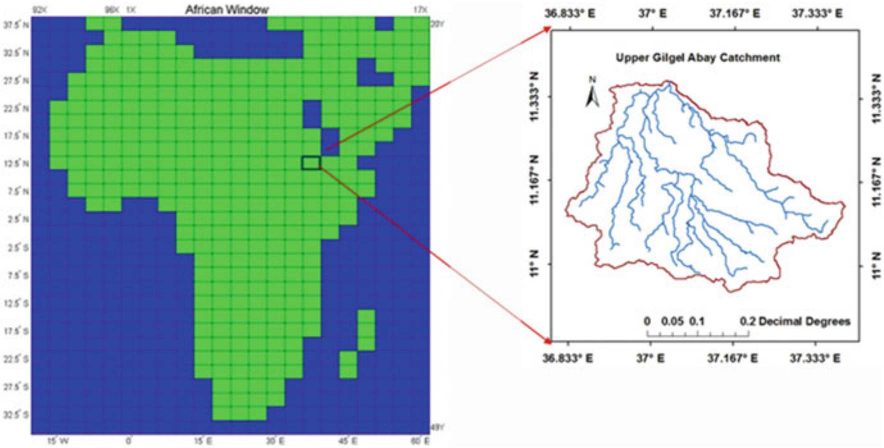

Fig. 19.5 The grid box where the study area is located

Meteorological Data Meteorological variables such as rainfall, maximum and minimum temperature were required as predictands to downscale the global climate GCM data to local climate variables. However, only Bahir Dar station was used as an input for SDSM to derive statistical relationships between the predictand and predictor that satisfy the baseline (1961–1990) historical data recommended by IPCC. These 30-year daily meteorological variables were collected from the National Meteorological Agency (NMA) Bahir Dar Branch Directorate.

GCM Data GCM data were required to project and quantify the relative change of climate variables between the current and future time horizon. One of the global circulation models, Hadley Centre Coupled Model, version 3 (HadCM3), was used for this study because the model is widely applied in many climate change studies and the model provides daily predictor variables which can be used for the SDSM. The predictor variables are supplied on a grid box by grid box basis. On entering the location of the study area, the correct grid box was calculated and a zip file was downloaded[1] (Fig. 19.5). The African continent window with a resolution of 2.5° latitude × 3.75° longitude of HadCM3 was, therefore, used as an input to the SDSM model. When unzipping this file, the following three directories are available (CCIS 2013):

- *National centers for Environmental predictions* (*NCEP*) *1961–2001*: This directory contains 41 years of daily observed predictor data, derived from the NCEP reanalyses and normalized over the complete 1961–1990 period. These data were interpolated to the same grid as HadCM3 (2.5° latitude × 3.75° longitude) before the normalization was implemented.
- *H3A2_1961–2099*: This directory contains 139 years of daily GCM predictor data, derived from the HadCM3 A2(a) experiment, and normalized over the 1961–1990 period.

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[1] http://www.cics.uvic.ca/scenarios/sdsm/select.cgi

Table 19.1 HadCM3 predictor variables

Number	Predictor variable	Predictor description
1	mslpaf	Mean sea-level pressure
2	p_faf	Surface airflow strength
3	p_uaf	Surface zonal velocity
4	p_vaf	Surface meridional velocity
5	p_zaf	Surface vorticity
6	p_thaf	Surface wind direction
7	p_zhaf	Surface divergence
8	p5_faf	500 hPa airflow strength
9	p5_uaf	500 hPa zonal velocity
10	p5_vaf	500 hPa meridional velocity
11	p5_zaf	500 hPa vorticity
12	p500af	500 hPa geopotential height
13	p5thaf	500 hPa wind direction
14	p5zhaf	500 hPa divergence
15	p8_faf	850 hPa airflow strength
16	p8_uaf	850 hPa zonal velocity
17	p8_vaf	850 hPa meridional velocity
18	p8_zaf	850 hPa vorticity
19	p850af	850 hPa geopotential height
20	p8thaf	850 hPa wind direction
21	p8zhaf	850 hPa divergence
22	p500af	Relative humidity at 500 hPa
23	p850af	Relative humidity at 850 hPa
24	rhumaf	Near-surface relative humidity
25	shumaf	Surface-specific humidity
26	tempaf	Mean temperature at 2 m

- *H3B2_1961–2099*: This directory contains 139 years of daily GCM predictor data, derived from the HadCM3 B2(a) experiment, and normalized over the 1961–1990 period.

To apply SDSM to GCM data, both observed predictand and GCM data should ideally be available on the same grid spacing. Individual predictor (Table 19.1) and predictand files (one variable to each file, time series data only) are denoted by the extension *.DAT (Wilby et al. 2002). The predictor represents large-scale atmospheric variables whereas the predictand represents local surface variables such as temperature and precipitation.

19.2.3 The Climatological Baseline

In order to assess the implications of future changes on the environment, society, and economy on an exposure unit, it is first necessary to have information about the present-day or recent conditions as a reference point or a baseline (Carter et al. 1999; McCarthy et al. 2001). Baseline information is important for: (1) characterizing the prevailing conditions under which an exposure unit functions and to which it must adapt; (2) describing average conditions, spatial and temporal variability, and anomalous events, some of which can have significant impacts; (3) calibrating and testing impact models across the current range of variability; (4) identifying possible ongoing trends or cycles; and (5) specifying the reference situation with which to compare future changes (Carter et al. 1999).

The baseline period is usually selected according to the following criteria (Carter et al. 1994): (1) It should be representative of the present-day or recent average climate in the study region; (2) be of a sufficient duration to encompass a range of climatic variations, including a number of significant weather anomalies (e.g., severe droughts or cool seasons); (3) should cover a period for which data on all major climatological variables are abundant, adequately distributed over space, and readily available; (4) include data of sufficiently high quality for use in evaluating impacts; and (5) be consistent or readily comparable with baseline climatologies used in other impact assessments.

A popular climatological baseline period is a 30-year "normal" period, as defined by the World Meteorological Organization (WMO). The current WMO normal period is 1961–1990, which provides a standard reference for many impact studies (McCarthy et al. 2001). As well as providing a standard reference to ensure comparability between impact studies, other advantages of using this baseline period include (Carter et al. 1999):

- The period ends in 1990, which is the common reference year used for climatic and nonclimatic projections by the IPCC in the first and second assessment reports (and retained for the third assessment report).
- It represents the recent climate, to which many present-day human or natural systems are likely to have become reasonably well adapted (though there are exceptions, such as vegetation zones or groundwater levels that can have a response lag of many decades or more relative to the ambient climate).
- In most countries, the observed climatological data are most readily available for this period, especially in computer-coded form at a daily time resolution.

According to the above-listed importance and advantage, this study considered the suggested IPCC baseline period (1961–1990). Aground the catchment, only Bahir Dar meteorological station fulfills the IPCC baseline period because the observed data cover the range from 1961 to 1990. Therefore, these data were used as predictands for downscaling.

19.2.4 Climate Scenarios

As per the IPCC description, climate scenarios are plausible representations of the future that are consistent with assumptions about future emissions of greenhouse gases and other pollutants and with our understanding of the effect of increased atmospheric concentrations of these gases on global climate. These assumptions include future trends in energy demand, emissions of greenhouse gases, land use change, as well as assumptions about the behavior of the climate system over long timescales. The IPCC- Task Group on Data and Scenario Support for Impact and

Climate Assessment (IPCC-TGCIA) classified climatic scenarios into three main types (Carter et al. 2007), based on how they are constructed. These are: (1) synthetic scenarios, also known as incremental scenarios; (2) analog scenarios; and (3) climate model-based scenarios.

Special Report on Emissions Scenarios The world will have changed by 2100 in ways that are difficult to imagine—as difficult as it would have been at the end of the nineteenth century to imagine the changes of the 100 years since (Nakicenovic et al. 2000). The IPCC Special Report on Emissions Scenarios (SRES) in replacing the old IPCC scenarios (IS92) identifies 40 different scenarios following four families of storylines (Santoso et al. 2008). Each storyline represents a distinctly different direction for future developments, such as demographic, socioeconomic, technological, and environmental developments. The four qualitative storylines yield four sets of scenarios called families (A1, A2, B1, and B2).

The main characteristics of the four SRES storylines and scenario families (Nakicenovic et al. 2000) are:

- A1: The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in the middle of the century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), nonfossil energy sources (A1T), or a balance across all sources (A1B)[2].
- A2: The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.
- B1: The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- B2: The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse

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[2] Balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies.

technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

As mentioned earlier, the HadCM3 climate model has been selected for this study. Climate change and climate change impact are more understandable with the use of all available GCMs and emission scenario. However, to show the technique of how one can study future climate change, only HadCM3 was used. HadCM3 model was developed by considering A2 and B2 SRES emission scenarios.

19.2.5 Climate Model Downscaling

Downscaling Techniques GCMs indicate that rising concentrations of greenhouse gases will have significant implications for climate at global and regional scales (Wilby and Dawson 2007). Due to their coarse spatial resolution and inability to resolve important subgrid scale features, such as clouds and topography, GCMs are restricted in their usefulness for local impact studies by their coarse spatial resolution. GCMs depict the climate using a three-dimensional grid over the globe, typically having a horizontal resolution between 250 and 600 km, 10–20 vertical layers in the atmosphere, and sometimes as many as 30 layers in the oceans (Nakicenovic et al. 2000). Their resolution is thus quite coarse relative to the scale of exposure units in most impact assessments. Several methods have been adopted for developing regional GCM-based scenarios at the subgrid scale, a procedure variously known as “regionalization” or “downscaling.” Two different approaches to downscaling are possible (Hewitson and Crane 1996):

I. Dynamic (nested model) downscaling
   The typical application in this case is to drive a regional dynamic model at mesoscale or finer resolutions with the synoptic- and larger scale information from a GCM (Giorgi and Mearns 1991; Jenkins and Barron 1997). Detailed information at spatial scales down to 10–20 km and at temporal scales of hours or less may be achieved in such applications (Hewitson and Crane 1996). Such models are computationally demanding and are not an easily accessible research avenue, but in the long term, this technique is likely to be the best solution and needs to be encouraged.
II. Statistical (empirical) downscaling
   Statistical downscaling is computationally efficient in comparison with dynamical downscaling and is a practical approach for addressing current needs in the climate change research community, especially in many of the countries liable to be most sensitive to climate change impacts (Hewitson and Crane 1996).

In the empirical approach, one seeks to derive quantitative relations between circulation and local climate in some form of:

$$y = f(x) \tag{19.1}$$

where *y* represents the predictand (a regional or local climate variable), *x* is the predictor (a set large-scale atmospheric variables), and *f* is a deterministic/stochastic function conditioned by *x* and has to be found empirically from observation or modeled data sets.

Many of the processes which control local climate, e.g., topography, vegetation, and hydrology, are not included in coarse-resolution GCMs. The development of statistical relationships between the local and large scales may include some of these processes implicitly (Fig. 19.6).

Under the broad empirical/statistical downscaling techniques, the following three major techniques, which include the others, have been developed. These are weather classification/typing schemes, transfer function/regression model, and stochastic weather generators methods.

Regression models are a conceptually simple means of representing linear or nonlinear relationships between local climate variables (predictands) and the large-scale atmospheric forcing (predictors; Wilby et al. 2004). Commonly applied methods include canonical correlation analysis (CCA; von Storch et al. 1993) and artificial neural networks (ANN) which are akin to nonlinear regression (Crane and Hewitson 1998) and multiple regression (Murphy 1999).

For this particular study, a type of regression model was used which is SDSM. SDSM is widely applied in many regions of the world over a range of different climatic condition. It permits the spatial downscaling of daily predictor–predictand relationships using multiple linear regression techniques. The predictor variables provide daily information concerning the large-scale state of the atmosphere, while the predictand describes conditions at the site scale (CCIS 2008).

19.2.6 General Description of SDSM

SDSM is a decision support tool that facilitates the assessment of regional impacts of global warming by allowing the process of spatial-scale reduction of data provided by large-scale GCMs (Wilby et al. 2002). It is best described as a hybrid of the stochastic weather generator and regression-based methods. This is because large-scale circulation patterns and atmospheric moisture variables are used to linearly condition local-scale weather generator parameters (e.g., precipitation occurrence and intensity; Wilby et al. 2002).

Users are allowed to simulate, through combinations of regressions and weather generators, sequences of daily climatic data for present and future periods by extracting statistical parameters from observed data series (Gagnon et al. 2005). The stochastic component of SDSM permits the generation of 100 simulations. The SDSM software reduces the task of statistically downscaling daily weather series into seven discrete steps: (1) quality control and data transformation; (2) screening of predictor variables; (3) model calibration; (4) weather generation (using observed predictors); (5) statistical analyses; (6) graphing model output; and (7) scenario generation (using climate model predictors). The structure and operations of SDSM can

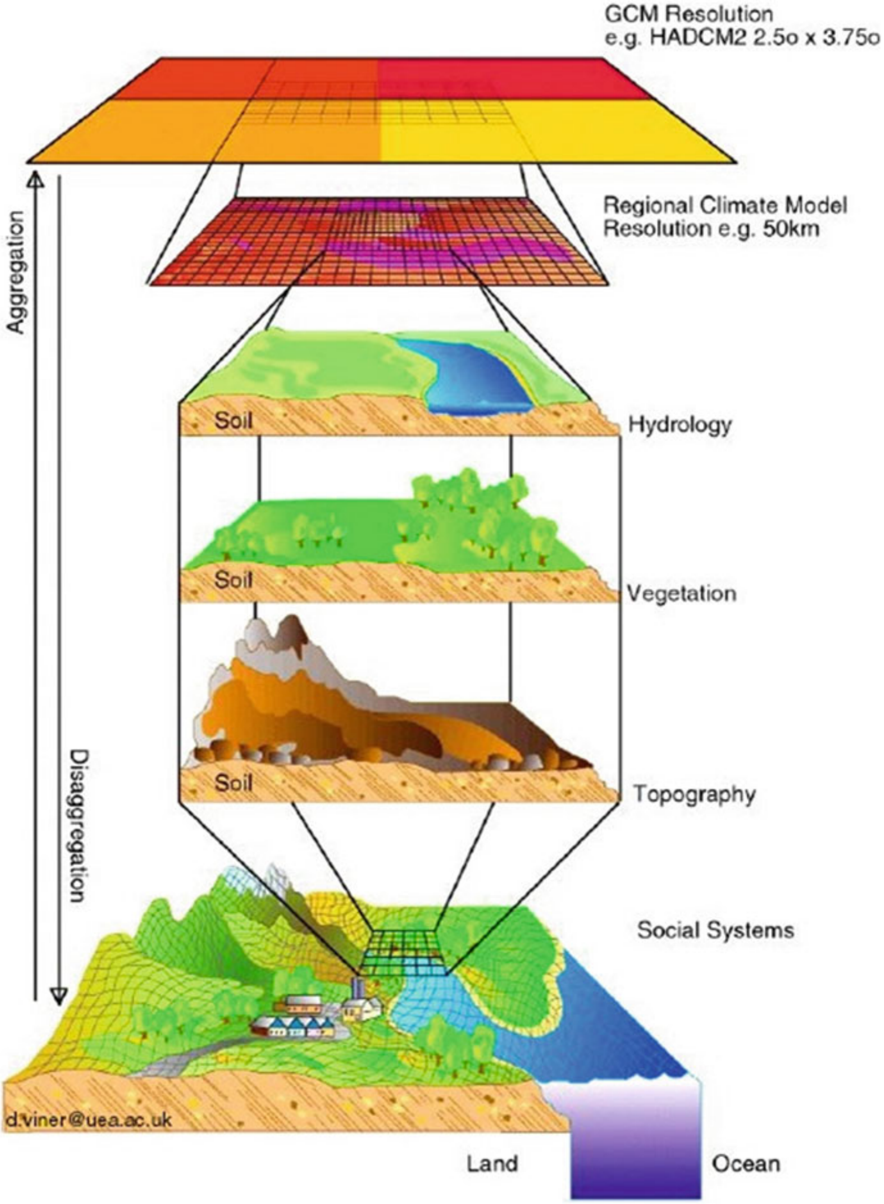

Fig. 19.6 The concept of spatial downscaling. (Source: David Viner, Climatic Research Unit, University of East Anglia, UK)

be best described with respect to the seven tasks as indicated in the bold box in the flowchart and their short descriptions below the flowchart as shown in Fig. 19.7 (Wilby and Dawson 2007).

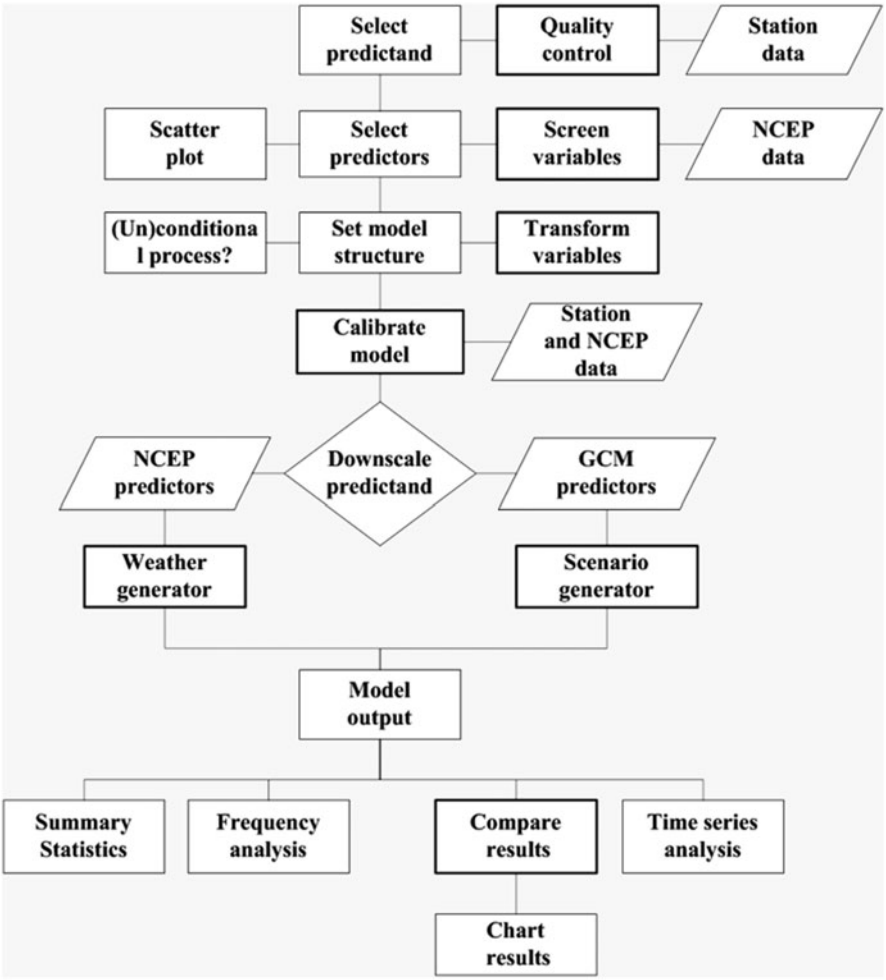

Fig. 19.7 SDSM version 4.2 climate scenario generation. (Wilby and Dawson 2007)

Quality Control and Data Transformation The quality control in SDSM is used to identify the gross data error, specification of missing data code, and outliers prior to model calibration. In many instances, it may be appropriate to transform predictors and/or the predictand prior to model calibration. The transform facility takes chosen data files and applies selected transformations (e.g., logarithm, power, inverse, lag, binomial).

Screening of the Predictor Variables Identifying empirical relationships between gridded predictors (such as mean sea-level pressure) and single-site predictands (such as station precipitation) is central to all the statistical downscaling methods. The main purpose of screen variables operation is to assist the user in the selection of appropriate downscaling predictor variables.

Model Calibration Model calibration takes the specified predictand along with a set of predictor variables and computes the parameters of multiple regression equations via an optimization algorithm (either dual simplex of ordinary least squares). Then, specification of the model structure, whether monthly, seasonal, or annual submodels are required; or whether the process is unconditional or conditional. In unconditional models, a direct link is assumed between the predictors and predictands, but in conditional models, there is an intermediate process between regional forcing and local weather.

Weather Generator The weather generator operation generates ensembles of synthetic daily weather series given observed (or NCEP reanalysis) atmospheric predictor variables. The procedure enables the verification of calibrated models (using independent data) and the synthesis of artificial time series for present climate conditions.

Data Analysis SDSM provides means of interrogating both downscaled scenarios and observed climate data with the Summary Statistics and Frequency Analysis screens. For model output, the ensemble member or mean must also be specified. In return, SDSM displays a suite of diagnostics including monthly/seasonal/annual means, measures of dispersion, and serial correlation and extreme.

Graphical Analysis Three options of graphical analysis are provided by SDSM 4.2 through the Frequency Analysis, Compare Results and the Time Series Analysis screens.

Scenario Generations Finally, the Scenario Generator operation produces ensembles of synthetic daily weather series for the potential atmospheric predictor variables supplied by a climate model (for either present or future climate experiments), rather than observed predictors.

19.2.6.1 Model Setup

I. General Model Setting

Year Length The normal calendar year (366) which allows 29 days in February every fourth year is used whenever dealing with predictand and NCEP predictor, whereas the year length of 360 days is used in the scenario generation since HadCM3 model uses years having 360 days. The 360-day calendar divides a year into 12 months, each of 30 days in length.

Event Threshold The event threshold is set to zero for temperature and 0.1 mm/day for precipitation to treat trace rain days as dry days.

Model Transformation The default (none) is used for predictand that is normally distributed and unconditional as in the case of daily temperature and fourth root transformation is applied for precipitation since the model is conditional and the data are skewed.

Table 19.2 Selected large-scale predictor variables for the predictands of Bahir Dar station

Predictand	Predictor	Description	Month correlated
Precipitation	ncepr500	Relative Humidity at 500 hPa	Jan, Feb, Apr, Aug, Nov, Dec
	ncephum	Near surface relative humidity	Jun, Sep, Oct
Maximum temperature	ncepp5_u	500 hPa zonal velocity	Feb, Apr
	ncepp500	500 hPa geopotential height	Jan, Oct, Nov, Dec
	nceptemp	Mean temperature at 2 m	Mar, May, Jun, Jul, Aug, Sep
Minimum temperature	ncepp500	500 hPa geopotential height	Feb, Mar, Apr, May, Jun, Jul, Aug
	ncepshum	Surface specific humidity	Sep, Oct, Nov, Dec
	nceptemp	Mean temperature at 2 m	Jan

Variance Inflation Variance inflation controls the magnitude of variance inflation in the downscaled daily weather variables. This parameter can be adjusted during the calibration period to force the model to replicate the observed data. The default (i.e., 12) produces approximately normal variance inflation prior to any transformation and is applied to maximum and minimum temperatures. For precipitation, this parameter can be adjusted during the calibration period.

II. Predictor Variables Screening

The choice of predictor variable is one of the most influential steps in the development of statistical downscaling procedure. Identifying empirical relationships between gridded predictors and single-site predictands is central to all statistical downscaling. The screen variable option in SDSM assists the choice of appropriate downscaling predictor variables through seasonal correlation analysis, partial correlation analysis, and scatter plots. One of the approaches is to choose all predictors and run the explained variance on a group of 12, at a time. Out of the groups, those predictors which have high explained variance are selected. Then, partial correlation analysis is done for selected predictors to see the level of correlation with each other. There could be a predictor with a high explained variance but it might be very highly correlated with another predictor. This means that it is difficult to tell that this predictor will add information to the process, and, therefore, it will be dropped from the list. Finally, the scatter plot indicates whether this result is due to a few outliers or whether it is a potentially useful downscaling relationship. The selected predictor variables for precipitation and temperature are shown in Table 19.2.

III. Model Calibration

The calibration model process constructs downscaling models based on multiple regression equations, given daily weather data (the predictand), and regional-scale, atmospheric (predictor) variables. The model structure for calibration can be specified by selecting either the unconditional or the conditional process. In conditional models, a direct link is assumed between the predictors and predictand. In unconditional models, there is an intermediate process between the regional forcing and local weather (e.g., local precipitation amounts depend on wet-/dry-day occurrence, which in turn depends on regional-scale predictors, such as humidity and atmospheric pressure). The model structure is set to unconditional for maximum and minimum temperatures and conditional for precipitation. The model type determines whether individual downscaling models will be calibrated for each calendar month, climatological season, or entire year. The model is structured as a monthly model for both precipitation and temperature downscaling, in which case, 12 regression equations are derived for 12 months using different regression parameters for each month equation. Finally, the data period should be set in order to specify the start and end date of the analysis. The calibration was done for a period of 20 years (1961–1980), and the rest 10 years were considered as validation period.

IV. Weather Generator/Scenario Generator

The Weather Generator operation generates ensembles of synthetic daily weather series given observed (or NCEP reanalysis) atmospheric predictor variables. The procedure enables the verification of calibrated models (using independent data) and the synthesis of artificial time series for present climate conditions. Scenario Generation operation produces ensembles of synthetic daily weather series given the regression weight produced during the calibration process and the daily atmospheric predictor supplied by a GCM (under either the present or the future greenhouse gas forcing). These functions are identical in all respects except that it may be necessary to specify a different convention for model dates and source directory for predictor variables.

The two operations that were settled synthesize 20 daily ensembles either in the case of NCEP (1961–1990) or in the case of GCM (1961–2099) for maximum and minimum temperatures. Precipitation downscaling is necessarily more complex than temperature because daily precipitation amounts at individual sites are relatively poorly resolved by the regional-scale predictors, and precipitation is a conditional process (i.e., both the occurrence and amount processes must be specified) (Wilby and Dawson 2007). Regarding precipitation complexity, increasing the ensemble number (up to 100) improves this problem.

19.3 Result and Discussion

19.3.1 Downscaling of Climate Variables

19.3.1.1 Selection of Predictor Variables

The best correlated predictor variables selected for precipitation, and maximum and minimum temperatures with the corresponding month which have a strong correlation between predictands and each predictor are listed in Table 19.2. Predictand and predictor have good correlations that means the predictor has the best performance to downscale the global climate variables to local-scale climate variable compared to others. For instance, relative humidity at 500 hPa and near-surface relative humidity had good performance to downscale precipitation rather than other predictors. Also, relative humidity at 500 hPa was very good predictor for the months January, February, April, August, November, and December, whereas precipitation for the months of June, September, and October was efficiently downscaled with near-surface relative humidity.

Table 19.3 Downscaled daily precipitation, maximum and minimum temperature efficiency (R^2) relative to observed data

Variables	R^2	
	Calibration (1961–1980)	Validation (1981–1990)
Precipitation	0.24	0.25
Maximum temperature	0.66	0.64
Minimum temperature	0.57	0.56

19.3.2 Baseline Scenarios

Baseline scenario analysis was performed for Bahir Dar station within 30-year period from 1961 to 1990. Thus, the HadCM3 was downscaled for daily base period for two emission scenarios (A2 and B2), and some of the statistical properties of the downscaled data were compared with daily observed data. One of the criteria commonly used in evaluating the performance of any useful downscaling is whether the historic or observed condition can be replicated or not.

The downscaled baseline daily temperatures show good agreement with observed data. However, due to the conditional nature of daily precipitation, downscaled values have less concurrence with observed daily data. In conditional models, there is an intermediate process between regional forcing and local weather (e.g., local precipitation amounts depend on wet-/dry-day occurrence, which in turn depends on regional-scale predictors, such as humidity and atmospheric pressure) (Wilby et al. 2004). Additionally, complicated nature of precipitation processes and its distribution in space and time are the other reasons for its concurrence. Climate model simulation of precipitation has improved over time but is still problematic (Bader et al. 2008) and has a larger degree of uncertainty than those for temperature (Thorpe 2005). This is because rainfall is highly variable in space and, so, the relatively coarse spatial resolution of the current generation of climate models is not adequate to fully capture that variability.

Coefficient of determination (R^2) for daily observed versus simulated (downscaled) data clearly shows the difference between unconditional and conditional models for both calibration and validation (Table 19.3).

The replication of the observed data by the model is much better (with coefficient of determination nearly one), when the timescale resolution is reduced to monthly and annual. For this reason, baseline scenario mean monthly precipitation, maximum temperature, and minimum temperature of observed and downscaled data are compared and discussed in the next section.

A. Precipitation SDSM estimated the mean monthly precipitation by performing reasonably. This is why temporal resolution of the analysis changed from daily to mean monthly values. Figure 19.8a shows this truth but there is a relatively small model error in the month of July and August as compared to other months. Mean monthly totals of observed and downscaled precipitation of July are 437.7 and 447.8 mm and of August are 382.5 and 395.4 mm, respectively. This result of precipitation was checked by plotting the absolute model errors monthly and shows (Fig. 19.9a) a good agreement to that obtained during downscaling.

B. Maximum Temperature The downscaled maximum temperature for baseline period shows good agreement between observed and downscaled values than that of precipitation and minimum temperature both in A2 and in B2 emission scenarios (Fig. 19.8b).

The monthly absolute model error of the downscaled maximum temperature for the baseline period shows an almost similar result. As compared to other months, February and July have somehow slightly higher model errors, though the magnitude is small (Fig. 19.9b).

C. Minimum Temperature Like that of the maximum temperature, the downscaled minimum temperature shows a satisfactory agreement with the observed minimum temperature for all months both under A2 and under B2 emission scenarios, except a little variation in the months of January, February, and May. Absolute model error of the downscaled minimum temperature ensures this truth. The model error therefore ranges from 0.1 to 0.2 °C. See Figs. 19.8c and 19.9c.

19.3.2.1 Future Scenario

Checking the efficiency of the downscaling model which can replicate the observed statistical properties for future scenarios or does not help to project daily future climate variables for the next century using the HadCM3 (A2 and B2) global circulation model. The projection generates 20 ensembles of daily temperature and 100 ensembles of daily precipitation variables. These ensembles are averaged out in order to consider the characteristics of all those ensembles.

The analysis was done for three 30 years of data ranges based on recommendation of the WMO as the 2020s (2011–2040), 2050s (2041–2070), and 2080s (2071–2099). The generated scenarios were dealt with individually for each baseline predictand as below.

A. Precipitation The result of rainfall projection is discussed on a mean annual, seasonal, and monthly basis. This research considered monomodal (one wet season) base seasonal classifications of Ethiopia which are namely *Bega* (October–January), a dry season, *Belg* (February–May), a short rainy season, and *Kiremt* (June–September), a long rainy season.

Keeping its spatial and temporal variability, rainfall projection did not show a magnified increasing or decreasing unlike the maximum and minimum temperatures for both A2 and B2 emission scenarios. Rainfall, experiences a mean annual increase by 2.21, 2.23, and 1.89 % for A2 scenario in the 2020s, 2050s, and 2080, respectively. This mean annual increase was repeated by B2 scenario with 2.06, 1.85, and 0.36 % in the 2020s, 2050s, and 2080, respectively. These values show that the trend is not increasing uniformly; instead, it differs from one time horizon to another.

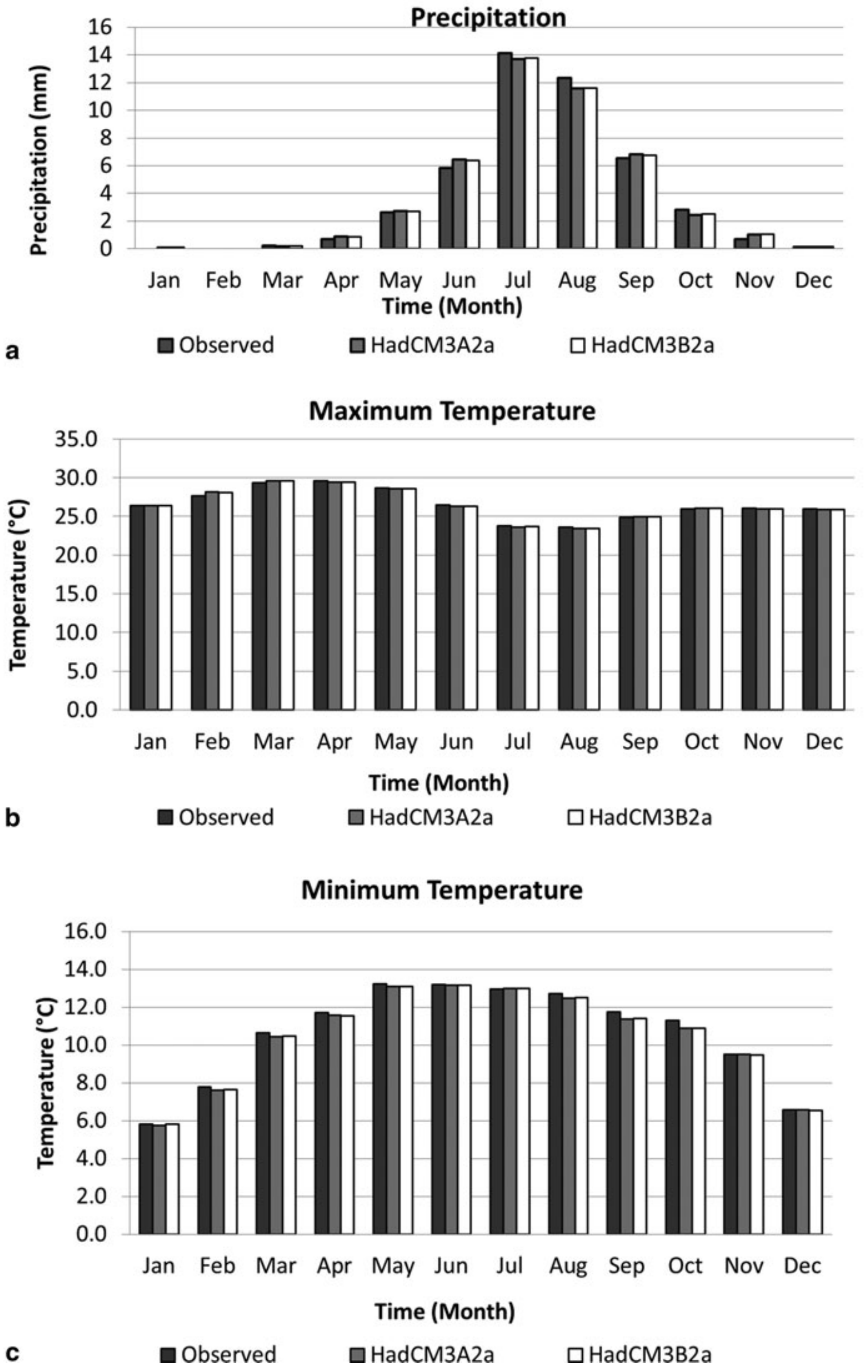

Fig. 19.8 Baseline period (1961–1990) mean monthly observed and downscaled precipitation (**a**), maximum temperature (**b**), and minimum temperature (**c**)

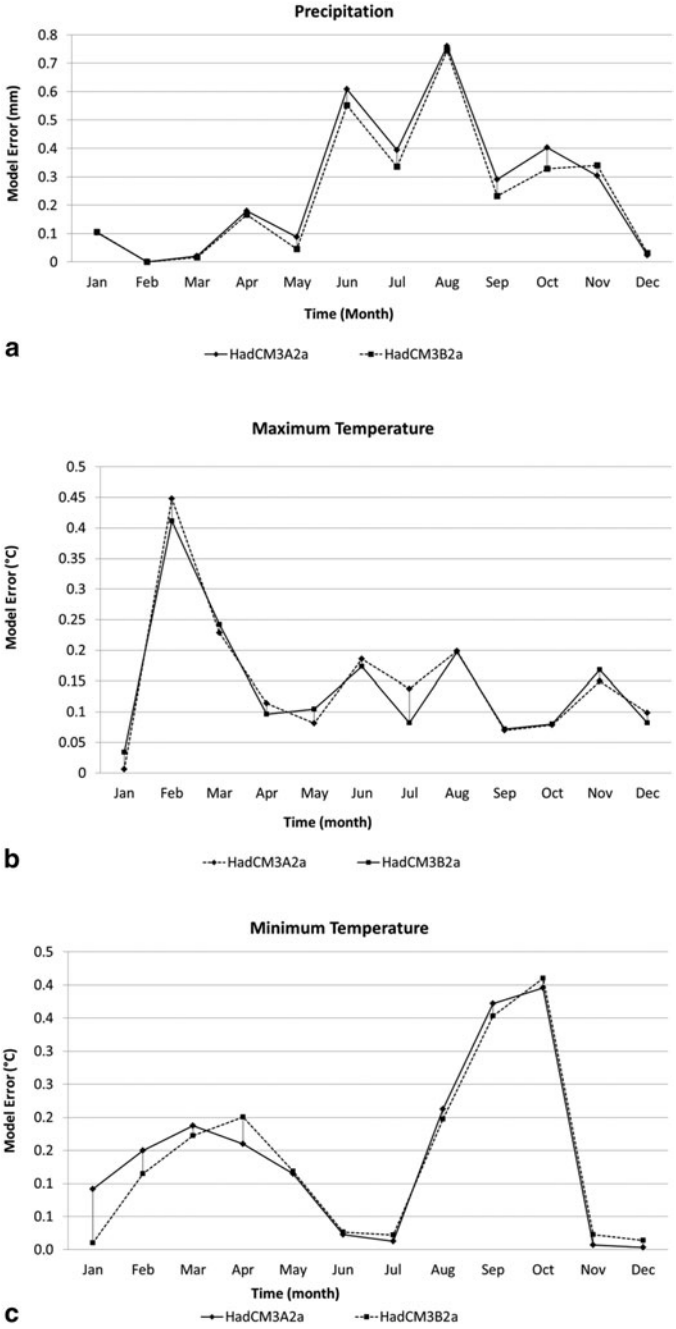

Fig. 19.9 Absolute model error of mean monthly precipitation (**a**), maximum temperature (**b**), and minimum temperature (**c**) (1961–1990)

Table 19.4 Future percentage precipitation changes of A2 and B2 scenario

Precipitation (percentage difference)						
Month	A2 scenario			B2 scenario		
	2020s	2050s	2080s	2020s	2050s	2080s
Jan	– 0.17	31.48	21.70	10.37	0.91	– 13.35
Feb	6.87	26.91	15.20	38.82	1.86	33.75
Mar	11.06	13.98	7.81	3.90	5.64	5.70
Apr	– 24.71	– 11.21	– 6.30	– 13.24	– 8.38	– 6.26
May	– 0.64	– 0.33	– 5.45	7.96	0.75	0.98
Jun	– 1.51	– 2.30	– 7.14	– 1.85	– 0.79	– 5.88
Jul	– 0.26	1.33	– 0.97	1.22	– 1.21	– 1.03
Aug	0.23	– 1.38	– 2.60	– 0.24	0.51	– 1.84
Sep	10.75	3.89	7.96	5.05	10.11	8.07
Oct	13.70	24.02	34.95	10.62	5.09	3.09
Nov	24.33	31.05	48.86	17.54	22.02	27.17
Dec	17.44	16.09	25.86	0.99	4.95	0.50
Annual	2.21	2.23	1.89	2.06	1.85	0.36

A rainfall projection of *Bega* (October–January) shows an increase for the two emission scenarios, except for the 2080s of B2 scenario. Whereas, *Belg* (February–May) projection shows a decrease in mean monthly rainfall for the first 2 months (February and March) and increase for the last 2 months (April and May) of the season for A2 scenario. In case of B2 scenario with this *Belg* season, rainfall is increasing in May in the 2020s. The *Kiremt* (June–September) season of the 2 months (June and July) shares the rainfall decrease of April and May in the 2080s. Except for September (increasing), the *Kiremt* season more or less has nearly constant rainfall (see Table 19.4, Figs. 19.10a, b).

The projected mean monthly rainfall of this study has a similar pattern to that of the work of Abdo et al. (2009) and deBoer (2007) using HadCM3 and European Centre Hamburg Model 5/Max-Planck-Institut für Meteorologie (ECHAM5/MPIOM) global climate models in the same catchment. These works were done on the Gilgel Abay River catchment and northern Ethiopian highlands. Both of the studies agreed with the mean monthly rainfall decrease in May, June, and July and increase in September, October, and November compared to the baseline period. Similarly, on IPCC third assessment report of McCarthy et al. (2001), rainfall is predicted to increase in December–February and decrease in June–August in parts of East Africa under intermediate warming scenarios. This IPCC report strengthens this research output on increasing mean monthly rainfall from December to February and decreasing a little bit from June to August, for both A2 and B2 scenarios.

B. Maximum Temperature The projected maximum temperature for mean annual shows an increase trend for all time horizons by 0.43, 1.05, and 1.92 °C for A2 scenario in the 2020s, 2050s, and 2080, respectively. B2 scenario also shows an increase of mean annual maximum temperature with 0.47, 0.87, and 1.38 °C in the 2020s, 2050s, and 2080s, respectively. As compared to B2 scenario, A2 scenario has a faster increasing trend. The increase will include all months largely for all time horizons except April (Table 19.5, Figs. 19.10c, d).

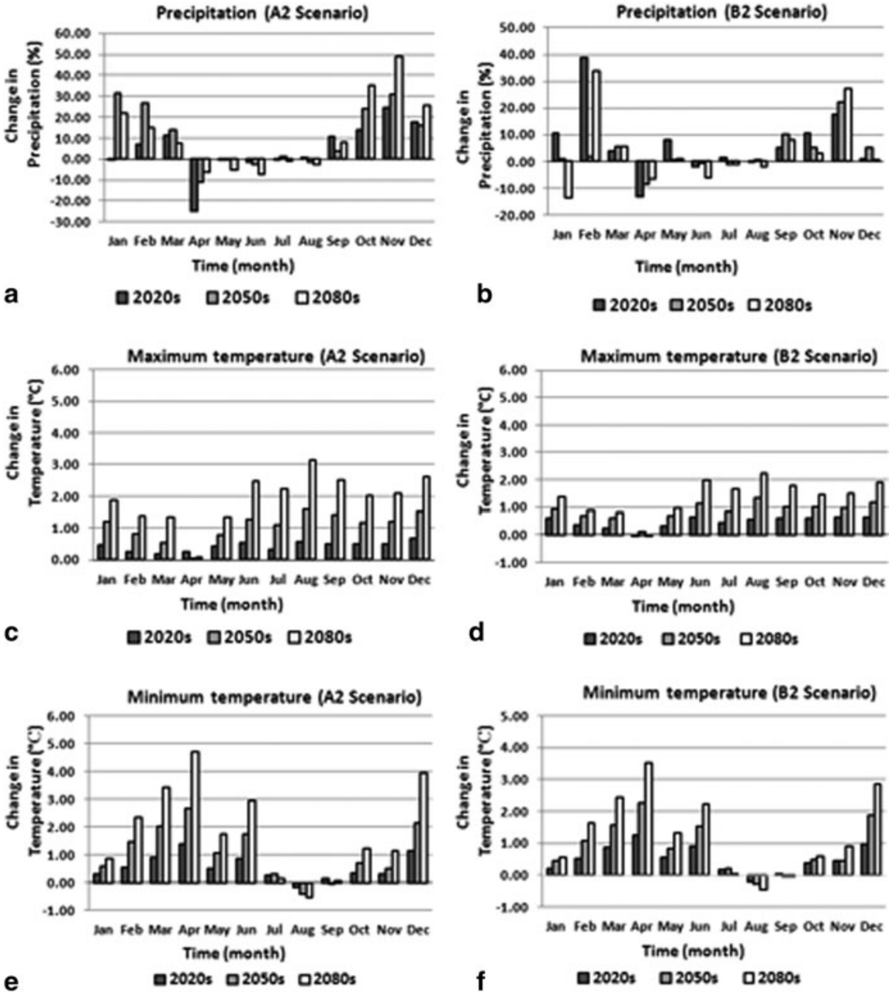

Fig. 19.10 The future absolute change in mean monthly precipitation for A2 (**a**) and B2 (**b**) scenarios; maximum temperature for A2 (**c**) and B2 (**d**) scenarios; minimum temperature for A2 (**e**) and B2 (**f**) scenarios from the baseline period

C. Minimum Temperature The projected minimum temperature shows an increasing trend in all time horizons. In this case, both the A2 and B2 emission scenarios generate the future minimum temperature in similar manner. For A2 scenario, mean annual minimum temperature increases by 0.55, 1.06, and 1.83 °C and for B2 scenario, 0.50, 0.87, and 1.29 °C in the 2020s, 2050s, and 2080, respectively. Mean monthly variation of minimum temperature is higher than maximum temperature. For both A2 and B2 emission scenarios, the minimum temperature will be expected

Table 19.5 Future absolute maximum temperature changes of A2 and B2 scenarios

Maximum temperature (absolute difference)

Month	A2 scenario			B2 scenario		
	2020s	2050s	2080s	2020s	2050s	2080s
Jan	0.45	1.20	1.87	0.61	0.92	1.38
Feb	0.24	0.80	1.36	0.34	0.66	0.87
Mar	0.18	0.54	1.34	0.25	0.58	0.82
Apr	0.26	0.02	0.07	– 0.01	0.12	– 0.03
May	0.42	0.77	1.33	0.32	0.67	0.97
Jun	0.54	1.26	2.48	0.63	1.15	2.00
Jul	0.34	1.10	2.23	0.43	0.86	1.67
Aug	0.57	1.59	3.15	0.56	1.34	2.21
Sep	0.49	1.42	2.50	0.60	1.02	1.77
Oct	0.51	1.15	2.02	0.59	0.99	1.47
Nov	0.50	1.21	2.09	0.63	0.97	1.50
Dec	0.68	1.54	2.61	0.65	1.16	1.90
Annual	0.43	1.05	1.92	0.47	0.87	1.38

to increase from October to June. The difference from other months is in July, August, and September. Especially in August, a decreasing trend will be expected to dominate (Table 19.6, Figs. 19.10e and 19.10f).

Generally, the projected minimum and maximum temperatures in all time horizons are within the range projected by IPCC, which says that the average temperature will rise by 1.4–5.8 °C toward the end of this century. In relation to this, one can understand and link the result of maximum and minimum temperature results to IPCC emission scenario storylines that increment for A2 scenario is greater than B2 scenario because A2 scenario represents a medium-high scenario which produces more carbon dioxide concentration than the B2 scenario which represents a medium-low scenario.

19.4 Conclusion

HadCM3, which is one of the global climate models used in this research, was downscaled for the Upper Gilgel Abay River catchment using Bahir Dar meteorological station climate variables as predictands. The statistical downscaling model (SDSM), which is a multiple regression model, was the tool to downscale the GCM by considering IPCC climatological baseline (1961–1990). The predictors supplied by HadCM3 contain daily observed predictor (NCEP) and daily GCM predictor data developed to A2 (medium-high emissions) and B2 (medium-low emissions) scenarios.

Downscaling results of baseline predictor variables (NCEP) showed that maximum and minimum temperature values gave a better R^2 of NCEP reanalysis versus observed data and the value ranges from 0.56 to 0.66. This shows that future projections of maximum and minimum temperatures would be well replicated. The

Table 19.6 Future absolute minimum temperature changes of A2 and B2 scenarios

Minimum temperature (absolute difference)						
Month	A2 scenario			B2 scenario		
	2020s	2050s	2080s	2020s	2050s	2080s
Jan	0.31	0.58	0.87	0.19	0.46	0.55
Feb	0.55	1.46	2.34	0.51	1.07	1.65
Mar	0.91	2.03	3.44	0.88	1.56	2.43
Apr	1.37	2.67	4.73	1.23	2.24	3.51
May	0.51	1.05	1.74	0.55	0.84	1.31
Jun	0.87	1.74	2.94	0.90	1.53	2.21
Jul	0.27	0.29	0.13	0.16	0.21	0.02
Aug	– 0.20	– 0.41	– 0.54	– 0.23	– 0.31	– 0.47
Sep	0.14	– 0.06	0.05	0.02	– 0.01	– 0.01
Oct	0.36	0.69	1.22	0.36	0.47	0.59
Nov	0.30	0.52	1.13	0.45	0.46	0.90
Dec	1.16	2.13	3.95	0.96	1.89	2.84
Annual	0.55	1.06	1.83	0.50	0.87	1.29

precipitation computation, on the other hand, showed that the calibrated model performed poorly to replicate the independent data set with R^2 of 0.24 and 0.25 for calibration and validation, respectively. This is due to complicated nature of precipitation processes and its distribution in space and time. However, when the daily data are aggregated to mean monthly, the observed data is simulated better.

Results of downscaling for future projections of climate variables showed that rainfall experiences a mean annual increase by 2.21, 2.23, and 1.89 % for A2 scenario in the 2020s, 2050s, and 2080s, respectively. Mean annual increases of rainfall are also expected in B2 scenario with 2.06, 1.85, and 0.36 % in the 2020s, 2050s, and 2080, respectively. Percentage changes of both A2 and B2 scenarios showed that the trend is not increasing uniformly; instead, it differs from one time horizon to another. Similar to the Abdo et al. (2009) findings, mean annual rainfall variation is less than mean monthly rainfall. The variation was clearly observed from one month to another and also from one time horizon to another.

Maximum temperature will be expected to increase for future time projections as the results showed. The projected maximum temperature shows an increasing trend for annual mean for all time horizons by 0.43, 1.05, and 1.92 °C for A2 scenario in the 2020s, 2050s, and 2080, respectively. B2 scenario also shows an increase of mean annual maximum temperature of 0.47, 0.87, and 1.38 °C in the 2020s, 2050s, and 2080s, respectively. Minimum temperature projections for A2 scenario showed mean annual increase of 0.55, 1.06, and 1.83 °C and for B2 scenario 0.50, 0.87, and 1.29 °C in the 2020s, 2050s, and 2080, respectively. Mean monthly variation of minimum temperature is higher than maximum temperature. As compared to B2 scenario, A2 scenario has a faster increasing trend because A2 scenario represents a medium-high scenario which produces more carbon dioxide concentration than the B2 scenario which represents a medium-low scenario. Based on the results of several GCMs using the data collected by the IPCC Data Distribution Center (IPCC-DDC), future warming across Africa will range from 2 °C (low scenario) to 5 °C (high scenario) by 2100 (Shaka 2008). Therefore, the results obtained from HadCM3 are supported by the recommended range of IPCC.

Generally, this work considered one climate model only. However, climate change and climate change impact studies will be fruitful if they account for different GCMs and emission scenarios to minimize all types of uncertainties due to assumptions and parameterizations of climate model representation and also different downscaling techniques.

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Chapter 20
Climate Change Impact on Water Resources and Adaptation Strategies in the Blue Nile River Basin

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Abstract We compared projected changes in precipitation and temperature across global climate models (GCMs) for two future periods to get an indication of the consistency of the projected changes in the Lake Tana subbasin of the Blue Nile basin. We found that the models projected temperature increases of around 2 °C to 5 °C for 2080–2100, depending on the model and emission scenario. The interquartile ranges of the projected temperature increases for 2070–2100 for the three emission scenarios show 2.0−4.4 °C in the wet season and 2.2−4.9 °C in the dry season. The ensemble of GCMs we examined includes models that project increases and decreases in seasonal precipitation. The interquartile ranges of the projected rainfall changes for 2070–2100 for the three emission scenarios show − 13 to + 12 % in the wet season and − 14 to + 16 % in the dry season. The study investigated how changes in temperature and precipitation might translate into changes in streamflows and other hydrological components using downscaled outputs from different climate models. The direction of streamflow changes followed the direction of changes in rainfall. The responses of evapotranspiration, soil moisture (SW), and groundwater (GW) were also examined, and it was found that changes in GW flow may be a significant component of the changes in streamflow.

The effect of climate change has the potential to cause agricultural drought, unless there is ample water available for irrigation. However, a reduction in rainfall may

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cause reduced GW recharge, which would significantly reduce its contribution to streamflow. Lake Tana is highly sensitive to variations in rainfall, as well as in river inflows and evaporation.

Keywords Climate change · Adaptation · Blue nile · Lake tana · Impact · Water resources

20.1 Introduction

A major effect of climate change is likely to be alterations in hydrologic cycles and changes in water availability. Increased evaporation, combined with changes in precipitation, has the potential to affect runoff, the frequency and intensity of floods and droughts, soil moisture (SW), and available water for irrigation and hydroelectric generation. In addition, watershed hydrology is affected by vegetation types, soil properties, geology, terrain, land use practices, and the spatial pattern of interactions among these factors and with climate (Richey et al. 1989; Laurance 1998; Schulze 2000; Fohrer et al. 2001; Zhang et al. 2001; Huang and Zhang 2004, Brown et al. 2005, van Roosmalen et al. 2009; Tu 2009; etc.). The Intergovernmental Panel on Climate Change's (IPCC 2007) findings suggest that developing countries like Ethiopia will be more vulnerable to climate change due to their economic, climatic, and geographic settings. According to IPCC (2007), the population at risk of increased water stress in Africa is projected to be between 75 and 250 million and between 350 and 600 million by the 2020s and 2050s, respectively. Moreover, yields from rain-fed agriculture could be reduced by up to 50 % in countries which depend mainly on rain-fed agriculture.

The economy of Ethiopia mainly depends on agriculture and this, in turn, largely depends on available water resources. Given a large part of the country is arid and semiarid and highly prone to drought and desertification, this represents a significant risk. Also, the country has a fragile highland ecosystem that is currently under stress due to increasing population pressure. The Blue Nile River basin is one of the most sensitive basins to changing climate and water resources variability in the region (Kim and Kaluarachchi 2009). But the effects of climate change on water availability (with respect to water resources analysis, management, and policy formulation in the country) in the Lake Tana basin have not been adequately addressed. Hence, it is necessary to improve our understanding of the problems involved due to the changing climate.

There are limited climate change impact studies in Ethiopia (Tarekegn and Tadege 2006; Kim and Kaluarachchi 2008; Abdo et al. 2009, Melesse et al. 2009). But much of the previous research focused on the influence of climate variability and change in the region has been based on a limited number of global climate models (GCMs). To make a conclusion about the effect of climate change on the watershed hydrology using a particular GCM may not give a clear representation of the future changes.

High uncertainty is expected in climate change impact studies if the simulation results of a single GCM are relied upon (IPCC 1999, 2007).

Different studies have been conducted to assess the impact of climate change on hydrology in different parts of the world (Gleick and Chalecki 1999; Neff et al. 2000; Groisman et al. 2001; Chang 2003; Novotny and Stefan 2007; Kim and Kaluarachchi 2009; Abdo et al. 2009). Many of these studies indicated water resource variability associated with climate change. We note that a few studies have quantified the combined effects of future climate and land use changes on hydrology (Tu 2009; van Roosmalen et al. 2009; Quilbe et al. 2008) which is a key study area for the future.

In this study, we investigated the potential effects of climate change on water resources in the Lake Tana basin, Ethiopia, by analyzing outputs from GCM models. To get an indication of the consistency of the projected changes in the region we first compared projected changes in precipitation and temperature across models for two seasons and three time periods. We then investigated how changes in daily temperature and precipitation might translate into changes in streamflow and other hydrological components, using outputs from nine climate models for two time periods (2046–2065 and 2080–2100). We generated daily climate projections by modifying the historical datasets to represent the changes in the GCM climatologies. The physically based Soil Water Assessment Tool (SWAT) model was used to determine the impact of climate change on the surface and groundwater (GW) resources availability in the Lake Tana basin. The SWAT model was calibrated and validated using historical data from four rivers which flow into Lake Tana: Gumera, GilgelAbay, Megech, and Ribb rivers (Setegn et al. 2009).

20.2 Water Resources in Ethiopia

20.2.1 River Basins

Ethiopia consists of three climatic zones depending on topography and geographic location: the cool zone above 2,400 m where temperatures range from near freezing to 16 °C; the temperate zone at elevations of 1,500–2,400 m with temperatures from 16 to 30 °C; and the hot zone below 1,500 m with both tropical and arid conditions and daytime temperatures ranging from 27 to 50 °C. Annual rainfall varies from less than 100 mm in the low lands along the border with Somalia and Djibouti to 2,400 mm in the southwest highlands, with a national average of 744 mm/year. The topography of Ethiopia ranges from very high mountain ranges (the Semien Mountains, Ras Dejen 4,620 m, and the Bale Mountains), to one of the lowest elevations in Africa (the Danakil depression 125 m). The main rainy season is from June to September (longer in the southern highlands) preceded by intermittent showers from February to March; the rest of the year is mainly dry weather. Ethiopia is known for its enormous water resources potential. It is still known as the water tower of Africa, the source of the Nile River and many transboundary rivers. The total annual runoff is estimated about 110 billion m^3, and only less than 5 % is used in the country, the remaining leaves the country as transboundary rivers such as Blue Nile, Baro-Akobo, Wabi Shebele, Tekeze, Genale-Dawa, etc. Ethiopia has three principal drainage systems. The first and largest is the western system, that includes the watersheds of the Blue Nile (known as the Abbay in Ethiopia), the Tekeze, and the Baro rivers. All three rivers flow west to the White Nile in Sudan. The second system is the Rift Valley internal drainage system, composed of the Awash River, the Lakes Region, and the Omo River. The Awash flows northeast to the Denakil Plain before it dissipates into a series of swamps and Lake Abe at the border with Djibouti. The Lakes Region is a self-contained drainage basin, and the Omo flows south into Lake Rudolf, on the border with Kenya. The third system is the Shebele and Genale rivers. Both of these rivers originate in the Eastern Highlands and flow southeast toward Somalia and the Indian Ocean. Only the Genale (known as the Jubba in Somalia) makes it to the sea; the Shebele disappears into sand just inside the coastline.

20.2.2 Blue Nile River Basin

The Blue Nile River originates from the Lake Tana in Ethiopia. It flows south from Lake Tana and then west across Ethiopia and northwest into Sudan. The Blue Nile eventually joins the White Nile at Khartoum, Sudan, and the Nile continuous through Egypt to the Mediterranean Sea at Alexandria. The river has a drainage area of 199, 812 km^2 and supplies nearly 84 % of the water of the Nile River during high-flow season. It accounts for about 17.5 % of the land area and 50 % of its annual average surface water resources of Ethiopia. It is the main source of water for Ethiopia, Sudan, and Egypt (Peggy et al. 1994). Flow volumes along the Blue Nile range from approximately 4 billion m^3 annually at the outlet of Lake Tana to 50 billion m^3 at the Ethio-Sudan border. From Lake Tana, the Blue Nile travels 35 km to the Tissisat falls, where the river drops 50 m; it then flows through a gorge, which in some places is as deep as 1,200 m. The major tributaries joining the Blue Nile between Lake Tana and the Sudan border are: Beshilo, Didessa, Finchaa, Guder, Muger, Wenchit, Jemma, Birr, Temcha, and Beles. The flow of the Blue Nile reaches its maximum discharge in the main rainy season (from June to September), when it supplies more than two thirds of the water of the Nile River. The basin has an average annual runoff of about 50 billion m^3.

20.2.3 Lake Tana Basin

Lake Tana basin (Fig. 20.1) is one of the major basins that significantly contributes to the livelihoods of tens of millions of people in the lower Nile River basin. Lake Tana occupies a wide depression in the Ethiopian plateau. The lake is shallow, oligotrophic, and freshwater, with weak seasonal stratification (Wood and Talling 1988; Wudneh

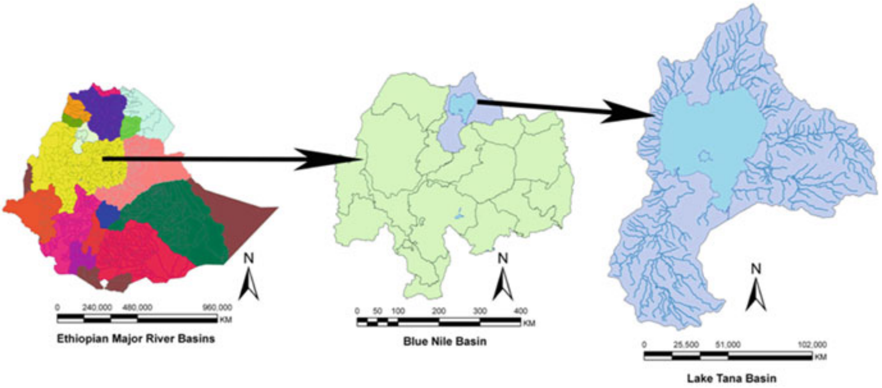

Fig. 20.1 Lake Tana subbasin, upper Blue Nile River basin

1998). The lake is believed to have been formed due to damming by lava flow during the Pliocene (Mohr 1962), but the formation of the depression itself started in the Miocene (Chorowiz et al. 1998). Lake Tana basin comprises a total area of 15,096 km^2 including the lake area. The estimated mean annual precipitation of the study area ranges from 1,200 to 1,600 mm based on data from 1961 to 2000 depending on the studies (Gamachu 1977; Conway 2000; Kim et al. 2008; Setegn et al. 2009). The annual mean actual evapotranspiration (AET) and water yield of the catchment area is estimated to be 773 and 392 mm, respectively (Setegn et al. 2009). It is rich in biodiversity with many endemic plant species and cattle breeds; it contains large areas of wetlands and is home to many endemic birds and cultural and archaeological sites. This basin is of critical national significance as it has a great potential for irrigation, hydroelectric power, high-value crops and livestock production, ecotourism, and others. Lake Tana is located in the country's northwest highlands (Lat 12° 0' North, Lon 37° 15' East) (Fig. 20.1). The lake is a natural type which covers 3,000–3,600 km^2 area at an elevation of 1,800 m and with a maximum depth of 15 m. It is approximately 84 km long and 66 km wide. It is the largest lake in Ethiopia and the third largest in the Nile basin. Gilgel Abay, Ribb, Gumera, and Megech are the main rivers feeding the lake which contributes more than 93 % of the inflow. It is the main source of the Blue Nile River that is the only surface outflow for the lake. The climate of the region is tropical highland with the main rainy season between June and September. The air temperature shows large diurnal but small seasonal changes with an annual average of 20 °C.

20.3 Global Climate Models (GCMs)

Global climate models, also known as general circulation models (GCMs), numerically simulate changes in climate as a result of slow changes in some boundary conditions (such as the solar constant) or physical parameters (such as the greenhouse gas (GHG) concentration) (Abbaspour et al. 2009).

For this study, we have used two sets of GCM output data obtained from the World Climate Research Programme's (WCRP's) Coupled Model Inter-comparison Project phase 3 (CMIP3) multi-model dataset. Monthly precipitation and average surface air temperatures for 15 GCMs were downloaded to quantify the range of the projected climate changes for the region. A single run was downloaded for each of the Special Report on Emissions Scenarios (SRES) B2, A1B and A2 scenarios, and data extracted for the pixel containing the observation stations. Changes in climate variables were calculated for three periods: 2010–2039, 2040–2069, and 2070–2100. The changes are expressed as the differences between the scenarios and a 1950–1999 baseline from the Climate of the Twentieth Century Experiment (20C3M) runs. The statistical significance of the changes for each scenario/time period "ensemble" was assessed using a Wilcoxon signed-rank test. This is a nonparametric alternative to the better-known *t*-test and tests the assumption that the ensemble members are drawn from a continuous, symmetric distribution with zero median (i.e., no change in the ensemble median) against the alternative hypothesis that the distribution does not have zero median.

Daily data were extracted from the outputs of nine models. These data were used to modify historical datasets, which were then input to the hydrological model to compare runoff in the region for a base period (1980–2000) with two future periods (2046–2065 and 2080–2100). These nine models were selected, because the modeling groups had provided daily precipitation, minimum and maximum temperature outputs to CMIP3.

20.4 Climate Change Scenarios

Climate change scenarios are images of the future or alternative futures. But they are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future might unfold. Scenarios help in the assessment of future developments in complex systems that are either inherently unpredictable or have high scientific uncertainties (IPCC 2007).

The SRES (IPCC 2000) are grouped into four scenario families (A1, A2, B1, and B2) that explore alternative development pathways, covering a wide range of demographic, economic, and technological driving forces and resulting GHG emissions. In this study, three SRES scenarios (A1B, B1, and A2) were used. These scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse and aerosol precursor emissions. Each scenario assumes a distinctly different direction for future developments. The SRES A1B Emissions Scenarios (a scenario in A1 family) describes "a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies." The SRES A2 Emissions Scenarios describes a very heterogeneous world with high population growth, slow economic development, and slow technological change. B1 describes “a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in materials intensity, and the introduction of clean and resource efficient technologies” (IPCC 2000).

20.5 Downscaling of Global Climate Models to Watershed Level

The choice of GCM downscaling method will depend on the details of the research question. This study generated daily climate projections by modifying the historical datasets to represent changes in the GCM climatologies. The historical modification approach was used because hydrological models often perform poorly when applied to datasets with distributions of daily climate data that are different from their training data. The historical modification procedure used the changes in ranked GCM daily rainfalls and temperatures to scale the ranked historical station daily rainfalls and temperatures. In summary, the method involved calculating the difference between the daily cumulative frequency distributions (CFDs) of a GCM output variable for a present-day period and a future period, and then applying these differences to an observed dataset. This simple “downscaling” technique has been used in several hydrological climate impact studies (e.g., Wood et al. 2002; Harrold and Jones 2003; Taye et al. 2010). It provides a good compromise between the requirement to produce realistic time series and the desire to represent the effects of climate change across different weather situations, as these are simulated in the GCMs. In addition, the method is easy to implement and fast to run. It is a good solution for producing climate change scenarios for impact assessments.

The details of our historical modification procedure were as follows. CFDs for daily precipitation, maximum, and minimum temperatures were first calculated for the GCM outputs, both for a base period (1980–2000) and for two scenario periods (2046–2065 and 2080–2100). The CFDs were calculated independently for each month of the year, using data from that month of the year and the preceding and subsequent months. The differences between the base-period CFD and the scenario-period CFDs were then determined for the cumulative frequencies 0.05, 0.15, 0.25,. . . , 1.0. Absolute differences were calculated for minimum and maximum temperature CFDs, while for precipitation, the changes were derived as ratios with respect to the present period values. Because fractional changes in the low rainfall end of the CFDs may be large, all GCM rainfall values < 0.1 mm/day were considered to be zero, and zero values were omitted from the CDF calculations. The extremes of the CFDs (e.g., 0.001, 0.999) were deliberately not sampled: The time windows used are not long enough to define the tails of the CFDs or changes in them. The changes in the CFDs sampled at cumulative frequencies 0.05, 0.1, 0.15,. . . , 0.95 were then linearly interpolated and extrapolated to cover the entire cumulative frequency range (0–1). Finally, the historical data were ranked and modified to reflect the changes in the GCM CFDs for each scenario and time period. The result is “downscaled,” daily climate time series.

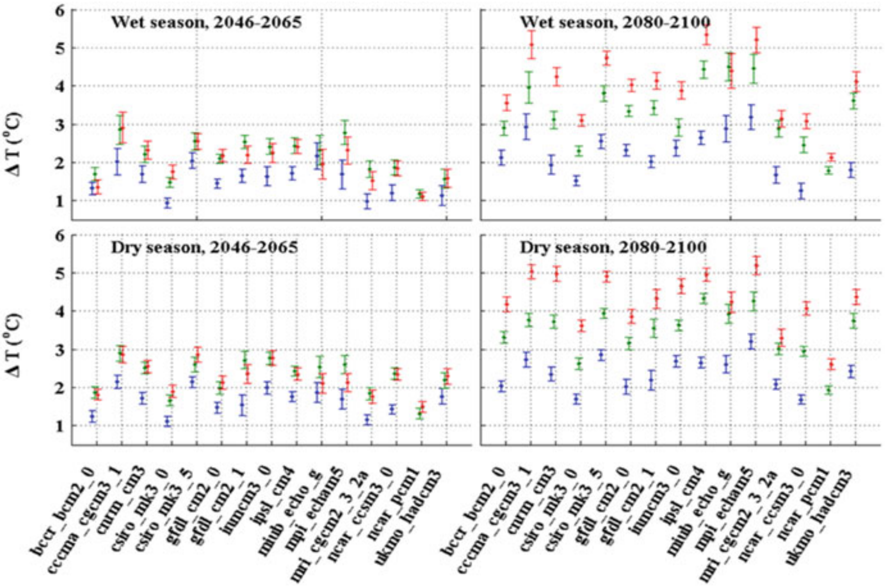

Fig. 20.2 Projected changes in mean temperature at the location of Adet station for a range of GCMs from the CMIP3 dataset. *Top row* are changes in wet season temperature, *bottom row* are changes in dry season temperature. *Left column* are changes to 2046–2065, *right column* are changes to 2080–2100. *Colors* denote the SRES scenario used: *Blue* are B1, *green* are A1b, and *red* are A2. *Error bars* are 1 standard deviation

20.6 Results and Discussions

20.6.1 Climate Change Projection

The analysis was separated into a wet season (June to September) and a dryseason (October to May) so that the results are easier to interpret from the perspective of possible impacts. Projected changes in seasonal mean temperature at the location of representative weather station (Adet station) for a range of GCMs are shown in Fig. 20.2. Temperature changes are given in °C, and precipitation changes as a percentage change on the base-period mean. Changes in mean seasonal accumulated precipitation are shown in Fig. 20.3. In Fig. 20.2, the bars show plus/minus the quadrature-sum of the errors in the base- and scenario-period means. The error bars in Fig. 20.3 have been converted to percentage changes in the base-period mean. The results from Figs. 20.2 and 20.3 are summarized in Tables 20.1, 20.2 and 20.3.

Figure 20.3 suggests that the GCMs do not give us a confident picture of rainfall change in the region. Firstly, approximately half of the models suggest increases in rainfall, and half suggest decreases, so there is no consensus between GCMs. Further, in most cases, the projected rainfall changes are less than 3 standard deviations; even though some of the changes are large in absolute terms (greater than 50 %), we

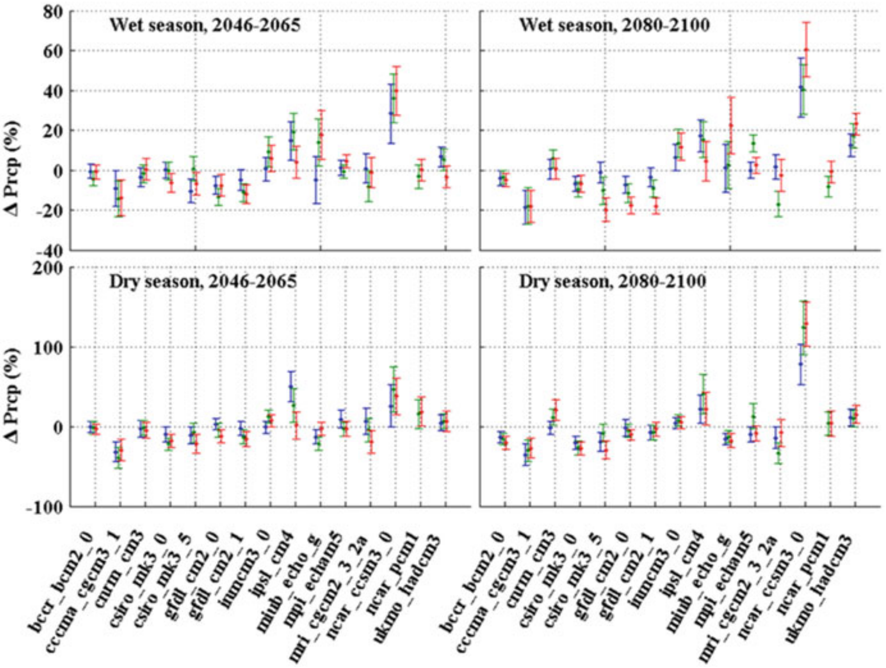

Fig. 20.3 Projected changes in mean precipitation at the location of Adet station. *Top row* are changes in wet season precipitation, *bottom row* are changes in dry season precipitation. *Left column* are changes to 2046–2065, *right column* are changes to 2080–2100. *Colors* denote the SRES scenario used: *Blue* are B1, *green* are A1b, and *red* are A2. Changes are expressed as percentages of the base-period (1980–2000) precipitation. Error bars are 1 standard deviation

Table 20.1 The ranges of projected changes (given as 25–75th percentiles) for the study region for the 2080–2100 period from the 15 GCMs

Scenarios	Rainfall changes		Temperature changes	
	Wet season (%)	Dry season (%)	Wet season	Dry season
SRES B1	– 52–7	– 60–7	1.8–2.7 °C	2.0–2.7 °C
SRES A1b	– 73–38	– 56–34	2.9–4.0 °C	3.0–3.9 °C
SRES A2	– 61–33	– 81–24	3.3–4.7 °C	3.9–4.9 °C

note that the larger changes are projected in the GCMs with the largest interannual variations. Further, for many GCMs, the changes in Fig. 20.3 are not ranked according to the emission scenarios. In fact, for several models the changes are similar for all three scenarios; that is, they appear to be independent of the emission scenario. This suggests that for these models, the differences between the 1980–2000 base period and the future periods is partly attributable to natural variation with the base period, because common base-period data were used for all three SRES scenarios.

Table 20.2 The ranges of projected changes (given as 25–75th percentiles) for the study region for the 2046–2065 period from the 15 GCMs

Scenarios	Rainfall changes		Temperature changes	
	Wet season (%)	Dry season (%)	Wet season	Dry season
SRESB1	– 42–8	– 45–16	1.1–1.7 °C	1.4–1.9 °C
SRES A1b	– 47–27	– 61–20	1.7–2.4 °C	1.9–2.6 °C
SRES A2	– 48–16	– 77–7	1.6–2.3 °C	1.9–2.6 °C

Table 20.3 Number of the nine downscaled GCM time series that showed a statistically significant decline in annual streamflow in the SWAT model results. (none of the nine downscaled GCM time series showed a statistically significant increase in annual streamflow)

Scenarios	Time period	
	2046–2100	2080–2100
SRESB1	1/9	2/9
SRESA1B	3/9	3/9
SRESA2	2/9	5/9

20.6.2 Impact of Climate Change on Streamflow

20.6.2.1 Annual and Seasonal Streamflow Change

Streamflow is one of the hydrological components that are greatly influenced by climate and land use changes. Figure 20.4 shows the projected effect of climate change on annual streamflow. The numbers of models showing statistically significant declines in mean annual flow for the different time periods and scenarios are shown in Table 20.3. For the most extreme climate change scenario, SRESA2 for the 2080–2100 period, five of the nine models show statistically significant declines in annual flows. The results from the hydrological modeling for the wet season (June–September) streamflow in the Gilgel Abay River are shown in Fig. 20.4 for each downscaled GCM. Again, reduced streamflow is the dominant result.

Even though declining streamflow is the dominant result from the nine GCMs downscaled in this study, we note that this cannot be taken as a general result. In this analysis, we can conclude that the directions of the streamflow changes generally follow the changes in rainfall. This is expected given the fact that local evapotranspiration does not dominate the water cycle in the wet season. But we also see that the streamflow changes are larger in magnitude than the rainfall changes. We interpret these aspects of the modeling results to imply that runoff changes in the region could be significant, even though the GCMs do not agree on the direction of the precipitation change.

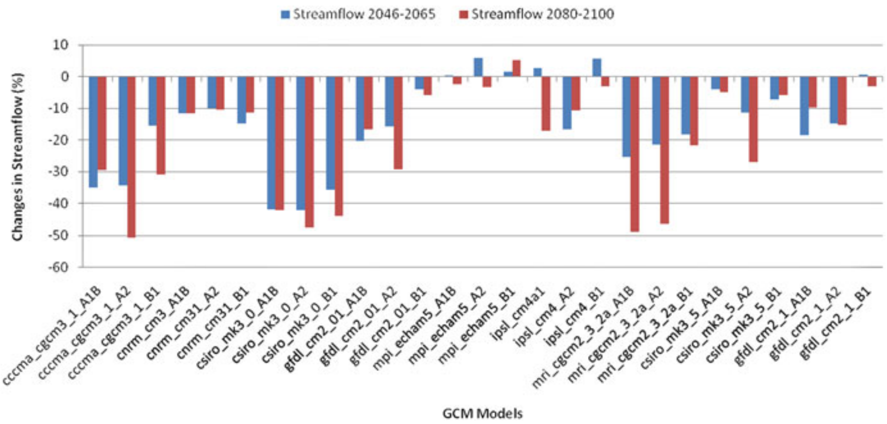

Fig. 20.4 Change in annual streamflow due to changes in daily precipitation and temperature derived from nine GCM models under A1B, A2, and B1 scenarios for the periods 2045–2065 and 2080–2100 expressed as a percentage of streamflow in the base period 1980–2000

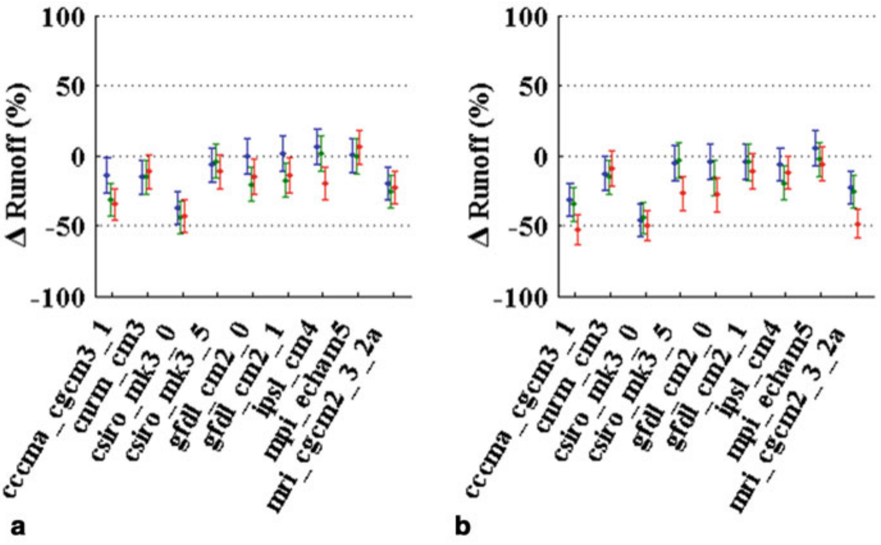

Fig. 20.5 Projected changes in wet season runoff in the Gilgel Abay River compared to the base period 1980–2000, calculated with the SWAT model: (**a**) changes to 2046–2065 (*left*) and (**b**) changes to 2080–2100 (*right*). *Colors* denote the SRES scenario used: *Blue,* B1; *green,* A1B; and *red,* A2. Changes are expressed as percentages of the base period (1980–2000) wet season runoff

20.6.3 Impact of Climate Change on Agricultural Water Resources

In this study, we understand how the changes in climate variables can affect the different hydrological components of the basin that control the final streamflow. Changes in AET, SW and GW are of the most important components of the hydrological cycle. The possible impact of climate change on the annual changes in AET, SW, and GW for the periods of 2046–2065 and 2080–2100 indicated that AET increases considerably in many models. This is attributed to the increase in air temperature. It was observed that SW showed little change (between 0 and 5 % increase) for many of the models, except a small reduction in the Geophysical Fluid Dynamics Laboratory USA (GFDL) and National Centre for Atmospheric Research (NCAR) models during 2046–2065 and for AlB scenario and Max Planck Institute (MPI) model during 2080–2100 time period for SRES A1B and B1. GW flow is reduced for the downscaled GFDL and MPI models, but the downscaled NCAR model has shown an increase in the groundwater flow.

The increase in ET is mainly due to increased air temperatures. This is consistent with previous studies, which have shown that a significant variation in AET is expected to follow changes in air temperature (Abbaspour et al. 2009). The changes in modeled GW flow clearly influenced the changes in streamflow. This is consistent with the Setegn et al. (2009), who indicated that 60 % of the streamflows from the inflow rivers of Lake Tana are base flow, and that future reduction in GW might contribute to reduced streamflow in the basin. Moreover, previous studies have indicated that more than 60 % of the hydrological loss in the present system is through evapotranspiration. This suggests that increased evapotranspiration in the future may be a significant factor leading in the direction of decreased streamflow, which may or may not be compensated by changes in rainfall. Considering the combined effects of land use change and climate change will also raise the question of the effect of climate change on land use changes, and vice versa. Unless we quantify the proportion of the land use changes due to humans and those caused by the changing climate (rainfall and air temperature) variability, understanding the combined feedback to the water resources variability will be misleading. There is much uncertainty in our modeling results. This is a combination of uncertainties in the GCM outputs, as a result of the downscaling, hydrological parameter uncertainty and neglect of land use changes or potential changes in soil properties.

20.6.4 Climate Change Impact and Adaption Strategies

Ethiopia is known to be one of the countries most affected by drought. Given a large part of the country is arid or semiarid and highly prone to drought and desertification, a further decrease in precipitation could increase the frequency and intensity of droughts in the country. Also, Ethiopia has a fragile highland ecosystem that is currently under stress due to increasing population pressure.

Our analysis suggests that the northern highlands of the country could experience reduced rainfalls and hence become susceptible to even more severe drought conditions. A dramatic reduction in precipitation or increase of AET would cause SW stress. The resulting negative agricultural water balance would reduce both rainfed and irrigated agriculture productivity. A reduction in rainfall coupled with land degradation and other factors would also significantly reduce effective rainfall, that is, rainfall which could be available for crop consumption. The combined effect has the potential to cause a great agricultural drought unless there is ample water available for irrigation. However, a reduction in rainfall may cause a reduction in GW recharge, which would significantly reduce its contribution to streamflow. Lake Tana is highly sensitive to variations in rainfall, as well as in river inflows and evaporation. Setegn et al. (2009) showed that inflow river discharge to Lake Tana contributes more than 90 % of the lake inflow. It is, thus, very likely that changes in river inflow would also change the volume of the lake and the water balance, which could ultimately adversely affect the lake ecosystem.

The effect of climate change has the potential to cause a great agricultural drought, unless there is ample water available for irrigation. However, a reduction in rainfall may cause reduced GW recharge, which would significantly reduce its contribution to streamflow. Furthermore, Lake Tana is the source of Blue Nile that contributes more than 7 % of the total annual Nile River flow and any possible change in the basin may contribute to the reduction of the Nile flow. Adaptation to climate change will help in anticipating the adverse effects of climate change and taking appropriate action to minimize the damage that it can cause. It has been shown that well-planned and early adaptation action helps to reduce the impact of climate change that, in turn, helps to save money and lives. Examples of adaptation measures include: using scarce water resources more efficiently; adapting strategies to future climate conditions and extreme weather events; developing drought-tolerant crops; choosing tree species and forestry practices less vulnerable to storms and fires, and so on. Although not all efforts are designed with adaptation as a primary goal, such actions increase resilience to expected changes in climate. Water management adaptation efforts include a wide variety of activities based on current and anticipated climate change impacts.

20.7 Conclusion

In this study, we investigated the sensitivity of water resources to changing climate in the Lake Tana sub-basin of the Blue Nile basin. Studies show that the possibility of a reduction in water resources is a major threat in the northern highlands of Ethiopia due to alterations in hydrologic cycles and changes in water availability. We compared projected changes in precipitation and temperature across GCM models for two future periods to get an indication of the consistency of the projected changes in the region. We found that the models projected temperature increases of around 2−5 °C for 2080–2100, depending on the model and emission scenario. The interquartile ranges of the projected temperature increases for 2070–2100 for the three emission scenarios show 2.0−4.4 °C in the wet season and 2.2−4.9 °C in the dry season. The changes in ensemble median were statistically significant for each of the time period/scenario combinations we examined.

The ensemble of GCMs we examined includes models that project increase and decrease in seasonal precipitation. The interquartile ranges of the projected rainfall changes for 2070–2100 for the three emission scenarios show − 13 to + 12 % in the wet season and − 14 to + 16 % in the dry season. For no time-period/scenario ensemble did we find a statistically significant change in median seasonal precipitation, and we were not able to draw any definite conclusions about probable rainfall changes in the region.

The effect of climate change has the potential to cause a great agricultural drought unless there is ample water available for irrigation. However, a reduction in rainfall may cause reduced GW recharge, which would significantly reduce its contribution to streamflow. Lake Tana is highly sensitive to variations in rainfall, as well as in river inflows and evaporation. Setegn et al. (2009) showed that inflow river discharges to Lake Tana contributes more than 90 % of the lake inflow. It is, thus, very likely that changes in river inflow would also change the volume of the lake and the water balance, which could ultimately adversely affect the lake ecosystem. Furthermore, Lake Tana is the source of the Blue Nile that contributes more than 85 % of the total annual Nile River flow, and any possible change in the basin may contribute to the reduction of the Nile flow.

The study investigated how changes in temperature and precipitation might translate into changes in streamflows and other hydrological components using downscaled outputs from different climate models. The direction of streamflow changes followed the direction of changes in rainfall. The responses of evapotranspiration, SW, and GW were also examined, and it was found that changes in GW flow may be a significant component of the changes in streamflow. We interpret the different aspects of the hydrological response and it indicates that changes in runoff and other hydrological variables in the region could be significant. Climate change may well affect the surface and GW resources of the Lake Tana basin, and the lake may experience a change in water balance due to a change in river inflow in the forthcoming decades.

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Chapter 21
Climate Change and Rangeland Degradation in Eastern Sudan: Which Adaptation Strategy Works Well?

Hussein M. Sulieman and Khalid H. A. Siddig

Abstract Despite the recent dominance of oil production, livestock has consistently played a central role in the economy of Sudan represented by Gross Domestic Product and the livelihood of its people. In spite of providing such value, pastoralist areas in Sudan tend to have the highest incidence of poverty and the least access to basic services compared to other areas. In Gadarif State of eastern Sudan, livestock production is made by pastoral and agro-pastoral traditional systems that have evolved in response to the region's diverse environments. Recently, this region has been hit by climate change and rangeland degradation leading to considerable changes in the way livestock is being kept and its products are being made. Pastoralists are forced to follow permutations of adaptation measures that led many small keepers to lose their livestock and others to leave the business altogether. This study assessed the possible adaptation measures, initiatives, and strategies that are potential combatants to range degradation and climate change. To track and evaluate the outcomes of adaptation interventions, a scheduled interview is used to collect quantitative data from pastoralists' households. Applied adjustments such as destocking, changing herd composition, less watering frequency, changing grazing time, transportation of water using tankers, and buying crop residue are among major adaptation measures followed by pastoralists. Some applied adaptation measures are led to deplete households' assets. Nowadays, pastoralists need to pay a high price for supplement forage and also to water their flock. The study identified a significant drop in number of livestock heads owned by households. Under such circumstances, it is clear that the adaptation measures followed by pastoralists are not reducing their vulnerability to rangeland degradation and climate change.

Keywords Climate change · Range degradation · Adaptation strategies · Sudan

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21.1 Introduction

Climate change has destructive impacts on many sectors all over the world and these impacts cannot be totally avoided. In such situations, adaptation to climate change remains an indispensable option. In East Africa, pastoralists have been adapting to climate change and variability for decades and their measures helped them to cope with the challenges. Recently, however, pastoralists face a number of challenges that hinder their way of life and challenge their ability to adapt to changes in their external environment due to many reasons (Watkinson and Ormerod 2001; Oxfam 2008; El Hadary et al. 2012; Sulieman and Elagib 2012). Pastoralist communities are marginalized on the basis of their geographical remoteness, their ethnicity, and their livelihood, which is still seen by many governments across the region as an outmoded way of life that needs replacing with "modern" livelihood systems (Ahmed 2008; Oxfam 2008; Sulieman 2013). Taking the Gadarif State of eastern Sudan as an example, in the recent decades, pastoralism has been declining because of threats posed by rapid encroachment of mechanized rainfed agriculture, human population growth, and other human activities that shift extensive livestock production to areas that are of increasing marginal primary productivity (Shazali and Ahmed 1999; Sulieman 2013). According to Oxfam (2008), pastoralists are often unaware of their rights and have no experience of an accountable government. Therefore, they have been unable to defend their traditional land rights and request an improved provision of basic services. Besides, services such as health and education are not adequately provided to the population of the dryland of East Africa.

There is widespread consensus that climatic conditions are changing, regardless of the cause, and that such changes may continue, they may become more apparent, or they may happen more rapidly in coming decades (Christensen et al. 2007). Pastoralists have always lived with climate variability. However, the changes being observed now and predicted over future decades represent a new challenge. They are unidirectional and the rate of change is expected to accelerate beyond what modern humans have experienced. Thus, climate change may manifest itself in unique ways at local and regional levels (Williams and Jackson 2007). Pastoralist communities across East Africa are starting to learn to live with the reality of climate change and adapt as much as they could to its impacts. According to Oxfam (2008), in the coming few years this will mean a continuation of current trends including successive poor rains, an increase in drought-related shocks, and more unpredictable and sometimes heavy rainfall events (Oxfam 2008). For example, climate exerts a strong influence over dryland vegetation type, biomass, and diversity. Precipitation and temperature determine the potential distribution of terrestrial vegetation and constitute the principal factors in the genesis and evolution of soil (WMO 2005).

In response to the combined impact of climate change and rangeland degradation, evaluation of adaptation measures taken by local pastoralists' communities remains a key to success. Therefore, systematic assessment and evaluation of adaptation activities that have been taken by a particular community remain as an imperative issue. While climate change is global in scale, these adaptive strategies are local or regional in nature and must consider the ecological, social, and economic drivers as well as the responses of rangeland systems. Adaptation can encompass changes to processes, practices, and structures to mitigate potential damages or take advantage of opportunities (IPCC 2001).

Given the scope and variety of specific adaptation options across sectors, individuals, communities, and locations, as well as the variety of participants being private or public involved in most adaptation initiatives, it is important to systematically evaluate particular adaptation measures, improving and applying knowledge on the constraints and opportunities for enhancing adaptive capacity (Smit et al. 2001).

Changes in climate is certainly happening everywhere, but the way they are perceived by local communities determines their formulated strategies to cope with in the short run and to adapt to in the long run. In other words, it is necessary to realize that some changes are going on in order to take actions to adjust to those changes (Deressa et al. 2011). This chapter discusses the possible adaptation measures, initiatives, and strategies that are potential combatants to rangeland degradation and climate change among settled pastoralists in the Butana area of eastern Sudan. It focuses on the applied adjustments and changes in processes, practices, and structures of their assets to moderate potential damages or to benefit from opportunities associated with climate change. Moreover, this study is expected to enhance capabilities for responding to range degradation and climate change by advancing scientific knowledge and linking scientific and policy communities.

21.2 Study Area

The Butana is historically known to be a very good pasture area due to its excellent grassland vegetation cover. Geographically, the area is located in the northern part of Gadarif State of eastern Sudan (Fig. 21.1). It is a flat clay plain where land-use patterns and population distribution, to a large extent, have been determined by the combined effects of erratic rainfall and a geological structure which largely contains no water-bearing rocks (Sørbø 1985). Rainfall shows a remarkable variation in incidence, intensity, and distribution over the entire area (Akhtar 1993). Precipitation occurs during a 3-month period from approximately mid-June to mid-September, but in the northern part, mean and annual rainfall variability is 45 %, and further south about 20 %. Total rainfall varies from 75 mm in the north to about 600 mm along the southern frontier of the region (Abu Sinn 1970). The compact nature of the clay soils covering most of the Butana accelerates runoff, which, in turn, accelerates soil erosion and increases the domination of annual plants. Most of the Butana area is completely open without bushes or trees. In the northern part, the sparse vegetation consists of semi-desert grasses and Acacia shrubs. The latter are generally limited to the soils around the few hills and to narrow belts along seasonal watercourses. Moving southwards, the vegetation gradually changes into Acacia trees, bushes, and savanna-type grasses. In the wet season, the Butana area becomes greener and covered by the evolvement of different grasses and herbs (Akhtar 1993). The Basement

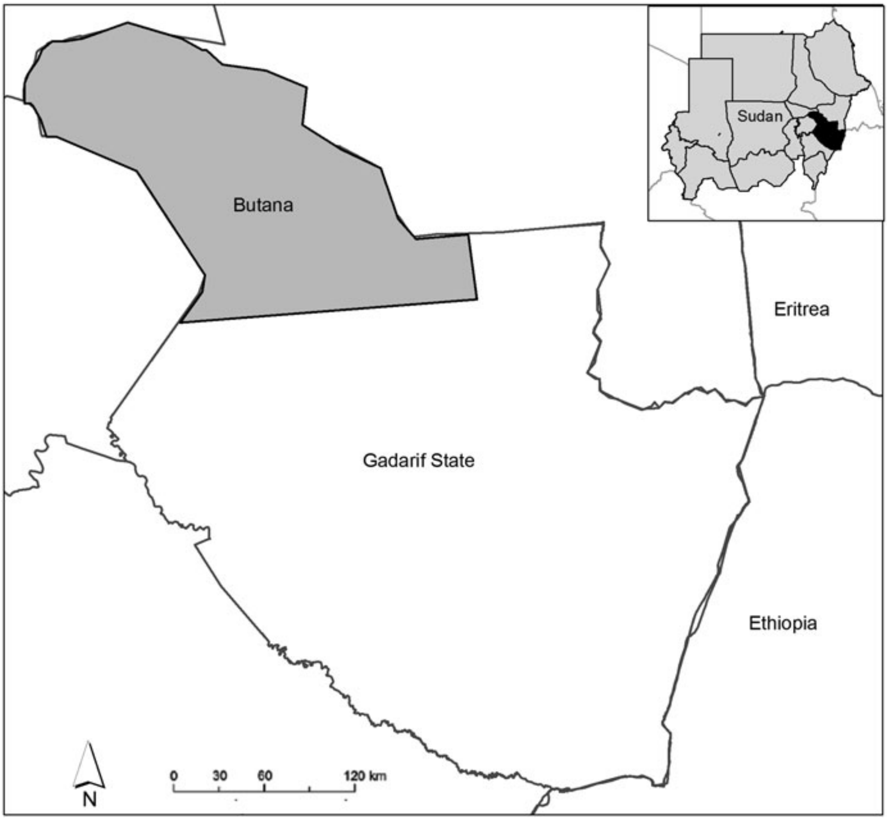

Fig. 21.1 Map showing the location of the Butana area in the northern part of Gadarif State, eastern Sudan

Complex of the underlying solid geology of the area bears no water except in joints. In the northern part, water-bearing rocks exist (the Nubian Formation), but their extension northwards into the desert has limited their value as a main source of permanent settlements. The only permanent natural sources of water are the large rivers bordering on the Butana (Sørbø 1985).

It is only during the past decades that the Butana has been subject to severe overgrazing due to the introduction of an open grazing system which allows any pastoral group from different parts of the surrounding region to enter during the rainy season. This has led to a rapid spread of desertification since the 1970s, which was accelerated further by the droughts of the 1980s (Akhtar 1993). Casciarri (2002) states that, in the past two decades inhabitants of Butana have experienced a general crisis, namely increasing sedentarization, a shift from nomadism to transhumance, the forced switching to new sources of income, a general proletarization, and continuous marginalization. Nevertheless, the extreme rapidity of this recent change has had a strong disruptive impact on the entire society and threatens to reshape not only the economic processes but also the entire community's social relationships, thus putting at risk its production and social reproduction. People have gradually shifted from their long-distance pastoral movement to transhumance where herds are followed by young men from the household and/or hired pastoralists. They changed their residence patterns and built permanent houses of mud next to each other, unlike the way they used to organize their tents.

21.3 Methodology

The study is based on household survey conducted among 206 randomly selected pastoralists' households across 13 villages in the Butana area, in the northern part of Gadarif State of eastern Sudan. The survey was conducted during the last week of March and first week of April 2013. Respondents were carefully selected with the assistance of local leaders after explaining the objectives of the research. The survey collected a wide range of data including demographic characteristics of household, household herd composition before degradation takes place and now, people's perceptions of rangeland degradation and climate change, and other related data. Questions about adaptation and the constraints to adaptation were also posed. Data collected at a village level include date of village establishment, ethnicity, number of households, and availability of services such as schools and health-care centers. Field notes and photographs were taken at each site providing anecdotal data that inform the discussion contained in the subsequent sections. Descriptive statistics was adopted for categorical and quantitative information.

21.4 Results and Discussion

21.4.1 Demographic characteristics of respondents

Of the 206 respondents of the survey, 165 (80.1 %) were men while 41 (19.9 %) were women. The age of respondents ranged from 14 to 90 years, with the average age being 43 years. The average number of people per household was 6.5. All households were headed by males. Concerning the level of education, 87 (42.2 %) of respondents were illiterate (i.e., cannot read or write). A small share of them (4.9 %) had not attended any formal schooling other than the *Khalwa*, which is a religious school that teaches the Quran and other Islamic sciences besides providing some instruction in reading and writing in Arabic. A substantial number of respondents, which make up to 33 % of the surveyed households, had attained a primary school level of education.

It is known that members of pastoralists' households join the activities of animal rearing earlier compared to other activities such as crop farming. Thus, this wide range of age detected among respondents is expected anyhow. The average size of a household is almost similar to the national household size (CBS 2012). Large

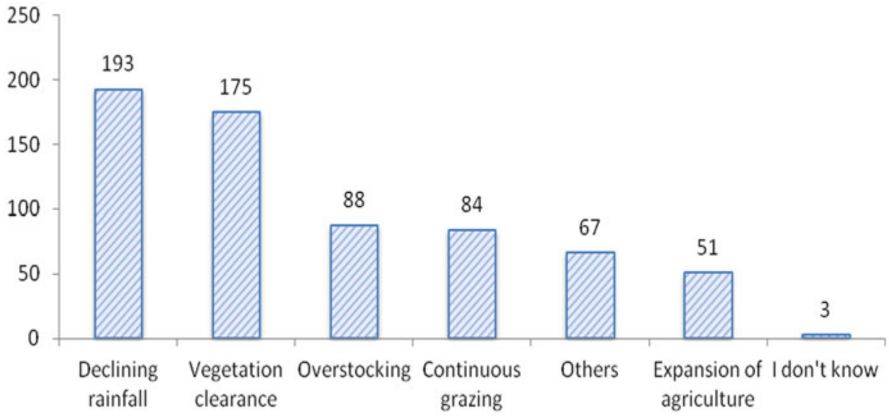

Fig. 21.2 Pastoralists' perception of reasons for rangeland degradation

families tend to divert a part of their members to provide labor force into diverse activities in order to generate more income and reduce consumption demands (Mano and Nhemachena 2007). Households with large sizes were therefore expected to have enough labor to take up adaptation measures in response to climate change (Hassan and Nhemachena 2008). According to Sulieman (2013), lack of education is among the main factors that hinder the pastoralists to influence decisions that impacted their system. Additionally, the state failed to provide the needed services, such as education, for the purpose of developing human capital.

21.4.2 Pastoralists' Perceptions to Rangeland Degradation and Climate Change

According to the World Bank (1998), community-based knowledge represents a principal component of global knowledge on the development, use, and management of natural resources. Community-based knowledge could improve the understanding of local conditions and provide useful expertise with regard to activities designed to help the local communities. Additionally, such knowledge may provide new insights for improving existing scientific knowledge (Calheiros et al. 2000; Oba and Kotile 2001).

It became clear that pastoral communities in the Butana area have a detailed knowledge of the environment of the grazing lands. They stated a comprehensive group of factors influencing the rangeland in their vicinity and reasons beyond the degradation. Most of the respondents believe that the declining amount of rainfall is the most important factor that causes rangeland degradation (Fig. 21.2). Other important factors are vegetation clearance and overstocking. Pastoralists are blaming themselves for the continuous grazing, especially surrounding their dwellings.

Besides intensive overgrazing, the recent introduction of mechanized farming in the area has been quoted by respondents as one of the main factors leading to

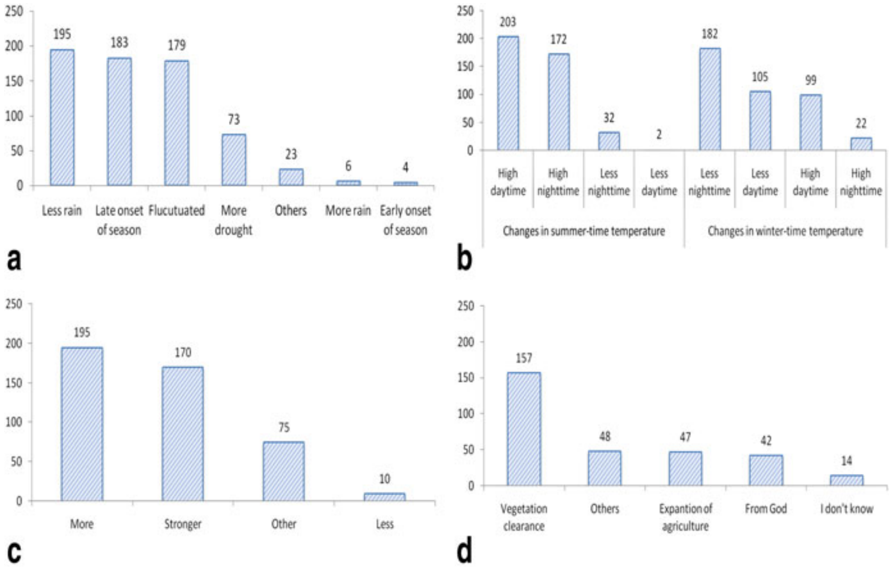

Fig. 21.3 Pastoralists' perception to changes in main climate parameters: **a** rainfall, **b** temperature, **c** wind, and **d** drivers of climate change

the significant increase of bare land in the Butana area. Mechanical working of the shallow soils, using tractors and wide-level disks, have led to mechanical soil damage, and, in many cultivated areas, gravels appeared on the top after few seasons of cultivation and the land is abandoned. Holter (1994) stated that the deterioration in the woody vegetation in the area is usually due to either drought, extensive use of trees for fuel or expansion of the rain-fed cultivated area. Butana has experienced severe drought in 1984, 1990, and 2000 (Elhag and Walker 2009). Nevertheless, the increasing scarcity of virgin land in the southern part of Gadarif State has resulted in the limit of large-scale mechanized farming being illegally pushed northwards until it is currently just into the heart of the Butana area (Babiker 2011; Sulieman and Ahmed 2013). It should be emphasized that the expansion of cultivation is one of the major forces driving land cover change in the Sudano-Sahelian zone (Hiernaux and Turner 2002) within which the Butana area is located.

The study showed that pastoralists have observed changes in diverse aspects of the natural phenomena that are related to the climate, ecosystem, and livelihoods. They were asked questions about the long-term visible changes in their surroundings, health, and natural environment. The study collected interesting observations and experiences of pastoralists about climate change. Some of them observed only one aspect of the phenomenon, while others perceived links between different arenas (e.g., climate change and the outbreak of some new diseases). Pastoralists' perceptions appear to be in accordance with recent climate record analysis (Sulieman and Elagib 2012). Most interviewed pastoralists observed that the rainfall amount is declining and the rainy season comes or begins late and lasts for a shorter period. Season-to-season fluctuations of rainfall are also observed (Fig. 21.3a). Concerning the temperature, pastoralists mentioned that during the summer time there is a real increase in day and night temperature (Fig. 21.3b). According to their observations, the summer is getting hotter, whereas the winter is getting shorter and warmer. Some of them said that there had been almost no winter season in recent years. They believe that the rising temperatures are the reason for some new diseases such as unknown types of inflammations that have recently appeared in the area. In the past three seasons, there were strong and highly frequent dust storms prior to the onset of the rainy season (Fig. 21.3c). According to their perception, as shown in Fig. 21.3d, the main reasons of climate change are natural vegetation clearance and expansion of mechanized agriculture. Nonetheless, 20 % of surveyed pastoralists have stated that these changes are something from their almighty, Allah. That is why the observations of rural households tell interesting stories about climate change and its impact on the diverse aspects of natural phenomenon.

21.4.3 Adaptations to Climate Change and Rangeland Degradation

Adaptation is widely recognized as a vital component of any policy response to climate change. Studies show that without adaptation, climate change is generally detrimental to the pastoral sector, but with adaptation, vulnerability can largely be reduced. The degree to which a pastoral system is affected by climate change depends on its adaptive capacity (Gbetibouo 2009). Indeed, adaptive capacity is the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damage, to take advantage of opportunities, or to cope with the consequences (IPCC 2001). Thus, the adaptive capacity of a system or society describes its ability to modify its characteristics or behavior so as to cope better with changes in external conditions.

With respect to the findings of this study, the most important adjustments taken by the pastoralists of the study area are distance roaming. They mentioned, “before we only utilize the area around our village” (locally called *harem elgeria*). Other adaptation measures are destocking, changing the composition of the herd (i.e., from large ruminants, such as cattle, to goat and sheep). Another measure is the avoidance of grazing during daytime in order to reduce water loss and watering frequency (Fig. 21.4).

For those who preferred to change from cattle to smaller animals, their justification is that small animals are easier to sell in local markets when there is a need and their revenue is adequate for covering urgent expenses that are usually at the price of a sheep or goat. This is, of course, besides that smaller animals consume less fodder and water. Other adaptation strategies taken by pastoralists included seasonal migration during the dry season or total out-migration to big urban centers (e.g., Gadarif and Khartoum). Some maladaptation practices, such as tree lopping and commercial charcoal production, are also practiced in the study area. Such problems should be considered while planning for new extension programs and awareness-raising

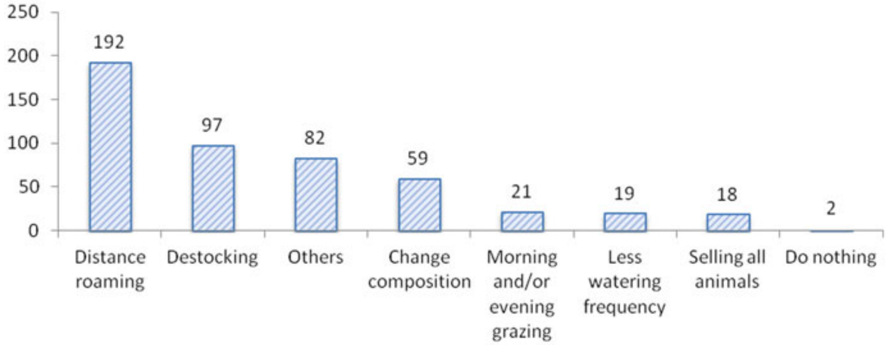

Fig. 21.4 Adaptation measures taken by pastoralists to cope with climate change

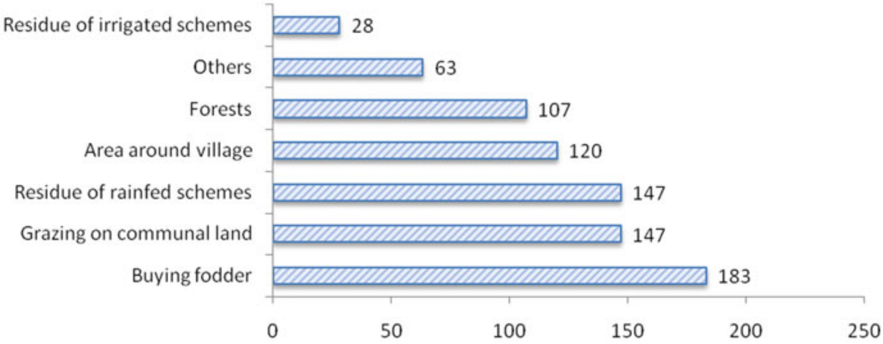

Fig. 21.5 Major forage resources utilized by pastoralists in the study area

activities. Whenever questions on land degradation were raised, our respondents tended to justify rangeland degradation by changes in climate. This superimposing of climate impacts could be due to substantially poor rainfall amounts during the past years with the exception of 2012. Nonetheless, some respondents have also stated that they are also suffering from land degradation.

21.4.4 Main Forage and Water Resources and its Accessibility

Figure 21.5 shows the major forage resources utilized by pastoralists in the study area. To overcome the forage gap, pastoralists recently began to rent agricultural schemes after crop is harvested in order to use the crop residues as forage for their

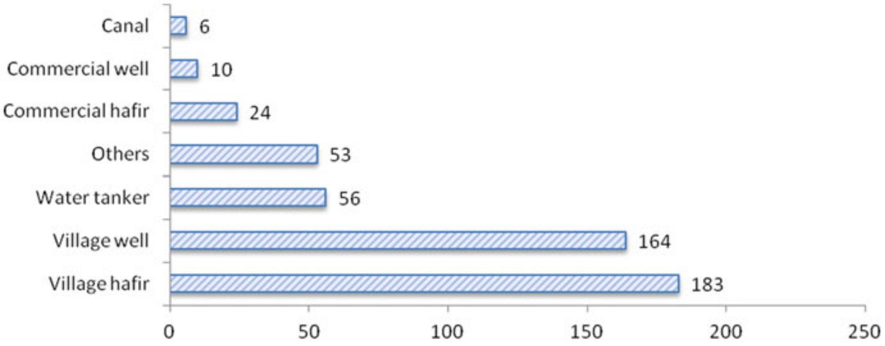

Fig. 21.6 Main watering sources for livestock

animals. *Harem* around villages, which was previously the first source of grazing, is ranked as number four according to the survey findings.

The findings of this study are consistent with those of Glover (2005), who reported that crop residue formed a significant portion of the livestock diets in Rawashda village, Gadarif State, where all transhumant pastoralists mentioned that they partially depend on crop residue. Currently, the area under mechanized cultivation is estimated to be 4.2 million hectares (MFC 2012). According to SKAP (1992), although natural grazing and forage in the Gadarif area have been depleted in both quantity and quality due to recent changes in land use, they are now supplemented by livestock feed sources provided by arable farms. Crop residues, fallow fields, and failed crops of the area now provide four fifths of the available grazing and forage sources of the entire area.

The main sources for livestock watering in the area are *hafirs* (hafirs are artificial water ponds that collect rainwater) and wells. Figure 21.6 depicts the main sources of livestock watering used by the respondents. Substantial proportion of pastoralists has used tankers to transport water when their flock is kept in a remote area. They have developed a system of using tankers to take water to the animal where they can have enough grass.

During the survey, pastoralists reported that competition over water resources has caused many clashes between villagers and transhumance groups. Nonetheless, under the condition of climate change (which is clearly observed during the field trips, e.g., early drying of hafirs, rapid vegetation dry-up), such clashes may, at any time, transform to local herder–villager conflicts. Water resources should be considered as public goods, but the grazing areas rendered accessible under dry conditions are normally controlled by specific groups such as farmers and villagers, who might not fully accept opening it to all herders. Problems and the risks involved in developing water points with unclear property rights have been a primary target of looting and destruction under civil strife in many places in Sudan (Sulieman 2013).

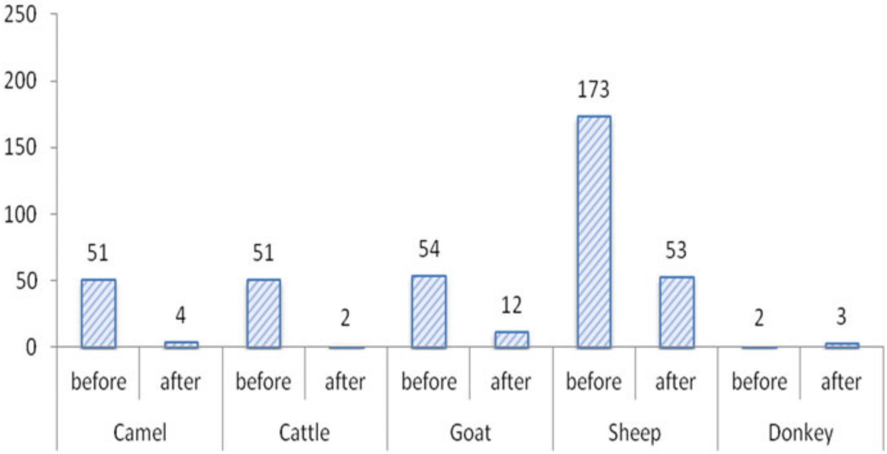

Fig. 21.7 Average number of livestock per household before and after adaptation

21.4.5 *Impacts of Climate Change and Rangeland Degradation on Livestock Ownership*

The findings of this study confirm that the adaption and coping mechanisms followed by pastoralists are depleting their livestock assets (Fig. 21.7). Sixty percent of our respondents mentioned that the adverse impact of rangeland degradation and climate change have started during the 1980s. The dominant livestock species, which is sheep, has significantly declined compared to their size in 1980. In addition, cattle rearing is disappearing from the area while the number of other animals such as donkeys increased by one third. This significant reduction in livestock ownership among small keepers in the Butana area is also observed by Ismail (2009). The increasing number of donkeys is justified by nowadays need to roam long distances searching for pastures. Moreover, donkeys are also used as a means of transportation as well as for carrying water from remote areas.

Coping mechanisms being adopted by the settled pastoralists in Butana to maintain their livestock herds are generally not perceived to be sufficient or sustainable. Many pastoralists have taken the decision of settling down after seeing that their herd size reached a specific threshold. More specifically, mobility becomes infeasible with small herd sizes. Nonetheless, the settling process was known to be started by poor households, who eventually attracted many of those who were well-off. However, such decisions necessitated major changes in livelihood systems and new ways of household time allocation. Under such circumstances, the grazing areas continued to shrink, which increases competition over the limited resources. Hence, poorer pastoralist households are forced to settle. According to Ahmed (2008), the settling process among *Rufa'a al Hoi* Ethnic Group in the Blue Nile state of Sudan was also

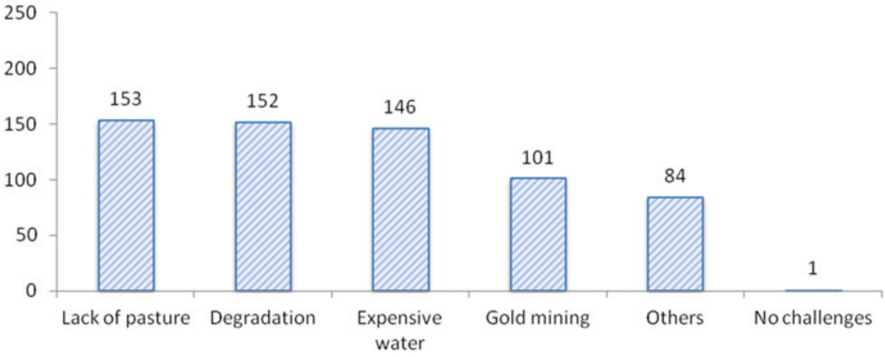

Fig. 21.8 Challenges facing pastoralists in the face of climate change

started by poor households, who did not have the minimum size of herd needed for maintaining a pastoral lifestyle. The early settlers encountered some difficulties in acquiring land for cultivation and hence were forced to hire their labor to scheme owners or other villagers to obtain necessary resources for their daily living.

21.4.6 Challenges to Adaptation

Figure 21.8 shows that over the past few decades, greater pressure has been put on pastoralist grazing lands and water resources due to the increasing populations and the decreasing grazing land that is moved into cultivation, conservation areas, and lands for the use of the State. Mechanized rain-fed agriculture in eastern Sudan took more land from pastoralists than the other factors altogether (Sulieman 2010). Therefore, this competition over resources may significantly increase the risk of conflict between the different users of land in the area. These risks reach their peak during the times of stress including both drought and floods. The reliance of many pastoralists on livestock alone as a means of livelihood is becoming increasingly vulnerable, yet other income-earning opportunities remain limited; a growing number of the pastoralists are impoverished. Traditional gold mining that was recently introduced to the area is acknowledged by respondents as one of the factors that fragmented the pastureland. This is because the mining activity has damaged vast areas in the surroundings of villages and converted many grazing areas into areas in which grazing itself is a risky business.

As shown in Fig. 21.8, almost half of the respondents have identified gold mining as one of the challenges that faces them to compact changes in climate and range degradation. In this context, gold mining could also be considered as a means of moving herders out of their traditional business of pastoralism by converting them into labor involved in the mining itself.

21.5 Conclusions

The pastoral resources in the Butana region are under pressure not only from unwise human activities but also as a result of climate change. Therefore, the objectives of this study are to evaluate and discuss issues on both land degradation and climate change and their relation to pastoralists' welfare and livelihood. Climate change is one factor among a number of major drivers of changes in the region. It has both direct and indirect impacts on the ecological and socioeconomic components of the grazing resources at different spatial and temporal scales.

Pastoralists' perception to climate change appeared to be in accordance with meteorological observations. The present accelerated rate of rangeland degradation and climate change have led to more difficulty in predicting rangeland productivity and changes in the availability of water and grass resources, making pastoral production more uncertain than ever before. Due to these factors, there is significant drop in household ownership of livestock. For example, cattle rearing is totally disappearing from the area. Besides, decades of political and economic marginalization, inappropriate development policies, increasing competition over resources, and increasing abnormal climatic events have been playing a great role in impoverishing pastoralists. These factors together have reduced the ability of many pastoralists to maintain a sustainable livelihood. However, since those communities are now settled, development of income-generation activities other than livestock rearing could help them to diversify the source of income which is expected to improve their livelihood.

According to the findings of this research, it became clear that the settled pastoralist communities of the study area need more investment in basic services including health care and education. They need financial and technical support that could be undertaken by intensive extension interventions and they need support on the means of improving the marketing of livestock. The central and state governments would need to strengthen the accountability and responsibility among their institutions so as to make pastoralist communities stand on the face of climate change and rangeland degradation. The baseline information generated from this study is expected to be of immense help in effective responses for the formulation of relevant policies and programs required for the development and planning of pastoralism.

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Chapter 22
Statistical Downscaling of Precipitation in the Upper Nile: Use of Generalized Linear Models (GLMs) for the Kyoga Basin

M. Kigobe, H. Wheater and N. McIntyre

Abstract General circulation model (GCM) climate projections cannot be relied on to provide information at scales finer than the GCM model-grid resolutions; hence, fine-scale information can be achieved by the use of high spatial resolution in dynamical models or empirical statistical downscaling. This study briefly reviews methods of downscaling climate projections with particular emphasis on rainfall simulation and the results of a first attempt to apply generalized linear models (GLMs) for statistical downscaling in the Upper Nile (a challenging equatorial climate of East and Central Africa).

Keywords General circulation models · Climate change · Statistical downscaling · Kyoga basin · Nile Basin

22.1 Introduction

Given that regional climate models (RCMs) depend on global climate model (GCM) boundary conditions, they can show poor performance due to the poor performance of GCMs in climate change predictions. To project local and regional rainfall in the Kyoga basin (Fig. 22.1) under different emission scenarios, precipitation outputs from global climate models (GCMs) or regional climate models (RCMs) were applied through statistical downscaling. However, in addition to the general absence of such models for the Kyoga basin, there are a number of issues related to using this

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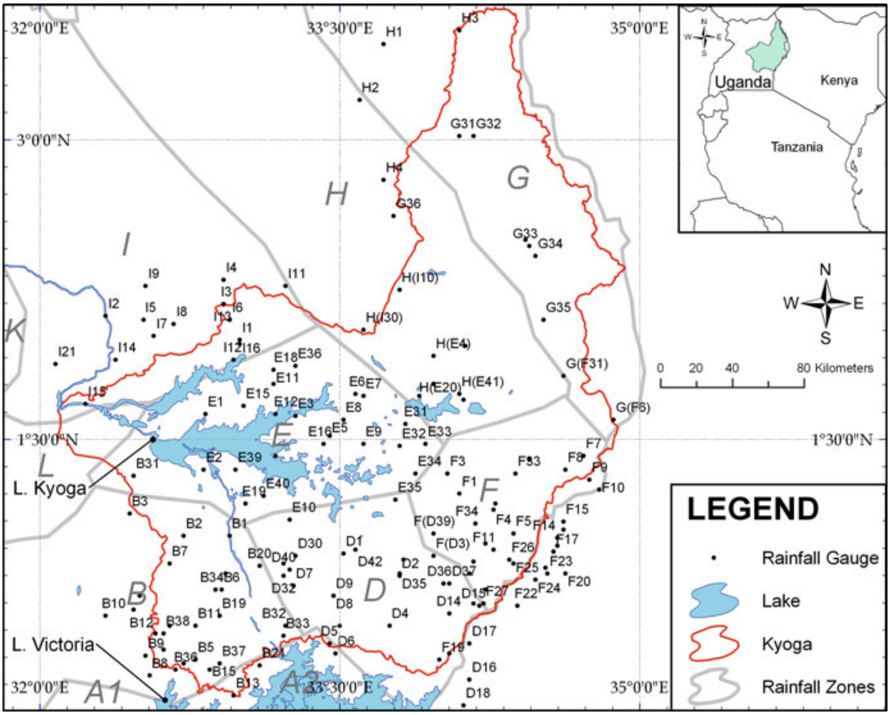

Fig. 22.1 Precipitation gauge network for Kyoga basin—the Upper Nile

approach, including, first, the requirement of large numbers of rainfall sequences. Second, RCMs run on grid resolutions that are not adequate for local-scale studies. Therefore, this study focused on the projection of local-scale rainfall at multiple sites in the Kyoga basin using statistical downscaling applying the GLM models developed by Kigobe et al. (2011) for the Kyoga basin.

22.2 Use of generalized linear stochastic model for downscaling of GCM projections in the Kyoga basin

The literature provides several approaches to assess the impact of climate change on precipitation patterns. This study adopted the statistical downscaling approach, using the generalized linear modeling (GLM) framework to simulate plausible daily sequences for the Kyoga basin as discussed in the following section. As mentioned before, statistical downscaling involves developing time-invariant relationships between large- and local-scale climate variables with the assumption that the large-scale variables are reliably simulated and the relationships remain constant with change in climate.

In this study, the use of statistical downscaling was required to: (1) provide daily simulation of rainfall at multiple sites; (2) assess the impact of climate change at several sites in the Kyoga basin; (3) use daily statistics that are more useful than monthly statistics to assess the impact of rainfall on runoff and groundwater; (4) avoid the use of GCMs that are not designed for studying hydrological responses to climate change, especially at local scales; (5) preserve the spatial variability of rainfall that remains after conditioning on the large-scale atmospheric structure; and (6) provide a mechanism suitable for assessing the uncertainty associated with the future projections. To give the best description of the future rainfall pattern at local scales in the Kyoga basin, a sensible model was needed to describe the data available on the basic assumption that past variability and trend are extrapolated to future climate.

This was done by fitting the GLM framework in Kigobe et al. (2011) by relating daily rainfall to atmospheric predictors. The GLMs were fitted to observed daily rainfall and the corresponding atmospheric reanalysis data. This relationship is subsequently applied to GCM outputs by estimating the conditional joint distribution for the entire time series $f(y|G)$, which, using Bayes' theorem can also be expressed as

$$\begin{aligned} f(y|G) = f(y_n|y_{n-1}, y_{n-2}, \dots y_2, y_1, G)^T f(y_{n-1}| \\ y_{n-2}, \dots y_2, y_{1,G})^T \dots f(y_2|y_1, G)^T f(y_1, G)^T \end{aligned} \tag{22.1}$$

where $f(y_1, y_2, y_n, G)^T$ is a time series of rainfall for a local gauge, at time T, G is a matrix containing the appropriate large scale atmospheric data and T represents the season.

The different components/data included in the downscaling exercise using the GLMs are described in the following sections. Using the GLM framework to provide weather generators for statistical downscaling, the persistence of rainfall over successive days can be explicitly represented without assuming that days are independent given the large-scale atmospheric structure. This also allows for simulation of dry and wet spells. Using the GLM framework to cater for rainfall persistence, transitional probabilities are catered for if the appropriate large-scale predictor and the autoregressive terms are included in the models.

Recent work by Leith (2005) and Leith and Chandler (2006) fitted GLMs relating observed single-site rainfall to observed sea-level pressure, temperature, and relative humidity obtained from either National Center for Environmental Prediction (NCEP) or European Centre for Medium-Range Weather Forecasts 40-Year Reanalysis (ERA40) reanalysis data. Their results showed that GLMs performed well when simulating the historical period used in fitting the models with acceptable interannual variability and monthly statistics successfully reproduced and the GLM framework to forecast local-scale precipitation under scenarios of global climate change. So in this chapter, the use of ERA40 reanalysis data has been explored as discussed in the following sections.

22.3 Atmospheric Data

For statistical downscaling, it is important to (1) identify atmospheric predictors that are closely related to rainfall and also reproduce the seasonality of the climate models; (2) select large-scale climate predictors based on how well they are reproduced by the various GCM; (3) develop some physical interpretation/meaningfulness of the predictor, and the relationship to local climate, which requires knowledge of the relevant processes that are responsible for local climate variability; and (4) ensure that the prediction of the relationships between predictors and predictands should be reproducible by the statistical downscaling procedure.

GLMs were conditioned on observed atmospheric data (Kigobe et al. 2011) and subsequently used to simulate future rainfall conditional on projections of climate change model outputs for the future periods of 2011–2040 (2020s), 2041–2070 (2050s), and 2071–2100 (2080s). Model performance and stability are affected by the large-scale atmospheric variables used in the model. Furthermore, the choice of the predictor variables and their domain (location and spatial extent) is critical (Wilby and Wigley 2000).

The range of atmospheric variables used in most of the recent studies includes sea-level pressure, geopotential heights, vorticity, wind direction, relative humidity, and specific humidity (Wilby and Wigley 2000). Atmospheric variables successfully applied in the UK studies have involved sea surface temperature fields (Wilby 2001), monthly mean values of airflow indices derived from sea-level pressure (Kilsby et al. 1998), North Atlantic Oscillation (NAO) index (Fowler 2002), near surface wind speed, near surface westerly and southerly winds, near surface vorticity, temperature at 850 mb, specific and relative humidity at 850 mb, and vertical stability (Murphy 2000). In this study, the atmospheric variables that were used included temperature, relative humidity, and sea-level pressure. This is mainly because, for the Kyoga basin, they are readily available both for the historical period (from reanalysis data) and for the future (from GCM simulation for the twenty-first century).

22.4 Climate Models

GCM data from the fourth assessment report (SRES-AR4) were obtained from the IPCC for the A2 scenario (www.mad.zmaw.de/projects-at-md/ipcc-data/). All the results presented here are based on the A2 transient greenhouse gas scenarios as specified by the Intergovernmental Panel on Climate change (IPCC) Appendix II SRES tables (IPCC 2001). The A2 scenario was chosen to represent the worst-case scenario. This restriction allows the analysis to focus on GCM model uncertainty rather than also on scenario uncertainty. Uncertainty in projected surface temperature, relative humidity, and sea-level pressures over East Africa is considered low for several GCMs.

However, to address this source of uncertainty, the results from six GCMs developed by different institutions, were considered, namely:

- CSIRO-MK3: A coupled ocean–atmosphere–sea-ice model with comprehensive representation of the atmosphere, land surface, oceans, and sea-ice. The model was developed by the Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO, Australia; key reference: Gordon et al. 2002).
- MPIM-ECHAM: An atmospheric general circulation model based on the weather forecast model of the European Centre for Medium Range Weather Forecasts (ECMWF). MPIM-ECHAM was developed by the Max-Planck-Institute for Meteorology (MPI-M, Germany; key reference: Roeckner et al. 2003).
- CM2.1: A global coupled climate model developed by the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration in United States (GFDL, USA; key reference: Delworth et al. 2002).
- NCAR-PCM (National Centre for Atmospheric Research Parallel Climate Model): A global coupled climate model developed by the National Centre for Atmospheric Research (NCAR, USA; key reference: Blackmon et al. 2001).
- MIROC3 (Model for Interdisciplinary Research on Climate): A global coupled climate model developed by National Institute for Environmental Studies (NIES, Japan; key reference: Hasumi et al. 2004).
- UKMO-HADCM3 (UK Met Office-Hadley Centre Coupled Model, version 3): A coupled model developed to include a detailed representation of the atmosphere, land surface, ocean, and cryosphere. The model was developed by the Hadley Centre for Climate Prediction and Research in the UK, UK Met Office (UKMO, UK; key reference: Gordon 2000; Gordon et al. 2002).

Monthly atmospheric data were obtained for the six climate models for several grids that cover the Kyoga basin. The data were then standardized to obtain monthly anomalies for the 2020s, 2050s, and 2080s for the A2 emission scenarios. Changes in mean climate between the baseline and the future are calculated either as the difference or the ratio between simulated forced climate and the baseline climate. IPCC advises the use of ratios for variables that are either positive or zero (e.g., precipitation and pressure) and use of differences for other variables (e.g., temperature; IPCC 2007). Absolute changes were used for temperature and change in precipitation was represented using ratios. The results of regional temperature analysis using ERA40 reanalysis datasets are presented in the next section.

22.5 Regional Temperature Analysis for Kyoga Basin

1. Mean temperature over the period 1961–1990

The mean air temperature in the basin over the 1990s remained almost constant with an average temperature of about 21 °C. Figure 22.2 gives the average monthly air temperatures in the Kyoga basin during the historical period 1961−2000. Interannual variation of temperature over the period 1961−1990 shows a slight warming trend for observed average temperature (Fig. 22.2). The period 1990−2000 has a positive trend compared to 1961−1990, although the trend from 1964 to 1974 is equally strong (Fig. 22.2). Hence, the basin annual mean temperature has generally increased since the 1990s.

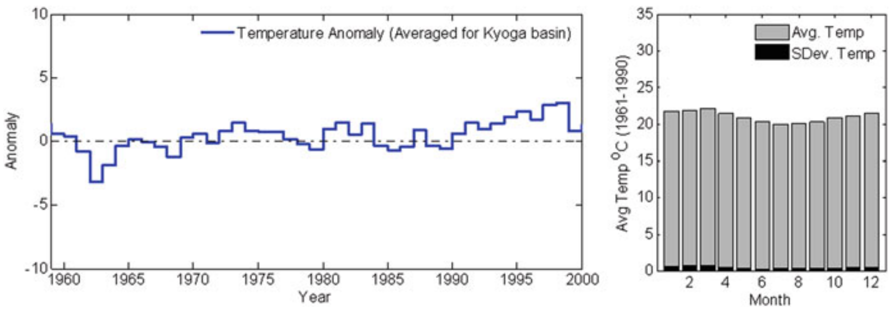

Fig. 22.2 Annual mean temperatures taken as anomalies from the 30-year (1961–1990) average for the Kyoga basin. (Reanalysis data: ERA40)

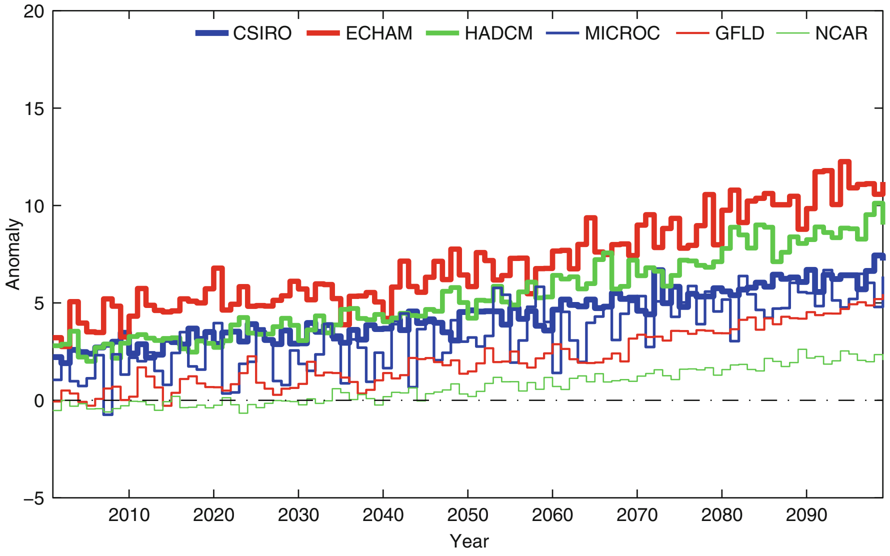

Fig. 22.3 Projected temperature anomalies for 2020s, 2050s, and 2080s using six GCM outputs: CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM

The projected temperature anomalies by the different GCMs are presented in the following section.

2. Temperature anomaly time series for future projections

Future climate scenarios are developed based on GCM modelling results. The average projection in temperature shows consistent behavior between all the six models, predicting an increase in temperature. In general, the six GCMs used in this study reveal that human-induced climate change is likely to increase temperature in the Kyoga basin by up to 1.6 °C by 2020s, 2.7 °C by 2050s, and by up to 4.0 °C by the 2080s. For the A2 SRES scenario, Figs. 22.3 and 22.4 show a mean annual temperature increase of 0.2–3.3 °C by 2020s, 0.8–4.2 °C by 2050s, and 1.7–5.3 °C

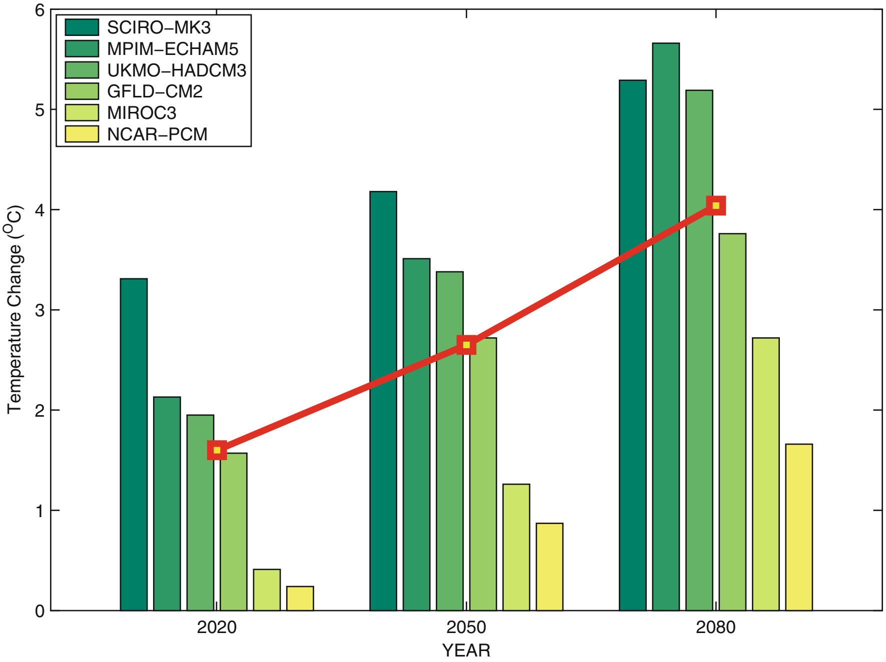

Fig. 22.4 GCM projected changes in temperature for 2020s, 2050s, and 2080s using six GCM outputs: CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM. The *line* represents the mean of all the GCMs

by the 2080s, with associated standard deviations of 0.8 °C for the 2020s, 1.1 °C for 2050s, and 1.5 °C for 2080s.

22.6 Regional Precipitation Analysis: Use of GLMs for Downscaling

Using the GLM model structures developed in the study by Kigobe et al. (2011), future climate projections for precipitation have been simulated by conditioning GLM models on GCM projections for temperature, pressure, and Indian Ocean Dipole (IOD)—estimated using the sea surface temperatures (SSTs) in the Indian Ocean. It must be emphasized that not all the GCM models used in the statistical downscaling exercise adequately simulate the 1960−1990 rainfall variability (Table 22.1); hence, the results should be interpreted with care. The projections are presented as an average over a 30-year period for each rainfall site and for each rainfall zone for the future periods centered on 2020s, 2050s, and 2080s relative to the 1960−1990 period. The seasonal changes in precipitation vary by region and by season.

GCM-simulated mean precipitation anomaly time series for 1961–1990: The GLM models developed for each rainfall zone were used to simulate the historical precipitation over the basin using relevant outputs of the six GCM models. That is to

Table 22.1 Zonal-average bias from six GCM experiments: simulation of observed precipitation for the 1961–1990 period

	Zone					
GCM	B	D	E	G, H	I	F
CSIRO.MK3						
DJF	0.83	0.91	0.65	0.62	0.74	0.93
MAM	0.98	1.00	0.95	0.88	1.00	1.02
JJ	0.67	0.61	0.69	0.68	0.76	0.77
SON	0.89	0.89	0.76	0.60	0.89	0.79
ANNUAL	0.87	0.88	0.80	0.71	0.88	0.87
UKMOHADCM3						
DJF	1.32	1.61	0.56	0.44	0.62	1.27
MAM	1.50	1.18	1.04	1.23	0.85	0.83
JJ	0.79	0.83	0.40	0.27	0.33	0.59
SON	1.54	1.14	0.92	1.14	1.04	0.93
ANNUAL	1.35	1.16	0.81	0.90	0.78	0.88
MIROC3						
DJF	0.81	0.92	0.58	0.51	0.59	0.75
MAM	0.71	0.76	0.64	0.40	0.63	0.58
JJ	0.69	0.77	0.60	0.64	0.71	0.76
SON	0.82	0.82	0.73	0.55	0.90	0.70
ANNUAL	0.76	0.81	0.65	0.51	0.72	0.67
MPIM.ECHAM						
DJF	1.01	1.03	0.82	0.68	0.75	1.06
MAM	1.03	1.17	1.06	0.79	0.84	1.04
JJ	0.66	0.52	0.65	0.57	0.67	0.69
SON	1.11	1.13	1.03	0.86	1.06	1.16
ANNUAL	0.98	1.02	0.94	0.75	0.86	1.02
GFLD.CM2						
DJF	0.34	0.16	0.12	0.07	0.11	0.12
MAM	0.32	0.24	0.24	0.12	0.26	0.13
JJ	0.31	0.12	0.16	0.11	0.17	0.15
SON	0.27	0.19	0.18	0.14	0.31	0.17
ANNUAL	0.31	0.19	0.19	0.11	0.23	0.15
NCAR.PCM						
DJF	0.76	0.86	0.38	0.26	0.36	0.52
MAM	0.85	0.79	0.70	0.59	0.72	0.61
JJ	0.44	0.32	0.33	0.33	0.39	0.35
SON	0.90	0.83	0.66	0.52	0.76	0.68
ANNUAL	0.78	0.72	0.57	0.47	0.62	0.57

say, GCM simulations of temperature, mean sea-level pressure, and humidity for the 1961−1990 period were used to run the GLM model for the different rainfall zones. If the GCM simulations are realistic (in that they represent the same variables as the reanalysis data), the observed values should appear to have been sampled from the simulated distributions.

The ability of each GLM model to simulate historical values consistent with gauged/observed data (1960−1990) using the GCM output was assessed by comparing the seasonal total using the "bias test." In this analysis, bias is defined as the ratio

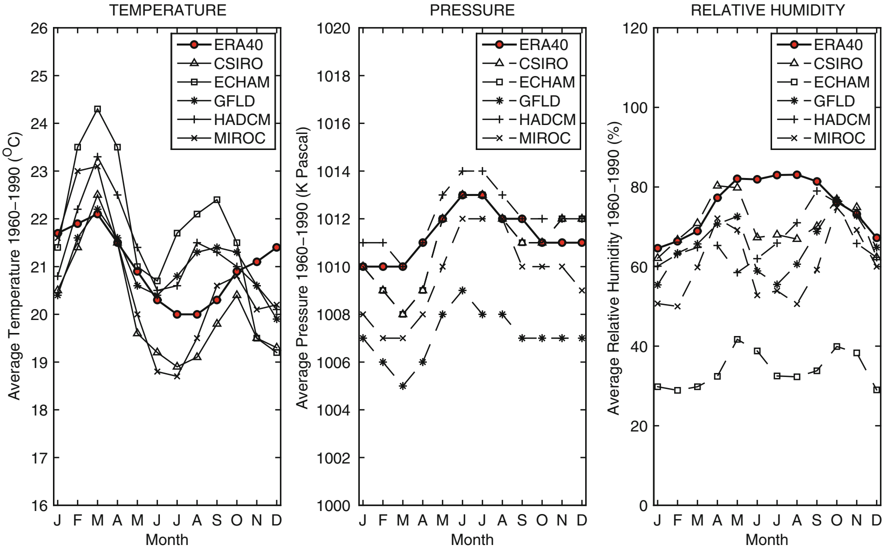

Fig. 22.5 ERA40- and GCM-simulated historical temperature, pressure, and relative humidity

of the sum of the GLM estimates using the GCM data for the period 1960–1990 to the sum of the GLM estimate using ERA40 reanalysis data. Table 22.1 summarizes the results.

The results show that GCM bias is not necessarily random and possibly cannot be reduced by averaging GCM outputs. For the Kyoga basin climate change impact studies, it is therefore important to identify and minimize biases in data to produce reliable climate study results. Model performance varies by region; however, for three GCMs (CSIRO-MK, MPIMECHAM, and UKMO-HADCM3), zonal average biases are generally low compared to the other three models (GFLD-CM2, MIROC3, and NCAR-PCM). All GCMs perform poorly for the June–July–August (JJA) season for reasons that are still not well understood.

The systematic biases across the different GCMs give a general indication of the simulations' strengths and weaknesses, when compared against the current climate. Despite the sophistication of present models in terms of scope of processes, limitations on the chaotic nature of climate still exist and additional work is required to refine GCM models for climate prediction (Dessai et al. 2009; Harrison and Stainforth 2009). Additionally, GCMs are reported to simulate poorly the teleconnections that are responsible for rainfall variability in Africa (Boko et al. 2007).

Although the limitations of empirical downscaling in Africa are less understood, possibly due to limited information on the likely changes to the spatial distribution of tropical cyclones in Africa (Christensen et al. 2007), the primary source of this bias appears to be deviations in simulated historical surface pressure and relative humidity by the different GCMs for the Kyoga basin (Fig. 22.5). The six GCMs used here have varying boundary conditions, and circulation biases are expected

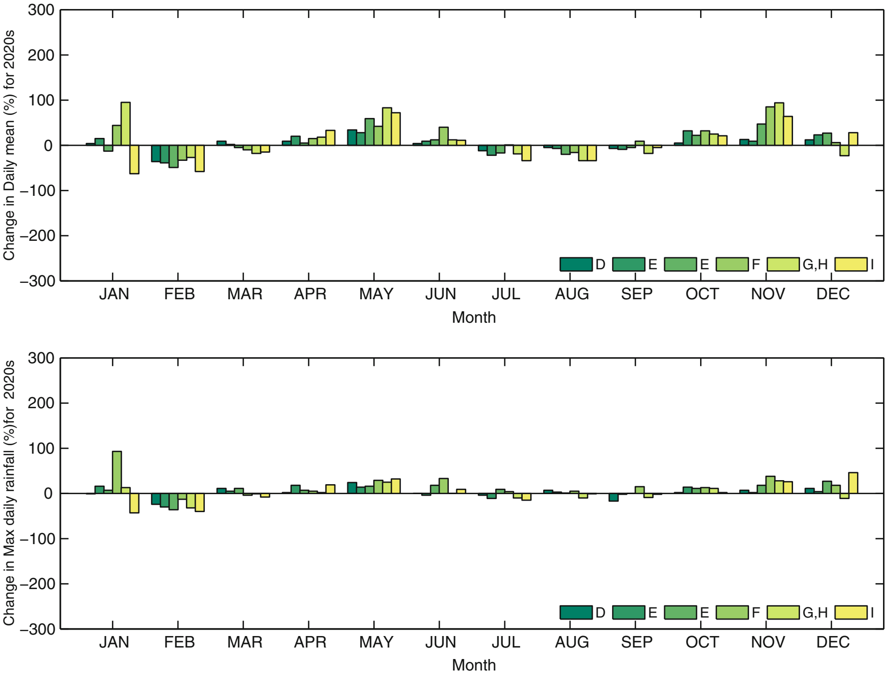

Fig. 22.6 Summary of average change in precipitation distribution for the 2020s relative to 1961–1990. The values are average predicted change for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM in each rainfall zone

while using the different GCM outputs. Hence, errors in simulated outputs may affect the GLM model response to various forcing data. Therefore, it is important to consider these caveats when analyzing climate change signals in this study and applying results to hydrological impact studies. The issue of biases is not unique to the equatorial regions in the Kyoga basin but has also been reported for southern Africa where 90 % (18 out of 21) of GCMs used in the IPCC's fourth assessment report overestimate precipitation by 20–80 % (Christensen et al. 2007).

Standard bias correction normally involves applying change factors based on the ratio of GCM simulations to the control climatology (Fowler and Kilsby 2007). A recent study by Elshamy et al. (2009) described a bias correction procedure that involves fitting gamma distributions to the observed and GCM projections. The method differs from the simple change factor method as it corrects both the mean intensities as well as extremes. In this study, to minimize bias, an average of the sets of GCM results with low bias was considered to provide climate simulations superior to any individual GCM—which justifies the use of a multimodel approach in the climate projection for the Kyoga basin. Despite these deficiencies, the GLM models that have been developed simulated the historical precipitation patterns well and so are considered suitable for simulating the future precipitation patterns for the twenty-first century.

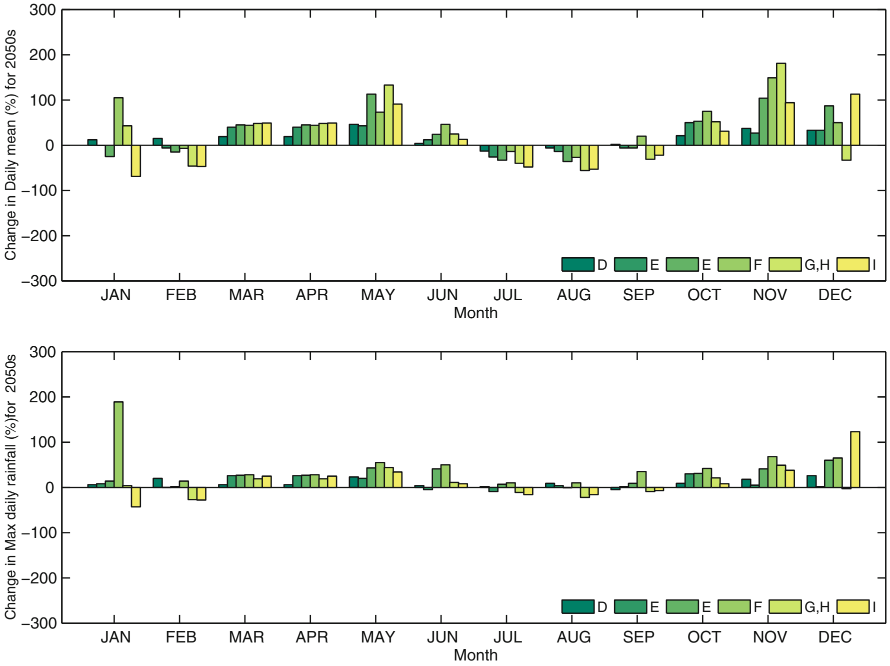

Fig. 22.7 Summary of average change in precipitation distribution for the 2050s relative to 1961–1990. The values are average predicted change for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM in each rainfall zone

22.7 Future Projections of Precipitation

For impact applications, the percentage change in precipitation is more relevant than the absolute amounts. This study mainly focuses on percentage change for each rainfall zone. For each site, 100 simulations are run for the 2020s, 2050s, and 2080s for each GCM using the SRES4A2 scenario. Seasonal and annual rainfall totals are computed for each gauge. The average totals for each rainfall zone are obtained by averaging all the rainfall sites in each zone. Also, anomalies of the projected precipitation are obtained by comparing the 50th percentiles of the projected precipitation totals to the 50th percentile of the historical (1960–1990) average at each gauge. In all the following results, the best estimate is therefore based on the 50th percentile (the midpoint of model ensembles). The assumption made here is that GCM projections are distributed about a “best estimate”; therefore, the uncertainty in estimate may decrease with the use of more models for statistical inference.

Average projections of precipitation vary by model and by rainfall zone. The projected annual changes in precipitation over the different rainfall zones vary from − 9 % to + 66 % for 2020s, from + 7 to 48 % for the 2050s, and from + 24 to 80 % for the 2080s (Figs. 22.6–22.8). There are substantial differences in the simulated quantities of annual precipitation change for the various rainfall zones. Generally,

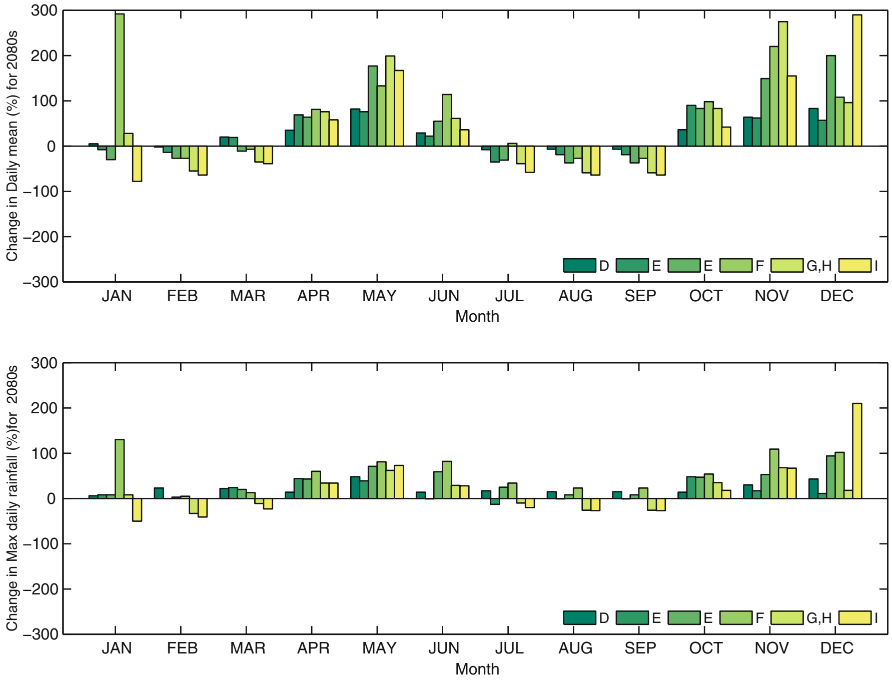

Fig. 22.8 Summary of areal average change in precipitation distribution (for 2080s) relative to 1961–1990. The values are average predicted change for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM in each rainfall zone

higher deviations are observed for rainfall zones F, G, and H for the future periods 2020s, 2050s, and 2080s. The least deviation is observed for rainfall zone I.

Except for HADCM3, all GCMs predict a relative increase in annual precipitation for 2020s, 2050s, and 2080s. For the HADCM3, precipitation for the 2050s is predicted to be higher than that for 2020s and the model predicts a decline in precipitation for the 2080s. The reason for the disparate prediction of the HADCM for the 2080s is unclear, although it is likely that the predicted reduction in precipitation patterns for the 2080s is caused by lower predictions in temperature for the 2080s.

The detailed projected changes in seasonal precipitation patterns found by the different models for the period 2020s, 2050s, and 2080s for the various rainfall zones are shown in Figs. 22.6–22.8. On average, there is a general increase in precipitation for the seasons December–January–February (DJF), March–April–May (MAM), and September–October–November (SON) and a general decrease in precipitation for the JJA season. It should be noted that some stations show an increase in precipitation for the JJA season despite the average decrease by rainfall zone. GCM projections suggest that rainfall zones E, F, G, and H are more sensitive than B, D, and I. The results suggest that rainfall zone F is most sensitive to climate change. The highest percentage increase in precipitation is observed for the DJF and SON seasons.

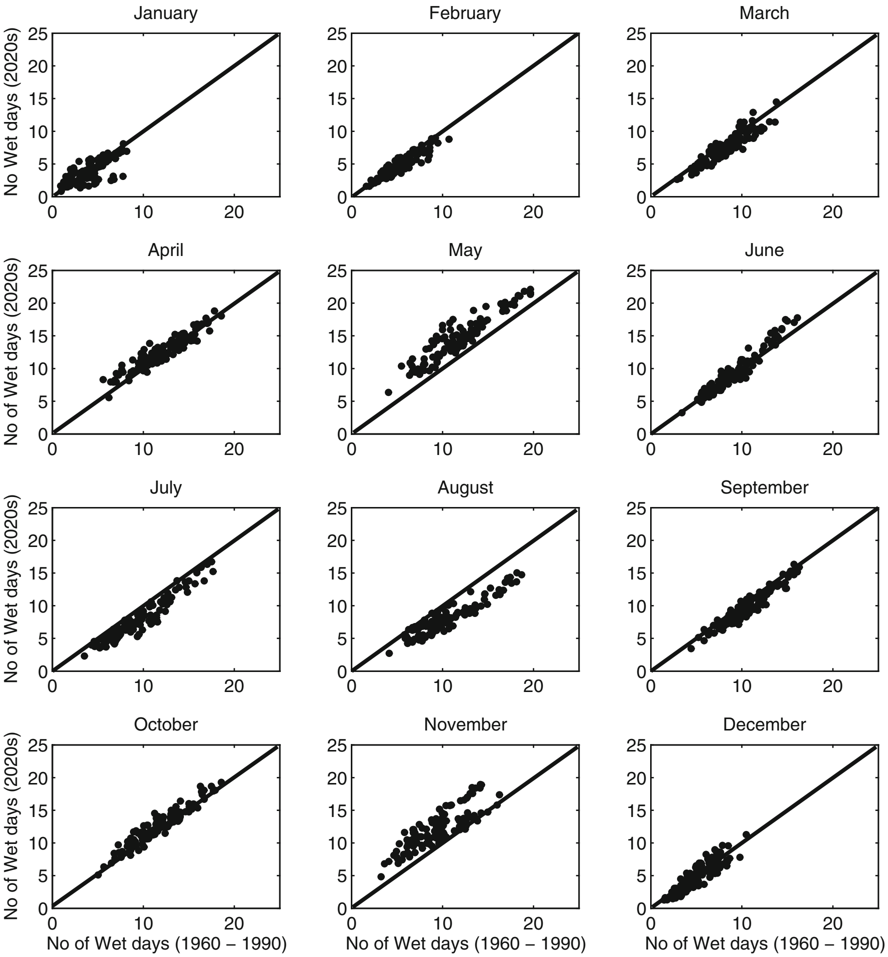

Fig. 22.9 Comparison of the 50th percentiles of historical and simulated mean number of wet days per month for the 2020s. The values represent the mean estimate from six GCMs (CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM). The *straight line* shows 1:1 relationships

However, discrepancies between individual models are very high. For most rainfall zones, there is little agreement in the magnitudes, although they generally agree in the direction of change—this is mainly observed for the MAM season. The simulated high seasonal changes in SON are in agreement with the finding of Schreck and Semazzi (2004), that regions experiencing bimodal rainfall pattern in East Africa might experience even more rainfall for the second rainfall season.

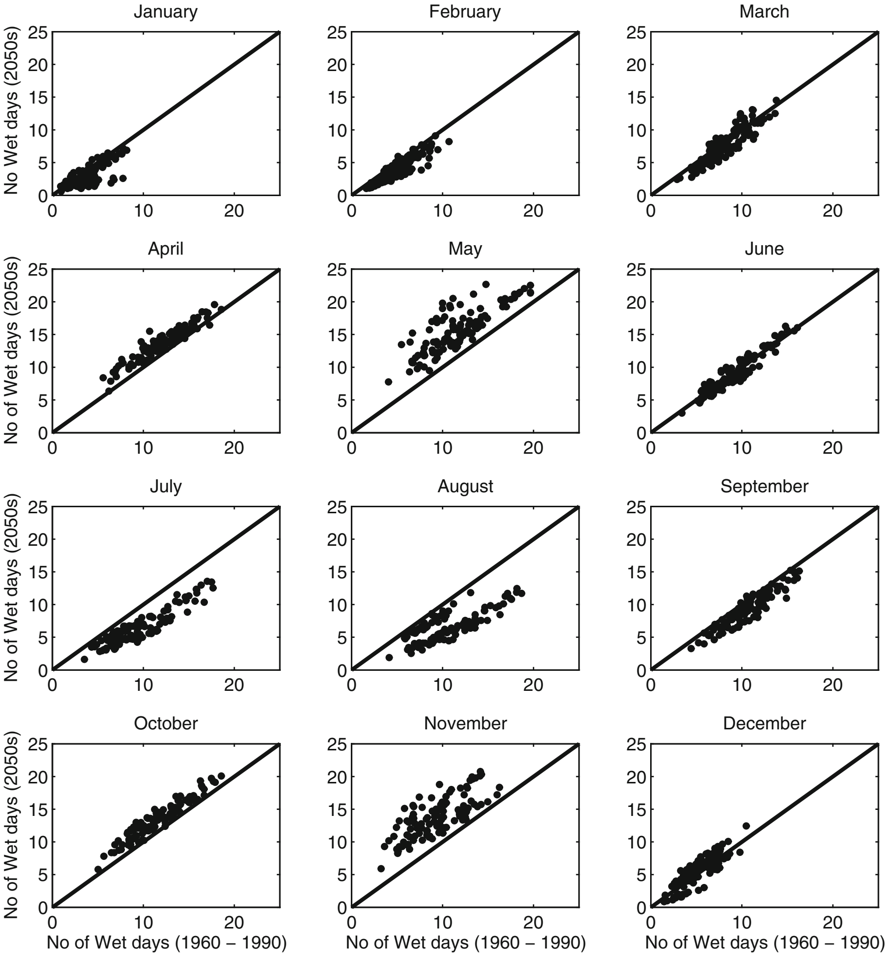

Fig. 22.10 Comparison of the 50th percentiles of historical and simulated mean number of wet days per month for the 2050s. The values represent the mean estimate from six GCMs (CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM). The *straight line* shows 1:1 relationships

22.7.1 Projected Changes in the Number of Wet Days

The simulated number of wet days is shown in Figs. 22.9–22.11. For the 2020s, and the 2050s, the simulations suggest an increase in the number of wet days for the months of May, October, and November, while July and August are predicted to have a decrease in the number of wet days. These trends are observed for the entire Kyoga basin and they generally explain the increase in the rainfall monthly totals for these months. The other months seem to be less affected. The simulations

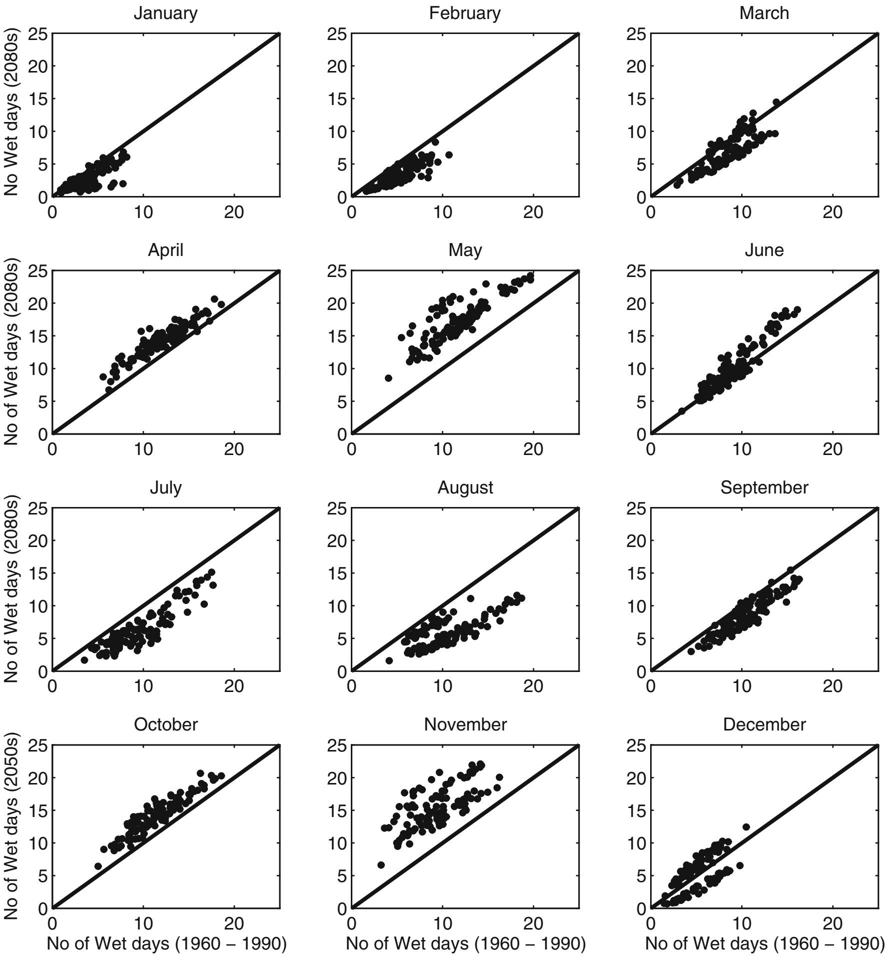

Fig. 22.11 Comparison of the 50th percentiles of historical and simulated mean number of wet days per month for the 2080s. The values represent the mean estimate from six GCMs (CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM). The *straight line* shows 1:1 relationships

for the 2080s reveal significant changes in the number of wet days compared to those observed for the 2020s and 2050s. Models suggest a likely increase in the number of wet days for April–June followed by a reduction in the number of wet days for July–September and an increase in October–November, as well as January–February. December shows major division in the simulated changes in the number of wet days. While most rainfall zones witness an increase in the number of wet days, rainfall zones F, D, and E are likely have a reduction in the number of wet days (Fig. 22.9).

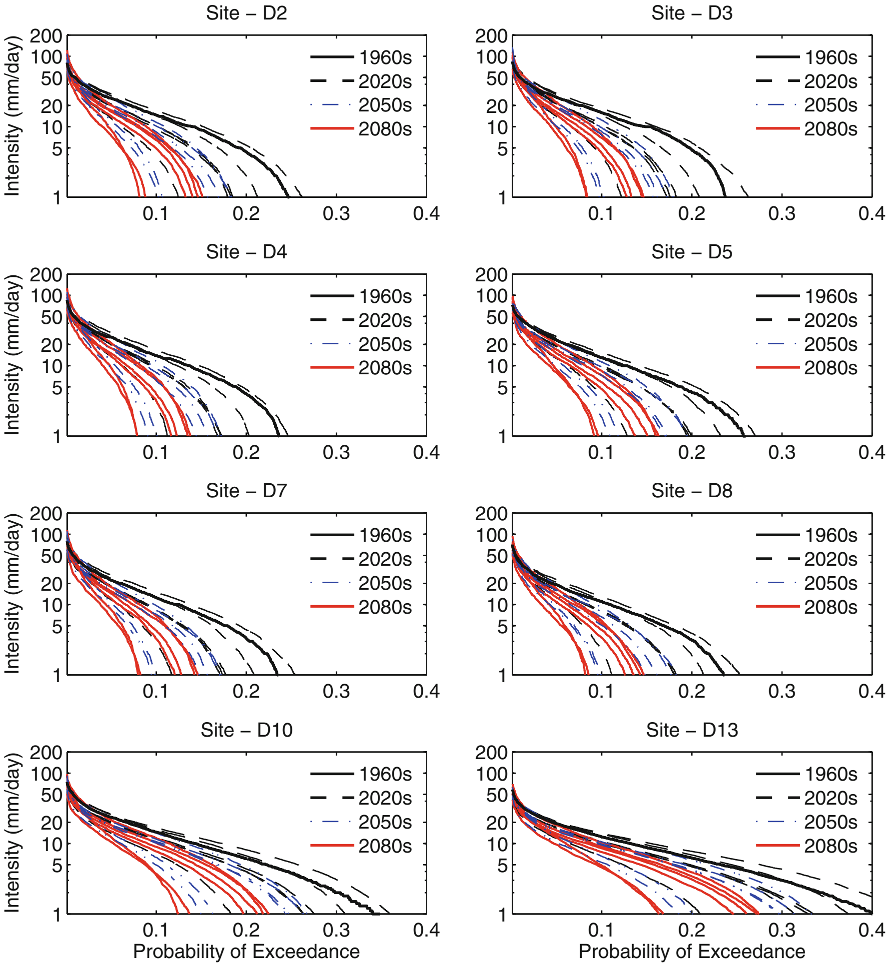

Fig. 22.12 Comparison of observed (*bold line*) and simulated frequencies (for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM) of daily precipitation as a function of precipitation intensities at eight gauges in rainfall zone D

22.7.2 Projected Changes in the Number of Wet Days

Change in Precipitation intensities: Figs. 22.12–22.15 show that, generally, precipitation events of less than 20 mm will be more frequent in the future, which also suggests that more precipitation events at reduced intensities will be observed. This is consistent with previous finding of Sun (2006) but inconsistent with the findings of Kundzewicz et al. (2007) and is observed for all the GCMs for most rainfall sites under all A2 scenarios.

A similar pattern, although of smaller magnitude, is observed for precipitation intensities greater than 20 mm/day. For all the intensities, the highest shift is likely to occur late in the century (2050s–2080s). Some exceptions are observed for a few

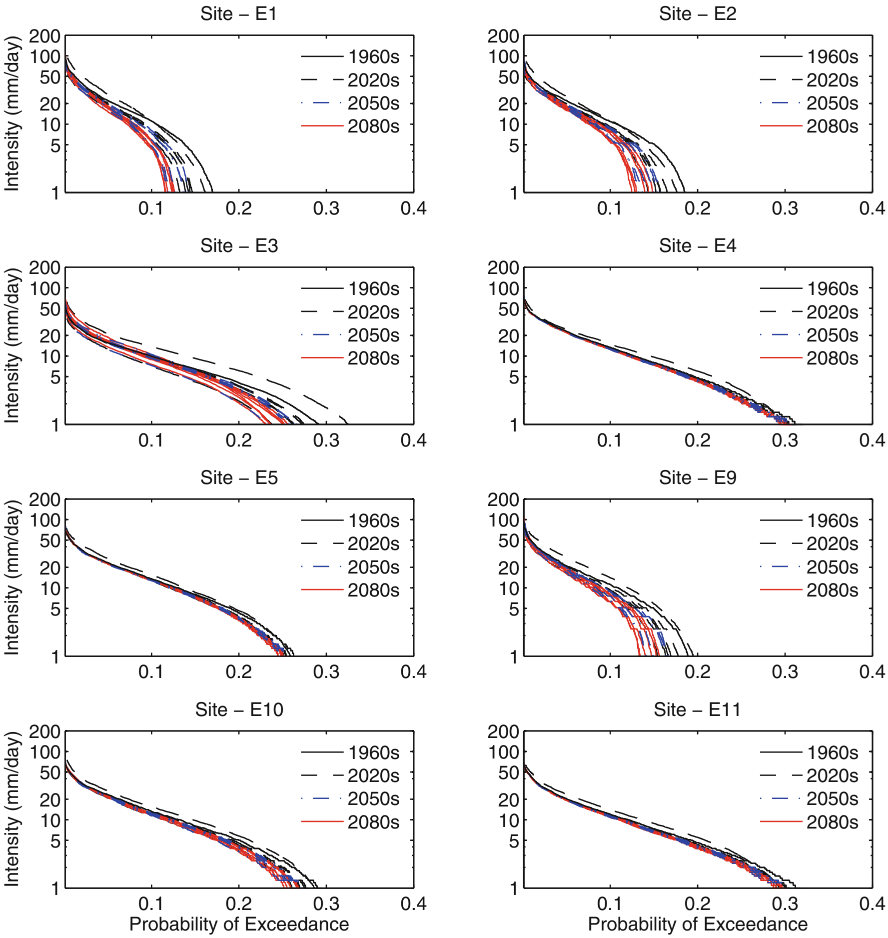

Fig. 22.13 Comparison of observed (*bold line*) and simulated frequencies (for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM) of daily precipitation as a function of precipitation intensities at eight gauges in rainfall zone E

sites in rainfall zone E (Fig. 22.16) where only slight variations are revealed by the simulations. Some sites show a shift toward more frequent heavy precipitation events, which creates an increased risk of flash floods in regions covered by rainfall zone F. The results generally support the argument that the increased number of wet days is likely to be due to the occurrence of more light precipitation events.

22.7.3 Projected Changes in Standard Deviation

An average of the simulated standard deviations from the six GCMs is shown in Figs. 22.16–22.18. For the 2020s, the simulated standard deviations are quite similar

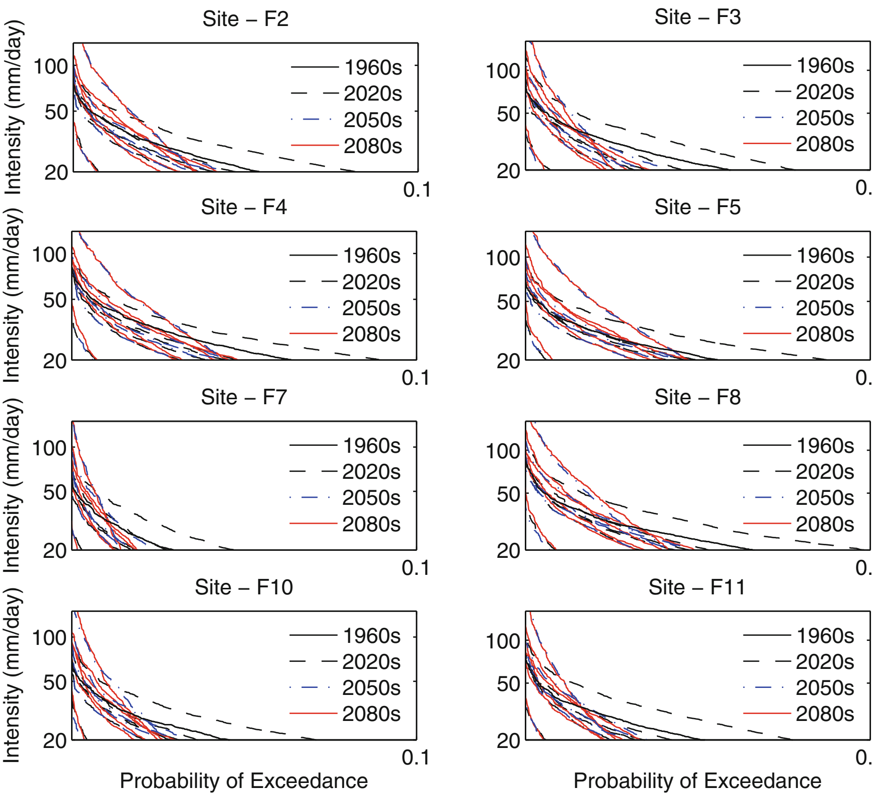

Fig. 22.14 Comparison of observed (*bold line*) and simulated frequencies (for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM) of daily precipitation as a function of precipitation intensities at eight gauges in rainfall zone F

to the historical trends, while during the 2050s and 2080s the models suggest major shifts especially for the second half of the year (May to December). The models suggest that during this period, there is likely to be a significant increase in the variability of monthly totals across most regions in the Kyoga basin. Major shifts tend to occur in May and November as shown in Figs. 22.16–22.21.

22.8 Summary of Precipitation Changes

The statistics in the 2020s–2080s presented suggest that it is likely that some modification in rainfall distributions would be observed and that the largest change is likely to occur late in the century (2080s). Using all the rainfall sites in the Kyoga basin, the monthly cumulative density function derived using the 50th percentiles from all the observed and simulated monthly totals at all sites and by month (Fig. 22.22) suggests that for the periods from April to June and from October to November all sites are

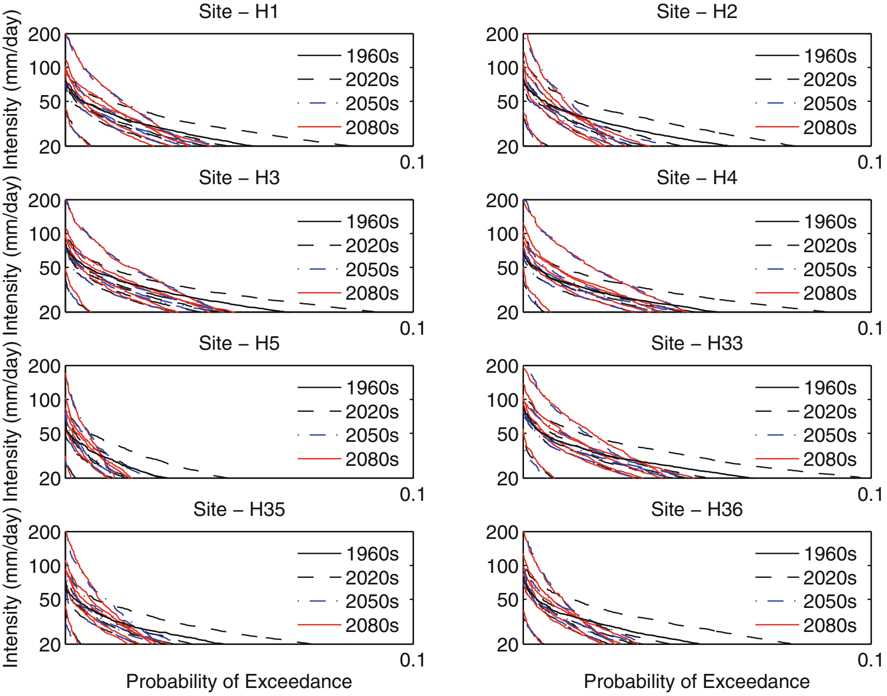

Fig. 22.15 Comparison of observed (*bold line*) and simulated frequencies (for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM) of daily precipitation as a function of precipitation intensities at eight gauges in rainfall zone H

likely to be affected in a similar way, with an increase in monthly totals for these periods. This is mainly due to the increase in the number of low intensity events and the total contribution of these events to the total monthly and annual totals.

During December to January, some sites are likely to become wetter than usual. This tallies with an increase in the number of wet days for some sites in December. During February, all sites are likely to have a reduction in monthly total, especially late in the century (2080s), which might be due to a reduction in the number of wet days. During March, sites historically receiving more than 100 mm of rainfall are likely to receive even higher rainfall totals during 2050 and 2080s, while those sites historically receiving less than 100 mm for March will have a reduction in monthly rainfall totals for the 2050s and this will reduce further by the 2080s. Given that the number of wet days is not influenced much for March, it is likely that the increase or reduction in rainfall is caused by the changes in rainfall intensities for March. Quite similar patterns are observed for September.

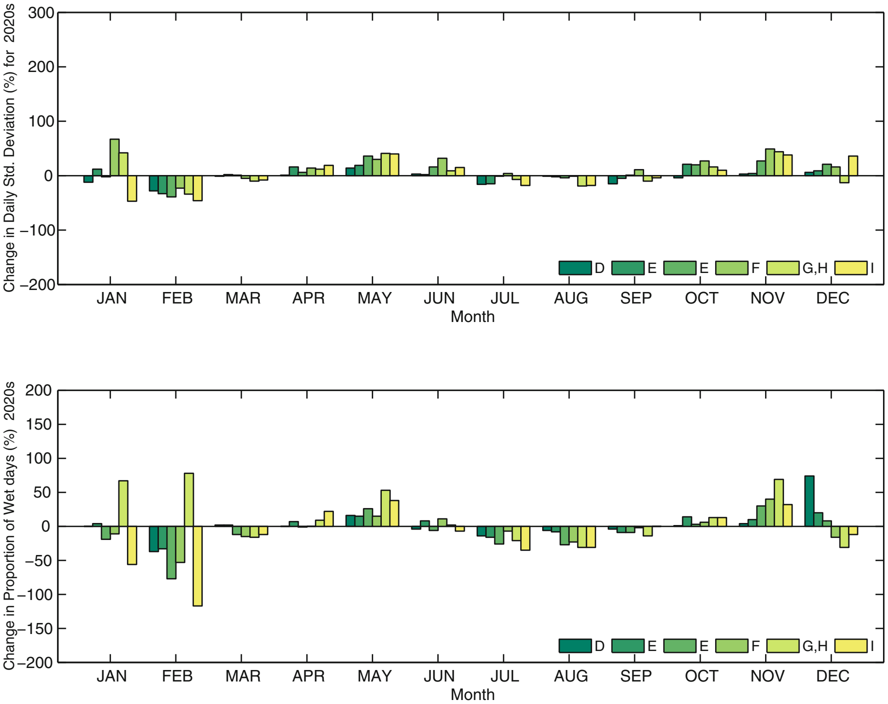

Fig. 22.16 Summary of areal average change in precipitation distribution (for 2020s) relative to 1961–1990. The values are averaged predicted change for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM in each rainfall zone

22.9 Prediction Uncertainty

To represent the uncertainty associated with the projected precipitation totals show the 5th, 50th, and 95th percentiles for 100 realizations of the GLMs for the 2020s, 2050s, and 2080s at all sites. The associated uncertainty is only slightly increased for the 2080s. Uncertainty in projected regional climate change is due to differences between the results of GCM models and the stochastic element of the downscaling rather than the different emission scenarios (since only one scenario was considered). It can be observed that the uncertainty in the prediction ranges is quite wide.

22.10 Summary of Annual Precipitation Changes

Results from GCMs with the least bias in simulating the historical precipitation patterns, that is, CSIRO, ECHAM, and HADCM3 have been used to estimate basin temperature and precipitation for the future climate of the 2020s, 2050s, and 2080s.

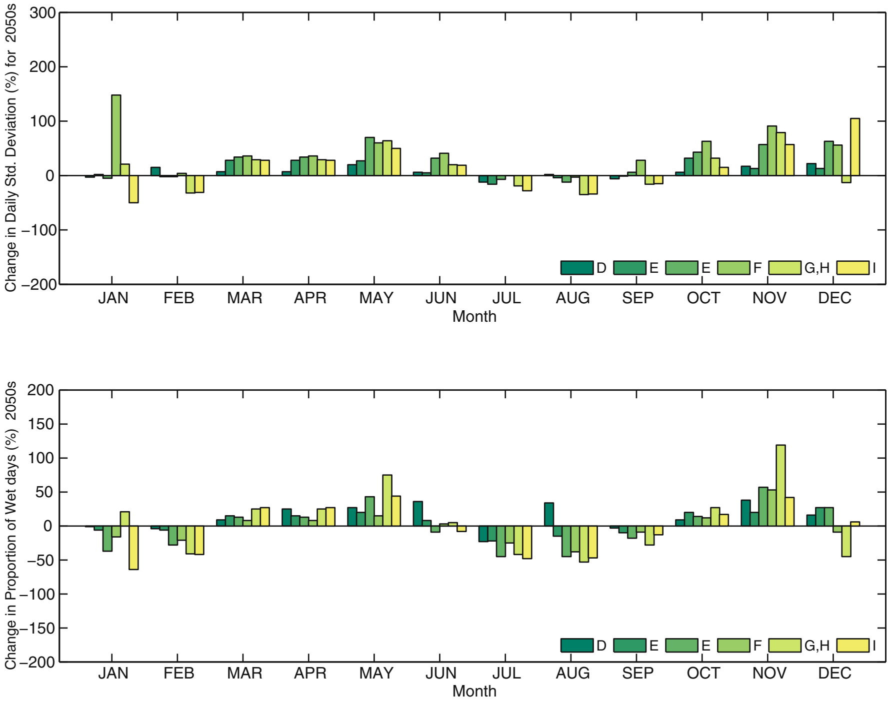

Fig. 22.17 Summary of areal average change in precipitation distribution (for 2050s relative to 1961–1990. The values are average predicted change for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM in each rainfall zone

The changes in precipitation and temperature are compared to the historical observations of 1961–1990. For the Kyoga basin, the spatial averaged monthly changes in precipitation are given in Fig. 22.23. The seasonal precipitation changes show an increase in precipitation amounts for the two rainfall seasons, although the magnitude of the projected change varies with rainfall zone. Spatial patterns vary by subbasin due to the spatial heterogeneity and difference in hydroclimatic variations associated with the general circulation teleconnections in the Kyoga region. The highest percentage increase in precipitation occurs during the periods from October to December and from April to June. Projected changes in JJA are mixed but generally, based on spatial averaging, precipitation is projected to decrease during JJA, although some sites revealed an increase. Although the seasonality of the rainfall is maintained, the monthly totals could be quite different, and generally, the wet seasons will be wetter, while the second dry season (JJA) will be dryer. The total rainfall received in the first rainfall season (MAM) is still higher than the total received in the second rainfall season (SON). The three models used for the sensitivity analysis tend to agree in direction of change for the twenty-first century (see Fig. 22.24). There was much more variation in GCM precipitation estimates by rainfall season and by rainfall region.

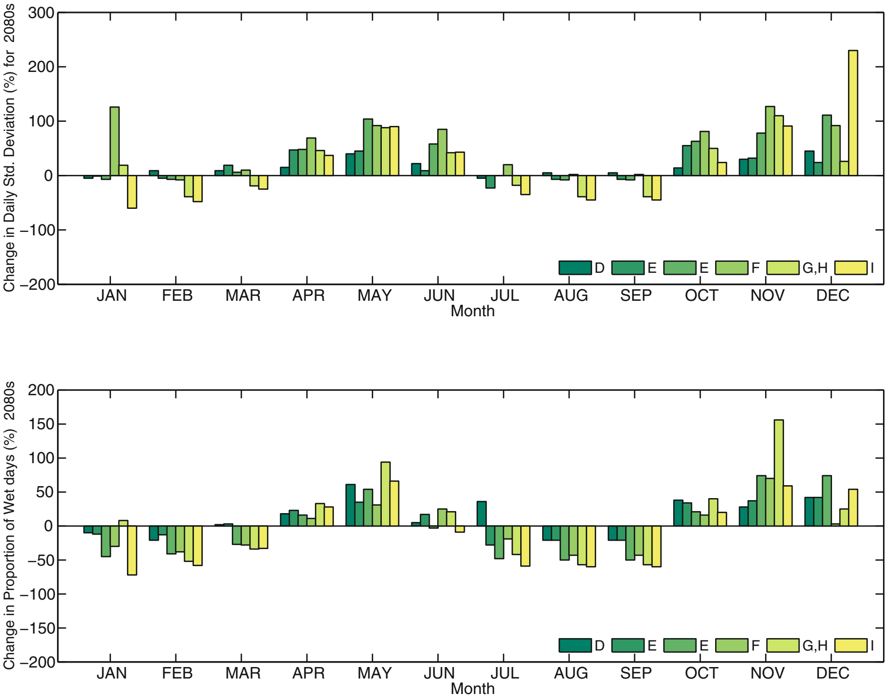

Fig. 22.18 Summary of areal average change in precipitation distribution for 2080s relative to 1961–1990. The values are average predicted change for CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM in each rainfall zone

22.11 Conclusion

The GLM models fitted to the observed data were applied as statistical downscaling tools for the Kyoga basin by conditioning the models to projected sea-level pressure, temperature, and relative humidity. Sequences of future rainfall were simulated for all gauges in the Kyoga basin for the 2020s, 2050s, and 2080s. The performance of GCMs varies by rainfall zone and not all GCMs perform well when simulating the baseline condition of 1961–1990. The CSIRO-MK3, MPIM-EHCAM, and UKMO-HADCM3 models generally have better ability (in terms of model bias) to simulate the historical seasonal precipitation patterns. GLM simulation of future rainfall suggests generally wetter DJF, MAM, and SON seasons and dryer JJA seasons.

The results generally agree with the reported direction of change by the IPCC for the wet tropics (IPCC 2007) and other studies particular to East Africa (Burke 2006; Christensen et al. 2007) : precipitation will generally increase in the wet tropics and the intensity of precipitation events is projected to increase particularly for areas that experience increases in mean precipitation (IPCC 2007). Similar to IPCC's reports,

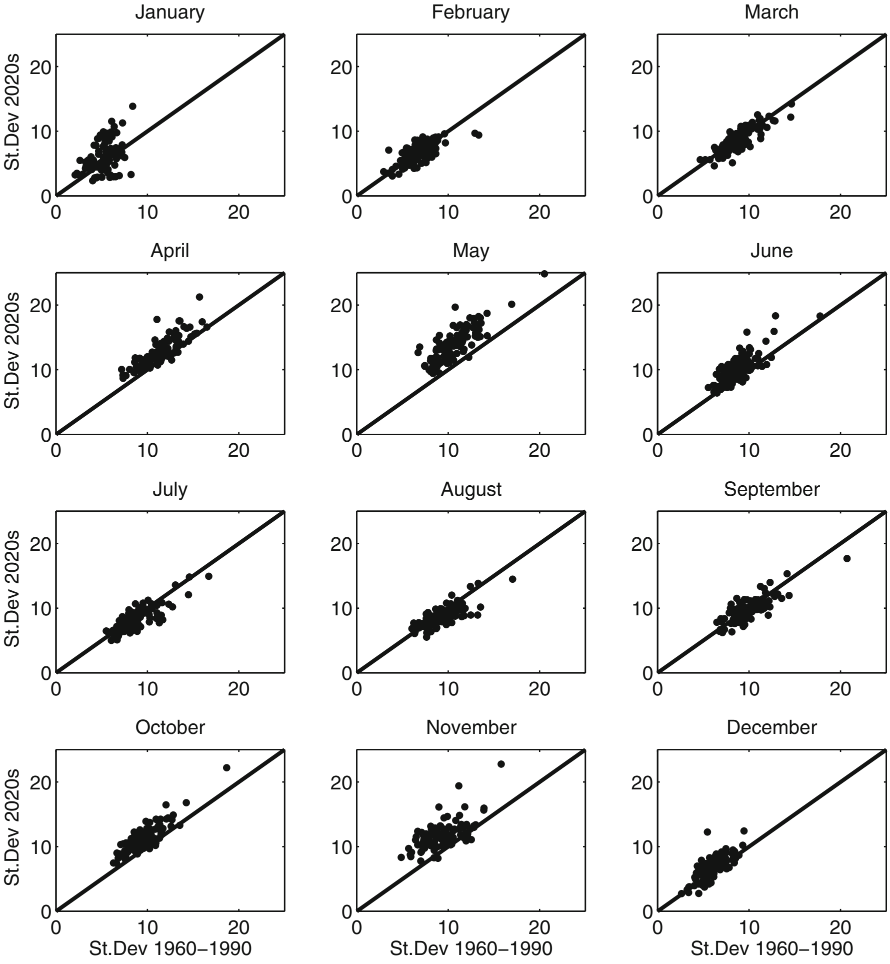

Fig. 22.19 Comparison of the 50th percentiles of historical and simulated mean standard deviation by month for the 2020s. The values represent the mean estimate derived from the six GCMs (CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM). The *straight line* shows 1:1 relationships

the strongest percentage increase in seasonal precipitation occurs for the DJF and the SON seasons (Schreck and Semazzi 2004; Christensen et al. 2007). The increase in rainfall is also qualitatively in agreement with the result of Hulme et al. (2000) for the projections based on the Third Assessment Report (TAR). Extreme events are not explicitly addressed in this study—limited information is available on extreme event analysis for GCM outputs (Christensen et al. 2007). However, the results suggest that conditioning GLMs on different GCM experiments gives significantly different projections and, therefore, more than one GCM output is needed to obtain a comprehensive range of plausible rainfall sequences.

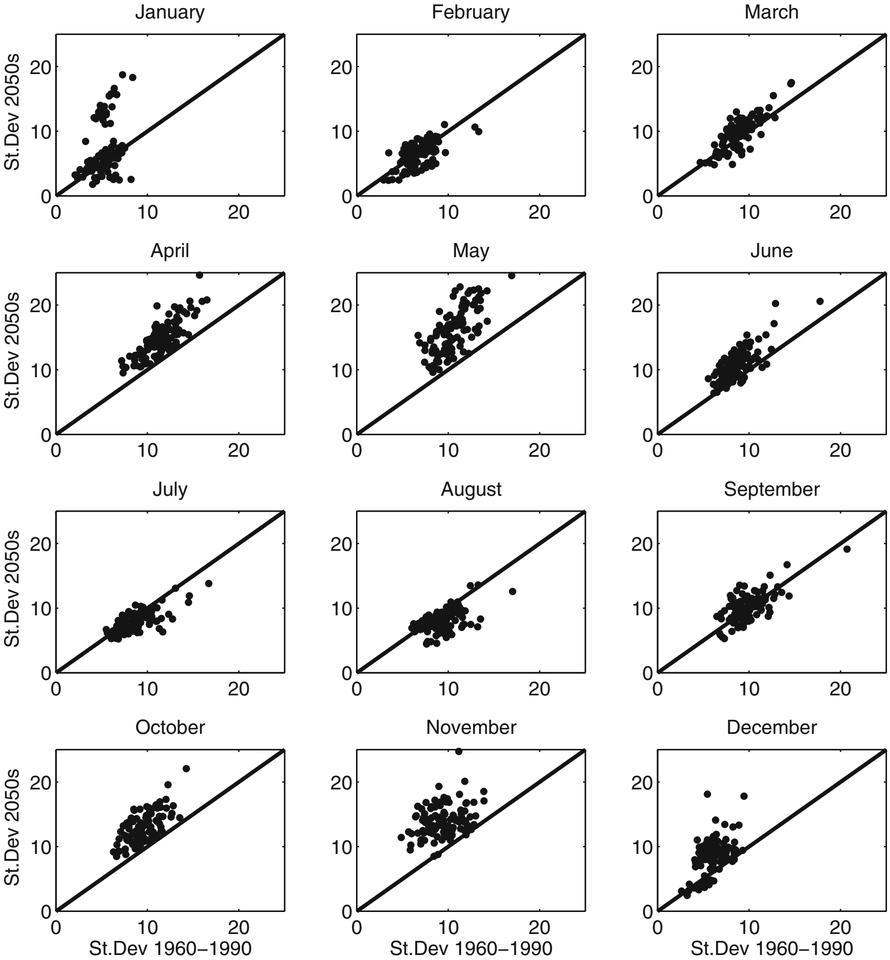

Fig. 22.20 Comparison of the 50th percentiles of historical and simulated mean standard deviation by month for the 2050s. The values represent the mean estimate from six GCMs (CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM). The *straight line* shows 1:1 relationships

The understanding of how climate change may affect precipitation at the local scale is important for planning and impact assessment. The results here reveal that the development of the balance between global and regional factors is still a challenge for the Kyoga basin; hence, more research is required to understand the variation in model precipitation responses in the Kyoga basin. However, the empirical models, applied here for the first time in the Upper Nile, provide a useful tool for simulating plausible daily rainfall sequences for hydrological application.

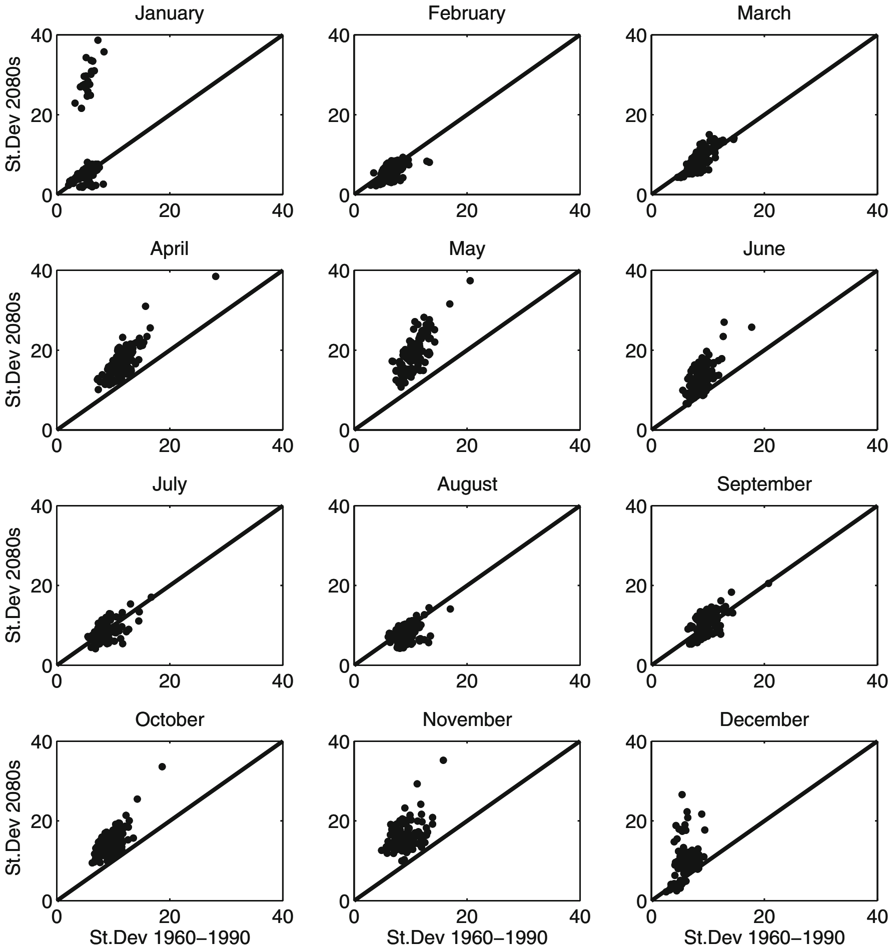

Fig. 22.21 Comparison of historical and simulated standard deviation by month for the 2080s. The values represent the mean estimate from six GCMs (CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM). The *straight line* shows 1:1 relationships

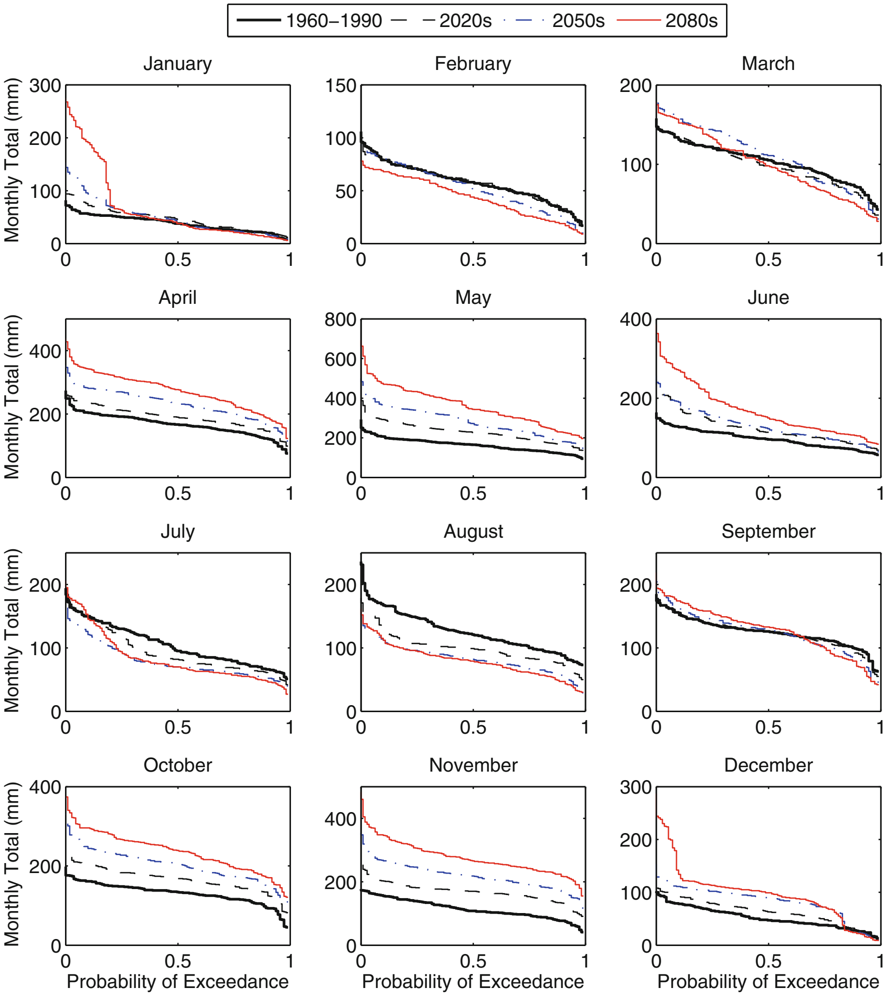

Fig. 22.22 Comparison of the cumulative density functions using all the monthly totals by site for the 50th percentiles of historical and simulated mean monthly total rainfall at all stations for the 2020s, 2050s, and 2080s. The values represent the mean monthly totals derived from six GCMs (CSIRO-MK3, MPIM-ECHAM, UKMO-HADCM3, GFLD-CM2, MICORC3, and NCAR-PCM)

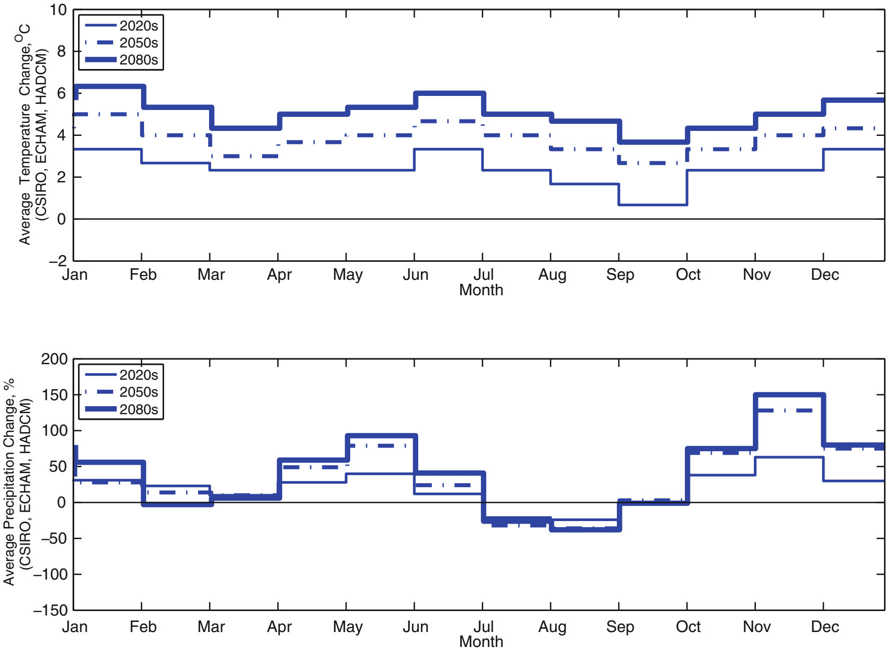

Fig. 22.23 Change in temperature (*top*) and precipitation from the 2020s, 2050s, and 2080s with respect to baseline period

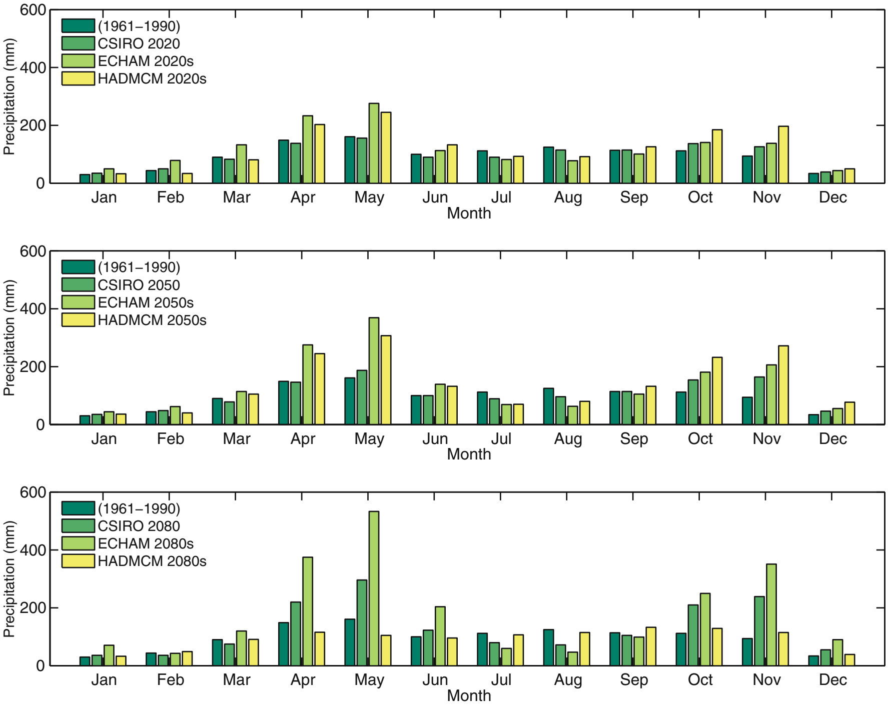

Fig. 22.24 Projected mean monthly precipitation totals for the 2020s, 2050s, and 2080s

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Chapter 23

Local and Indigenous Knowledge Systems in Subsistence Agriculture, Climate Risk Management, and Mitigation of Community Vulnerability in Changing Climate, Lake Victoria Basin: A Case Study of Rakai and Isingiro Districts, Uganda

Casim Umba Tolo, Enock Amos Majule and Julius Bunny Lejju

Abstract Developing countries are vulnerable to negative impacts of climate change due to over reliance on climate-sensitive sectors, mainly agriculture. Limited adaptive capacity makes them vulnerable to climate-induced hazards. However, over the years, indigenous knowledge systems (IKS) have proven effective in promoting sustainable development particularly for those in subsistence agriculture. For example, in Lake Victoria basin, local communities have coped and adapted to climate-induced hazards using traditional systems and IKS. This chapter presents findings of a cross-sectional survey on the use of IKS in subsistence agriculture to enhance climate risk management and mitigation of community vulnerability in a changing climate. Data were collected by household questionnaires, key informants' interviews, and focus group discussions. Results showed overall, significantly high community awareness levels prevail in study area, implicating climate change as the main challenge facing agricultural sector. Nevertheless, as climate change adaptation and mitigation measures, local communities use myriad of IKS to improve resilience and productivity. They use IKS in soil conservation, weather/climate forecasting, selection of planting seeds, and preservation of seeds/crops. This study, therefore, recommends incorporating IKS into scientific knowledge systems to promote climate change adaptation and mitigation among vulnerable communities dependent on climate-sensitive resources.

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Keywords Changing climate · Indigenous knowledge systems · Subsistence agriculture · Lake Victoria basin · Uganda

23.1 Introduction

Over the years, in the absence of scientifically proven approach, indigenous knowledge systems (IKS) have proven reasonable alternatives for promoting sustainable agricultural development, especially in developing countries. However, of recent, variety of interlinked human activities coupled with climatic variability/change have continued to negatively affect local communities in subsistence agriculture, particularly those living in Lake Victoria basin, East Africa.

Lake Victoria and its basin have undergone major environmental changes over the past decades resulting in rapid reduction in its natural resources, eutrophication, and significant drop in the water levels. At present, there is increasing demand for freshwater, agriculture land, urban expansion, and industrialization in the basin as well as changes in lake's flow regime (Phoon et al. 2004). Political instability, poverty, and frequent natural disasters are often reported in the basin. Today, increased pressure from human population is reported to be the major cause of rapid deforestation and conversion of water catchment areas into open farmlands in the lake's basin (e.g., Odada et al. 2004; Andama et al. 2012; Tolo et al. 2012); and also further reported in, e.g., Verschuren et al. (2002), Sida (2004), and Lejju (2012) that the extensive deterioration of the Lake Victoria resources is attributed to human activities and climatic variability.

According to IPCC (2001), signs of impacts of climate change observed around the world include the increase in surface temperature, sea-level rise, changes in precipitation, and decrease in snow cover. However, climate change also causes changes in rainfall regime, runoff, and evaporation, which in turn affect the water availability and variability worldwide, and especially so, for lakes like Victoria which receive 80 % of its water by direct overhead precipitation and loses about the same amount by evaporation (COWI 2002). Hence, the local communities in the lake's basin face a number of negative impacts of climate variability and change.

Climate risk management, especially in subsistence agriculture, is vital in order to assess and evaluate impacts of climate variability and change on agricultural productivity. According to NEMA (2010), climate vulnerability refers to the degree to which a system or organization is susceptible to, and unable to cope with, adverse effects of climate change/variability. Vulnerability is also regarded as a function of exposure to hazards such as droughts, conflicts, or extreme price fluctuations, and also underlying socioeconomic and institutional situation (NEMA 2010). Therefore, individual vulnerability assessment under changing climate would be able to determine, for example, if members of a given community are currently at risk or not, since people's livelihoods are directly affected by extreme weather events related to climate change and variability.

Application of indigenous knowledge (IK) and IKS would provide practical solution for local communities in meeting challenges of climate change/variability. Already, increasing importance of IK and IKS in promoting sustainable development in developing countries, including Africa, has been reported (e.g., Ulluwishewa 1993; DeWalt 1994; World Bank 1998; Makara 2002; Ngulube 2002). IK and IKS are learned ways of knowing and looking at the world (McClure 1989, p. 1), and Warren (1991) refers to it as traditional and local knowledge existing within and developed around specific conditions of women and men indigenous to a particular geographic area in contrast with knowledge generated within the international systems of universities, research institutes, and private firms. IKS have evolved from years of experience and trial-and-error problem solving by groups of people working to meet the challenges they face in their local environments, drawing upon the resources they have at hand.

World Bank (1998) contends that there is a need to learn from local communities and enrich the development process. For instance, about 80 % of the world's population depends on IK to meet their medical needs, and at least half rely on IK for crops and food supplies (CSOPP 2001). Generally, IK affects the well-being of the majority of the people in developing countries (Ngulube 2002). Similarly, Warren (1991) concludes that development projects cannot offer sustainable solutions to local problems without using local knowledge, and some scholars (e.g., Brokensha et al. 1980; Schoenhoff 1993) warn that failure to incorporate IK of local community in their development projects would inevitably result in failure of such projects.

In general, IK provides problem-solving strategies for local communities, especially the poor, and it represents an important component of global knowledge in development issues (World Bank 1999; Makara 2002). IK encourages participatory decision making and formulation and effective functioning of local organizations (Flavier et al. 1995). IKS and technology are "found to be socially desirable, economically affordable, sustainable and involve minimum risk to rural farmers and producers, and above all, they are widely believed to conserve resources" (Rouse 1999). On the other hand, Vanek (1989, p. 167; cited by DeWalt 1994) emphasize among other important features of IK for sustainable development, its traits of being convenient in rational decision making, various adaptive strategies for use at times of stress (e.g., drought and famine), indigenous system of intercropping, integration with social institutions, and flexibility with considerable entrepreneurial abilities.

23.1.1 IKS Use to Improve Agriculture and Natural Resource Management

Apart from its common use by rural communities in developing countries as local climate forecasting tool to guide farmers in timing planting seasons (e.g., Roncoli et al. 2002), on-farm research findings on IKS in Kentucky, USA, demonstrated that no-tillage farming resulted in greater production because it made double-cropping possible (Phillips and Young 1973; DeWalt 1994). In this case, no-tillage farming technology was a local initiative by indigenous farmers who effectively demonstrated to agricultural scientists that it was possible to plant soybeans followed by wheat while ensuring better soil moisture retention, saving in labor, less soil damage from machinery, better timing in planting and harvesting, and reduction of some weather risks (Choi and Coughenour 1979).

For local climate forecasting, IKS indicators which farmers mostly use are, e.g., fruit production of certain trees at the onset of rainy season and temperatures during dry season, intensity and direction of winds, cloud cover, behavior of birds and insects, as well as different phases of the moon throughout the year among others (e.g., Roncoli et al. 2002, 2010, 2011; Kangalawe et al. 2011). Local farmers from Burkina Faso also devised their own method of rehabilitating degraded land by improving the traditional planting pits through the application of organic matter, thereby attracting termites, which dig channels and, thus, improve the soil structure and water retention capability (Aly and Hamado 2005).

In the same way, Rubaihayo (2002) reports on peri-urban farmers around Kampala, Uganda, employing IK in producing and consuming traditional vegetables. In this practice, the farmers work back the organic indigenous plant matter into the soil after harvest and this was reported to have improved the vegetable yield in the following planting season. The farmers realized that rotating green beans (*Phaselous vulgaris*), “Ebugga” (*Amaranthus dubius*), and tomatoes (*Lycoperscum lycopersicon*) in that order makes “Ebugga” neutralize the soil after planting green beans, thereby preparing the soil for good tomato yields (Rubaihayo 2002). Similarly, Banyankole cattle keepers in Bubaare subcounty and other parts of Greater Mbarara, Uganda, have been using various indigenous herbs including, recently, *Moringa oleifera* seeds to treat water from ponds before feeding to their animals. The herbs are believed to have Molluscicide and other anti-microbial properties capable of reducing microbial load in water, hence reducing the cost of animal production and increasing milk yield. Other beneficial application of IKS in natural resources management has also been documented, e.g., among the Runa community of San José of Ecuadorian Amazon through resource enhancement practice within a shifting cultivation system (Irvine 1987). Similarly, in this chapter, we present findings of a study set to investigate and document local system and IKS used in subsistence agriculture to enhance climate risk management and mitigation of community vulnerability in a changing climate and promoting livelihoods security for vulnerable communities in Lake Victoria basin. It was guided by the following main research questions with focus on communities living in Lake Victoria basin: (1) What are the knowledge levels of local communities involved in subsistence agriculture on trends of climate variability and change? (2) Can we identify possible risks in subsistence agriculture related to climate variability and change and the strategies for the climate risk management? (3) What kinds of individual and community vulnerabilities exist in subsistence agriculture as a result of climate variability and change; and how do individuals and communities improve their resilience to changing climate? (4) Can we document local system and IKS used in subsistence agriculture to mitigate community vulnerability in a changing climate, adaptation options, and coping strategies?

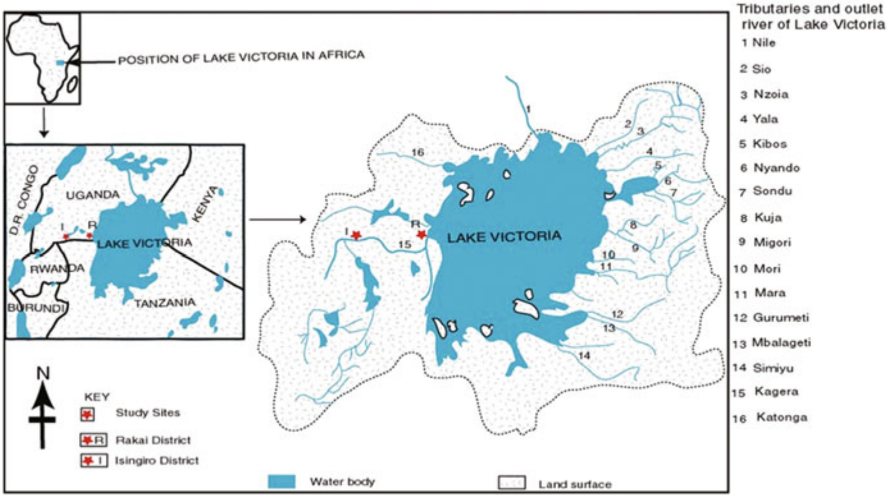

Fig. 23.1 Lake Victoria basin showing location of the two study villages of Kimbugu and Nyabuziba, Isingiro and Rakai districts, Uganda, respectively

23.2 Materials and Methods

23.2.1 Study Area

This study was conducted in the Lake Victoria basin, in Rakai and Isingiro districts, Uganda (Fig. 23.1). Lake Victoria situated in East Africa within 0° 20′ N to 3° 00′ S and 31° 39′ E to 34° 53′ E coordinates, an altitude of 1,134 m (Ssemmanda and Vincens 2002; Njiru et al. 2008) and a surface area of 68,800 km^2 (Crul 1995), is the second largest freshwater lake in the world and the largest in Africa (Crul 1995). The lake is shared by Kenya (6 % of shoreline), Uganda (43 %), and Tanzania (51 %), with a catchment area of ≈195,000 km^2 that also includes Rwanda and Burundi. Lake Victoria basin is one of the eight major subbasins identified within the Nile basin (Conway 1993). The water of the lake is a vital resource for an estimated 30 million inhabitants who are dependent on its resources for food, energy, water, building materials, and transport.

The Lake Victoria basin is covered by an extensive wetland ecosystem composed of macrophytes, papyrus, phragmites, typha, and vossia and contains more than 500 species of fish, including 300 endemic species of the haplochromine cichlids and several endemic Tilapiines (e.g., *Oreochromis esculentus* and *O. variabilis*). Introduction of exotic fish such as Nile perch (*Lates niloticus*) and Nile tilapia (*O. niloticus*) threatens this diversity and is blamed for the near extinction of more than 200 endemic species (Njiru et al. 2008). Other threats facing the resources of the lake and its basin include eutrophication, overexploitation of fisheries, catchment destruction, population pressure arising from people constantly being attracted to exploit economic potentials of the area, pollution from domestic, industrial, as well as agricultural wastes, and climate variability and change.

Rakai and Isingiro districts both lie in the western part of Lake Victoria basin, Uganda. The two districts represent typical rural setting common to many of the districts found in the lake's basin. The population is mainly dependent on natural resources to meet their basic needs at subsistence levels, and the local communities are extremely vulnerable to negative impacts of climate variability and change.

23.2.2 Research Design

A cross-sectional survey was the design. A household questionnaire was used for data collection; in addition, two different checklists were designed to guide key informants' interviews and focus group discussions, respectively. Participants were selected among the local communities of the study area.

23.2.3 Study Population

The population comprised selected local communities of the study area from two villages purposively selected (Fig. 23.1). Study population was carefully chosen to reflect true characteristics for cross section of total population of the study area. To this study population, a comprehensive questionnaire was administered at household level, Focus Group Discussions (FGDs) at village level, and key informants' interviews at subcounty and district levels to triangulate data collection process.

23.2.4 Sample Size

For households selected to participate in the study, sample sizes were calculated from the formula for estimating population proportion that is applied for finite populations (Krejcie and Morgan 1970).

23.2.5 Sampling Procedure

The participants included in the sample size were selected applying probability and non-probability procedures (Byaruhanga 2005). For each study village, questionnaires were administered to households using random sampling method until a required sample size was attained. A questionnaire was administered to not more than one member of each household, but often to the head of the household. About 10–15 participants from local communities of the study area took part in FGDs. At least two FGDs were conducted per village. In addition, key informants' interviews were conducted with participants purposively selected (Mugenda and Mugenda 1999) from subcounty and district levels. Key informants comprised mainly district technical staff and political leaders, community elders / opinion leaders, and community-based organizations (CBOs) /nongovernmental organizations (NGOs) staff in the area. In all cases, youths, elderly, and other interest groups were incorporated in participant-selection procedure.

23.2.6 Research Instruments/Tools Used for Data Collection

Tools used included household questionnaire, key informants' interview, and focus group discussion guides. To ascertain validity and reliability, all the tools were pretested, appraised, and retooled before use for data collection.

23.2.7 Data Analysis

Appropriate analytical techniques for qualitative and quantitative data analysis were used. A total of 164 duly filled household questionnaires were included in analysis in addition to synthesis of transcribed information from focus group discussions and key informants' interviews. Thematic content analysis was mainly used to handle qualitative responses. Data were coded according to inductive category (for open-ended questions) and deductive category (for close-ended questions), focusing on issues not captured in terms of frequency and other statistics (e.g., Denzin and Lincoln 1994; Krueger 1998; Morgan 1996). Quantitative data were subjected to nonparametric tests and coefficient correlations within a computer program, statistical package for social sciences (SPSS 17.0). For simplicity, the results of the survey are herein presented in tabular and graphic forms.

23.3 Results and Discussion

Here, we present, interpret, and discuss the main results of the study. Unless otherwise stated, results presented demonstrate perspectives of local communities as they relate to the use of IKS in subsistence agriculture in a changing climate to enhance community resilience and livelihoods. Overall, summary results are presented beginning with demographic characteristics of the study population and ending with IK used in storage/preservation of seeds/crops.

23.3.1 Generalized Demographic Characteristics of the Study Population

Overall, 60.37 % ($n = 99$) of the household respondents were male against 34.14 % ($n = 56$) female with 5.49 % ($n = 9$) not mentioning any gender, reflecting patriarchal nature of the community in Lake Victoria basin where men dominate socioeconomic and environmental issues (Tolo 2010). Respondents' age distribution reflects only mature individuals, who have lived in the area for decades, took part in the study, and are believed to have accumulated, over the years, considerable IKS used in subsistence agriculture, a similar view expressed in Kangalawe et al. (2011). Majority of the respondents reported having attained only basic primary level education, representing 62.2 % ($n = 102$). As a result, most of them, 78.65 % ($n = 129$), practice subsistence farming as their main occupation and livelihood. The low level of education cannot permit majority of the local population to be gainfully employed in service industry; and, therefore, as argued in NEMA (2010), local environment and/or natural resources in the area remain their primary source of livelihoods. This, they supplement with subsistence agriculture which is also threatened by land shortage, degradation, fragmentation, and general adverse effects of climate and change/variability in the area.

The demographic characteristics of the population is also challenged by a number of land-related problems, with households citing mainly land degradation and land shortage, each representing 78 % ($n = 128$), followed by unproductive land, 75 % ($n = 134$). Other land-related problems cited include land fragmentation, landlessness, land conflicts, and soil exhaustion. **S**imilarly, participants of FGD members of key informants' interviews cited the same reasons as above. Ironically, some of the land-related problems are the same reasons that led respondents to migrate from their previous settlement places. This implies, indeed, there are both social and physical factors that promote land-related problems in the study area. However, this may lead to vicious cycle of settlement abandonment with people not having incentive investing and/or developing their land to increase productivity.

23.3.2 Awareness Levels of Local Communities on Trends of Climate Variability and Change in Lake Victoria Basin

The study established that majority, 88.41 % ($n = 145$), of the local communities in the study areas are aware of trends in climate variability and change in their area, and the level of awareness is overall significant ($P = 0.000$) in the two study districts of Isingiro and Rakai. And the awareness level of trends in climate variability and change in the two districts compared is the same ($P = 0.213$). The findings clearly indicate that local communities in Lake Victoria basin, just like elsewhere in Africa (e.g., Roncoli et al. 2010, 2011; Kangalawe et al. 2011), are aware of trends in climate variability and change in their area. However, the level of awareness does not seem to reflect communities' readiness for climate change adaptation. Most of the level of awareness revolves around unpredictable onset and ending of rains and shortened growing seasons (e.g., West et al 2008; Mpeta 2009), incidences of severe droughts, and consequent widespread famine (e.g., Reardon and Taylor 1996). The problem is that most of these perceived indicators of trends of climate variability and changes remain highly variable, changing from season to season, year after year with

Fig. 23.2 A local farmer displaying a bunch of banana from a plantation suspected to have been affected by "banana bacteria wilt (BBW)" in Nyabuziba village, Rakai district, Uganda

no definite pattern, thus making it difficult for communities to take commensurate adaptation measures.

23.3.3 Effects of Climate Variability and Change on Agricultural Activities in Lake Victoria Basin

Most of the respondents in the study areas, 96.34 % ($n = 156$), reported that their agricultural activities in the past years have been affected by climate variability and change, and only a negligible number, 3.66 % ($n = 8$), could not directly attribute the losses to climatic factor. According to the local communities, some of the effects of climate variability and change on subsistence agriculture, as cited in decreasing order of severity, include decrease in crop productivity, frequent outbreak of pests/diseases (e.g., Fig. 23.2), frequent droughts, frequent floods, reduced water/pasture for livestock, and unreliable rainfall patterns among others. These have severely hampered agricultural activities in the villages, making local communities vulnerable in most cases, to the verge of famine and loss of livelihoods. Just like households, key informants and members of FGDs stressed increasing incidences of banana bacterial wilt (BBW) disease "toduura" in Luganda that keeps devastating banana plantations, and yet banana is a key income earner among the subsistence farmers in the area. Overall, climate variability and change has significantly affected local communities' agricultural activities in the two study villages ($P = 0.000$) as well as within the individual districts of Rakai ($P = 0.000$) and Isingiro ($P = 0.000$). However, the impacts experienced in the two districts compared are the same ($P = 0.340$).

Findings of the present study have revealed that climate variability and change is one of the greatest challenges facing agricultural activities in Rakai and Isingiro districts. However, on a regional and continental scale, Lake Victoria basin is not an exception. For example, Kangalawe et al. (2011) in Great Ruaha River catchment, Tanzania, also documented similar impacts. Nelson et al. (2009) report that agriculture, especially in developing countries, is extremely vulnerable to climate change, as higher temperatures lead to reduced yields of most desirable crops while encouraging weed and pest proliferation, and that overall, impacts of climate change on agriculture are negative, threatening global food security.

23.3.4 Sensitization of Local Communities on Trend of Climate Variability and Change in Lake Victoria Basin

Almost half of the local communities who took part in the study, 54.26 % ($n = 89$), admitted having been sensitized on trends of climate variability and changes. The remaining 45.74 % ($n = 75$) have never received any form of sensitization on the same. Myriad of organizations associated with the sensitization program include Millennium Development Goals (MDGs) Project termed as Millennium Village Project (MVP) which is being piloted in Isingiro district, National Agricultural Advisory Services (NAADS), media (radios and televisions), World Vision, and agricultural extension officers. On the contrary, National Environmental Management Authority (NEMA), a watchdog of environment in the country, was the least mentioned.

Nevertheless, communities still felt sensitization program falls far below expectation. To them, it is rather thin on ground and does not reach all communities and more can be done by government, NGOs, and CBOs in order to reach many citizens. Overall, the level of sensitization in the two districts compared is significant ($P = 0.000$). People seemed more sensitized in Isingiro than in Rakai district. This disparity may be attributable to the activities of United Nations Development Programme, Millennium Village Project operating in Isingiro. Lack of funding and inadequate capacity are, however, some of the common reasons cited especially by government-funded agents for not carrying out sensitizations, and for some NGOs/CBOs, climate change-related problems are simply not on their current agenda.

23.3.5 Risks in Subsistence Agriculture Due to Climate Variability and Change and Strategies for Climate Risk Management in Lake Victoria Basin

A number of risks have prominently been associated with subsistence agriculture in a changing climate. Owing to small-scale nature, lack of access to capital/finance, and relevant technologies, local farmers in the study area have become vulnerable to climate-induced risks affecting their livelihoods. In most cases, they are often made to adapt and cope with these hazards using IKS. In particular, local communities are wary of decreasing quantity of farm produce, frequent outbreak of pests/diseases, frequent droughts, insufficient amount of rainfall received per season/unpredictable

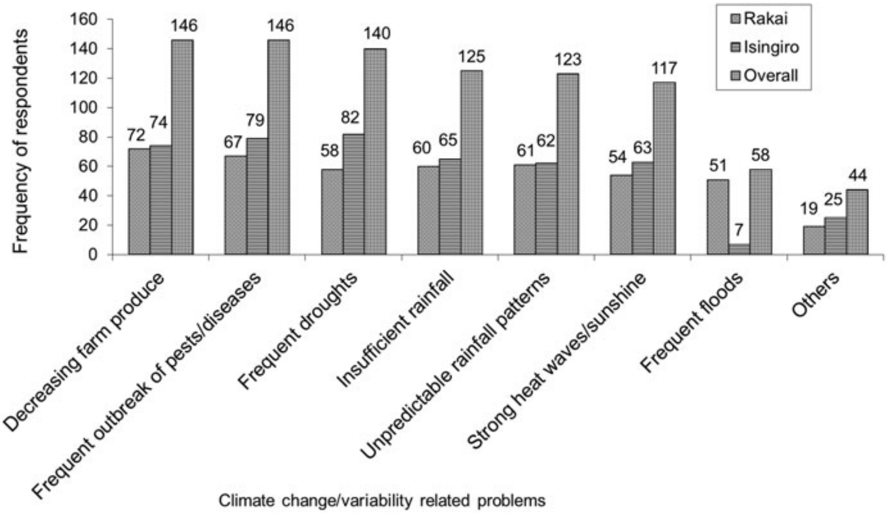

Fig. 23.3 Some of the climate change/variability-related risks on subsistence agriculture experienced in study villages of Rakai and Isingiro districts, Uganda

rainfall patterns, strong heat waves/sunshine, and frequent floods among others (Fig. 23.3). Similarly, participants of both FGDs and key informants unanimously agreed with the said risk factors. They also cited frequent famine in the area as a result of failed crops and unexpected heavy rains destroying crops, hence leading to increasing household poverty due to reduced income from produce sale. They also associate with climate change/variability, prolonged sunshine, and frequent strong winds that lead to drying of crops before maturity. Other risks relate to poor/muddy roads for transportation of produce to market, hence deteriorating the quality of produce on transit.

However, when the impact of climate change/variability-related risks on subsistence agriculture is compared in the two districts, no significant difference exists between all the other risk factors except for frequent droughts experienced in Isingiro district ($P = 0.043$) and frequent floods experienced in Rakai district ($P = 0.000$). These findings suggest that communities in districts of Isingiro and Rakai should, as necessities, adopt two different adaptation and mitigation measures against the impact of climate change/variability-related problems, with communities in Isingiro placing more emphasis on drought mitigation and coping measures, while those in Rakai should emphasize more on flood prevention and mitigation. Drought mitigation measures such as constructing water-harvesting tanks (on small scale, e.g., from rooftops) and planting quick maturing/pest-resistant crop varieties (i.e., drought-tolerant and early-maturing crop varieties) will help those living in drought-prone areas such as those in Isingiro district to adapt to negative impacts of climate variability and change, while those in flood-prone area like those in Rakai district should engage in constructing water channels to prevent floods in their areas as adaptation measures.

Fig. 23.4 Rain water harvesting in locally constructed water tanks (on small scale, e.g., from rooftops) as drought mitigation measure in Kimbugu village, Isingiro district, Uganda

23.3.6 Strategies Put in Place by Local Communities for Climate Risk Management in Lake Victoria Basin

A number of strategies have been put in place in the study area for climate risk management, with most of them incorporating IK and IKS. Some of these strategies, in the order of importance as mentioned by respondents include tree planting/afforestation, planting quick maturing/pest-resistant crop varieties (i.e., drought-tolerant and early-maturing crop varieties), avoiding environmental degradation, adopting modern farming techniques, constructing water-harvesting tanks on small scale, e.g., from rooftops (Fig. 23.4), constructing water channels to prevent floods, and animal rearing/setting up poultry to diversify livelihoods. Others include mulching, manuring, watering crops, swamp reclamation, contouring/terracing, and planting root crops.

On the basis of these findings, it is true that a number of risks in subsistence agriculture are related to climate change/variability in Lake Victoria basin, creating sense of uncertainty and vulnerability among the local population. These uncertainties make subsistence farmers feel wary and helpless. To them, climate change-related problems are far beyond their control. This is similar to the findings of Hassan (2010) in Zanzibar Island, where most farmers were found to be planting their crops during the planting seasons simply by trial and error with future of their crop success uncertain due to unpredictable climatic seasons. However, it will be important if local communities are equipped with right adaptation and mitigation measures in order to develop appropriate strategies for climate risk management in

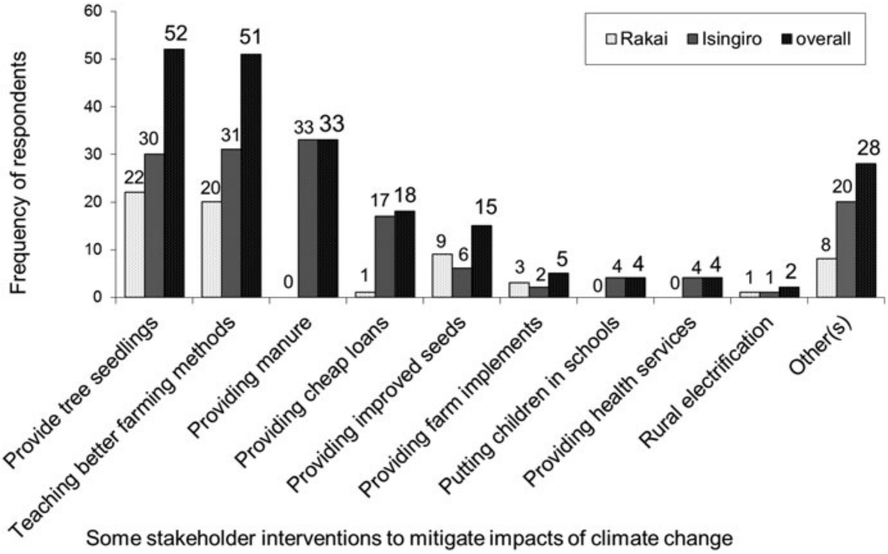

Fig. 23.5 Some interventions by different stakeholders (government, NGOs, CBOs, etc.) in addressing negative impacts of climate variability and change in the study villages of Rakai and Isingiro districts, Uganda

Lake Victoria basin. For example, farmers of the Central Plateau in Burkina Faso, after incorporating drought-mitigation adaptations into their agricultural systems, were found to view drought as "normal" (West et al. 2008). It is, therefore, important to encourage farmers in the study area to continue with strategies such as planting trees/afforestation, early planting of crops and planting of quick-maturing, pest-resistant, and drought-tolerant varieties, as well as diversification of livelihoods.

Nevertheless, there are some modest interventions (Fig. 23.5) by different stakeholders (e.g., government, NGOs, CBOs, etc.) that include providing tree seedlings, teaching better farming methods, and providing manure and cheap loans among others. However, when some of the key specific interventions by different stakeholders were compared across the two study districts, it is observed that statistical significant difference exists only in one intervention, providing cheap loans to the communities ($P = 0.000$), with local communities in Isingiro receiving much better financial services in the form of cheap loans than do those in Rakai district.

Vulnerability to climate change can vary within countries, communities, and even households, and, as such, adaptation requires context-specific activities, with strategies targeted to meet the needs of different vulnerable groups (Dazé et al. 2009). Relatedly, vulnerability to climate change has been defined as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (Dazé et al. 2009). Therefore, vulnerability is a function of the character, magnitude, and the rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC 2001).

By and large, and in the context of the findings of this study, local communities' perceived individual and community vulnerability has mainly been their inability to cope with the negative impacts of climate change/variability that directly affect their livelihoods. In their view, both rich and poor are vulnerable to the negative impacts of climate change/variability, although with varying degrees of vulnerability. This is consistent with the views expressed by Dazé et al. (2009) which recognizes that communities are not homogenous, so particular households or individuals within communities may have differing degrees of vulnerability.

The communities in the study area are dependent on rainfed agriculture, and, as such, most of their vulnerability stem from the way how climate variability and change affect their way of production. Their control over resources, particularly natural (mainly reliable water source and productive land), financial (diversified income sources), and human (knowledge of climate risks, conservation agriculture skills, and enthusiastic labor force), are all minimal, to say the least. In general, most of the vulnerabilities are weather related and, therefore, climate induced. Given that subsistence agriculture is the main form of livelihood in the area, their way of production is impacted heavily by vagaries of weather. It is, therefore, prudent to help local communities get access to information and enhance their adaptive capacity. One of the most important factors shaping the adaptive capacity of individuals, households, and communities is their access to and control over natural, human, social, physical, and financial resources (Dazé et al. 2009). IPCC (2007) defines adaptation as adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

A well-adapted community becomes resilient to negative impacts of climate change/variability. Resilience has been defined as the ability of a community to resist, absorb, and recover from the effects of hazards in a timely and efficient manner, preserving or restoring its essential basic structure, functions, and identity (e.g., IISD 2007; UNISDR 2009). On the other hand, hazard is defined as a dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury, or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR 2009). However, just as adaptive capacity, resilience varies greatly for different groups within a community depending on access and control over critical resources. A resilient community is well placed to manage hazards to minimize their effects and/or to recover quickly from any negative impacts, resulting in a similar or improved state as compared to before the hazard occurred (Dazé et al. 2009).

Similarly, from the results of this study, climate-related hazards have mainly been shocks, such as droughts and floods (characterized by rapid onset in nature), and stresses, such as changing rainfall patterns and rising temperatures (characterized by slow onset in nature). However, some of the effects of both climate-related shocks and stresses such as frequent famine, failed crops, low productivity/low income, high poverty levels, degraded farm lands/declining soil fertility, water scarcity, livestock deaths, and increased crop pests/diseases are widespread in the study area and, hence, communities must be helped to build resilience against them to sustain livelihoods.

23.3.7 Local/traditional IKS Used in Subsistence Agriculture in Mitigating Community Vulnerability in a Changing Climate and as Adaptation Options in Lake Victoria Basin

This study established that local communities use myriad of IK and IKS in subsistence agriculture. The use is multifaceted aimed at not only increasing productivity in terms of quantity but also enhancing quality. IK and IKS are, for instance, used in soil conservation, climate/weather forecasting in order to correctly time planting seasons, selecting suitable planting seeds, and storage/preservation of seeds and crops in a changing climate. Further still, the local communities have convincing rationale/reasons for use of each IK as summarized in Table 23.1.

Indigenous communities world over have had a well-developed traditional IKS for managing issues affecting their livelihoods in cost-effective, participatory, and sustainable manner since time immemorial. For example, in Africa, application of IKS in sustainable agriculture, including the practice of improving soil conservation and fertility (e.g., Rubaihayo 2002; Aly and Hamado 2005), have been documented. Similar practices have also been demonstrated elsewhere in the world with tremendous results (e.g., Phillips and Young 1973; DeWalt 1994). In the same way, the present study has also documented a rich array of IKS that relate to its use in subsistence agriculture with some positive aspects that can augment scientific knowledge as has been argued by DeWalt (1994).

Apparently, from the perspectives of the local communities, IKS appears to be universal and, hence, applicable in every sphere of life including its use in weather forecasting among others. For example, local communities in Lake Victoria basin are well versed with seasonality of weather in their area based on IK. They often use a number of indicators in predicting suitable planting seasons in a changing climate including knowledge of onset of rainy season (normally in the study areas expected to be the months of March and September, and also August and December of every year), knowledge of changes in particular wind movements/directions signifying onset of wet/dry seasons, knowledge of changes in ambient temperature associated with onset of wet/dry seasons, knowledge of flowering period of shrubs (“ehongwa”) signifying onset of dry season, knowledge based on observation of specific cloud cover types in the sky associated with onset of wet/dry seasons. Others include knowledge of swarming of butterflies and bees associated with onset of wet/dry seasons, health status of an individual (e.g., ear blockage and excessive seating at night, feeling backache and general body weakness signifying onset of wet season), knowledge of specific birds’ singing signifying onset of wet/dry seasons, and knowledge based on the presence of red ant colonies which indicates a ripe season specifically for panting onions. Also, the movement of group of birds and following of specific religious days/calendar, as well as blossoming of coffee plantation, are examples of all IKS indicators used in forecasting weather by local communities in the study area (Table 23.1).

The use of IKS as local indicators documented by this study for climate forecasting is consistent and agrees with its widespread use in most parts of Africa. For instance,

Table 23.1 Some of the local/traditional and indigenous knowledge systems used in subsistence agriculture in mitigating community vulnerability in a changing climate, Lake Victoria basin, Uganda. (Source: Field data 2012)

(a) IK for soil conservation in a changing climate in Rakai and Isingiro districts, Lake Victoria basin, Uganda

Local/traditional and indigenous knowledge	*Rationale/reasons for the indigenous knowledge*
Crop rotation	Usually for the soil to regain its fertility and avoid pests/diseases recurring
Mulching using banana leaves/grass/maize stems	Soil to retain moisture and improve soil conditions
Land/bush fallowing	To allow land regain its fertility and avoid pests/diseases recurring
Terracing/strip cropping/contour plowing	Stop or combat soil erosion/soil conservation
Application of cow dung as fertilizer	Improve on soil fertility
Tree planting in gardens	To prevent soil erosion and act as wind breakers
Construct water channels/trenches	Mitigate floods
Avoiding bush burning	Maintain soil cover and mitigate soil erosion
Growing cover crops, e.g., beans, cow peas	Mitigate soil erosion and improve soil fertility
Mixed cropping/farming	Maintain soil fertility
Burying weeds in composite pits	To be used as organic manure
Application of urine in farmlands	Enhances soil fertility

(b) IK for forecasting planting seasons in a changing climate in Rakai and Isingiro districts, Lake Victoria basin, Uganda

Local/traditional and indigenous knowledge indicators of climate	*Starting/ending of rainfall season*
Months of March and September; and also August and December every year	Known rainfall months in local calendar every year. So farmers prepare their gardens and plant their crops/seeds
Swarming of butterflies	Signifies starting of dry season. Hence, no planting of crops/seeds
Swarming of bees	Signifies onset of rain season. Hence, farmers prepare their gardens and plant their crops/seeds
Movement of groups of birds "Ebiranganseneneene," literally meaning "announcing arrival of grass hoppers" (Lunyankole)	Signifies onset of rain season. Hence, farmers prepare their gardens and plant their crops/seeds
West–east direction of wind movement	When the wind blows from west to east, it signifies onset of rain season. Hence, farmers prepare their gardens and plant their crops/seeds
Presence of "red ant" colonies "Empazi" (Lunyankole) and "Ensanafu" (Luganda)	Specifically signifying planting season for onions. Hence, farmers prepare their gardens and plant onions
Blossoming shrub "Ehongwa" (Lunyankole)	Signifies onset of dry season. Hence no planting of crops/seeds
Singing of specific birds, e.g., a bird known as "Ekishamututu" (Lunyankole)	Usually the songs of this bird signify rains are soon coming (rainfall season approaching). Hence, farmers prepare their gardens and plant their crops/seeds
Specific religious days, e.g., Easter and Ascension day, August 15 of every year	These religious calendar days are associated with rainfall, ideal for planting crops/seeds
Blossoming of coffee plants	Associated with rain season. Hence, farmers prepare their gardens and plant their crops/seeds

Table 23.1 (continued)

Local/traditional and indigenous knowledge indicators of climate	*Starting/ending of rainfall season*
Specific health status of an individual experienced, e.g., ear blockage (at night), excessive sweating (at night), backache, and general body weakness	The local communities associate these health conditions with onset of rainfall. Hence, farmers prepare their gardens and plant their crops/seeds

(c) IK for selecting suitable planting seeds in a changing climate in Rakai and Isingiro districts, Lake Victoria basin, Uganda

Local/traditional and indigenous knowledge (features/mode of selection)	*Indigenous knowledge and planting seed selection criteria*
Damaged vs. undamaged seeds	Undamaged seeds only are always selected for planting
Healthy vs. unhealthy seeds	Healthy seeds only are always selected for planting
Attractive vs. unattractive seeds	Attractive, mostly brightly colored seeds are selected for planting
Water soaking seeds	Only denser seeds as opposed to floating ones are selected for planting
Weevil infested vs. uninfected	Only weevil-free seeds are selected for planting
Disease resistance of the varieties	Only seeds from disease-resistant strains are selected for planting
Size of the seeds	Usually big-sized seeds are selected for planting
Maturity of the seeds	Only mature seeds are selected for planting
Number of cotyledons	For dicotyledonous seeds, e.g., beans, only those with two dicots are selected for planting
Seeds with or without embryo	Only those seeds with embryo are selected for planting

(d) IK for storage/preservation of seeds/crops in a changing climate in Rakai and Isingiro districts, Lake Victoria basin, Uganda

Local/traditional and indigenous knowledge	*Rationale/reasons for the indigenous knowledge*
Storing in cool/dry place	To avoid fungal attacks, eliminate moisture accumulation
Storing in granary	To ensure fresh air circulation eliminate moisture
Accumulation	
Mixing seeds with ash	To prevent weevil/fungal attacks
Smoke treatment of seeds	To prevent weevil/fungal attacks
Smearing seeds with mud obtained from anthill soils	To prevent weevil/fungal attacks
Storing in big calabashes	To prevent weevil/pest attacks
Inserting a "bone from unused meat" in stored seeds	To scare away weevils/pests
Brick-dusting seeds	To prevent weevil/fungal attacks
Herbal treatment of seeds (e.g., mixing with leaves from tobacco, red pepper, "Karwenda and Kanuka" in Lunyankole)	To prevent weevil/pest/fungal attacks
Hanging seeds/crops on house ceilings, usually near fire places	To prevent weevil/pest attacks
Partial harvesting of root crops (e.g., cassava, potatoes, yams etc.), i.e., leaving some in gardens	To avoid pest attack and rotting in storage areas
Storing in big baskets "Kyagi" (Luganda), sacs, and open jerricans	To prevent direct pest attacks
Treating seeds with a mixture of ash from cow dung and dry juicy banana leaves	To prevent weevil/pest/fungal attacks

Kangalawe et al. (2011) in the Great Ruaha River catchment area (GRRCA) Tanzania documented similar use of IK in seasonal climate forecasting: Here, he reports of the use of “Mipalamba” trees among the Wasangu. Usually, these trees produce flowers during the dry season, and if they do not produce sufficient fruits, it indicates that the following season will have little rains, while the reverse is true when it produces many fruits. The early sprouting of “Mihango” trees also indicates an early onset of rains. The Wanji (another major ethnic group in the Usangu plains) use birds known as “Njigu,” also known as “Sangual nyanzala” (Nyakyusa). When these birds fly very high in the sky and start singing, they are locally used to indicate that the following seasons will have good rains. Similarly, when “Dudumizi” and “Kolekyaka” (birds) start singing, they are locally interpreted to mean the rains are near. Further still, to other community members in their areas the sprouting of Acacia trees (locally known as “Mipogoro”) in the dry season indicates a good rainy season thereafter, while to others flowering of Christmas trees (*Delonix sp*) indicates that rains are approaching. Also, the use of IK in rainfall forecasting has been documented in Burkina Faso (e.g., Roncoli et al. 2002).

Similarly, Roncoli et al. (2010, 2011) found that the people of Rakai, southern Uganda, most of them long settled in their territory, have a collective memory of weather patterns that extends into the past. They share a strong sense of the climatology or characteristics of the seasons. Local people give different names to the two rainy seasons and are familiar with a number of attributes. They know the typical timing and duration of the seasons. The first rainy season (“toggo” in Luganda) is expected to run from March through May; the second season (“ddumbi” in Luganda) runs from September through December. Though they do not describe amounts in millimeters of precipitation, farmers distinguish the quantity of rain that has fallen during each season by scraping soil away with their hands, or digging with hoes to examine soil moisture content after rains.

However, comparing the data of present study with those of previous scholars, the main problem still remaining is how to standardize their meanings to cater across all cultural boundaries to mean the same thing. In most cases, all the local IK indicators, e.g., singing of a bird in one area does not necessarily mean the same thing in another. Also, the name of one bird or an insect, important as local climatic indicator, may vary from one ethnic language to another and, hence, its associated climatic indicator. In the same way, Roncoli et al. (2010, 2011) contend that the question of accuracy often arises in discussions of IK, particularly in cases of relatively arbitrary or symbolic signs such as those presented above. Similarly, work elsewhere, for example, has linked shifts in the flowering patterns of trees to El Nio events (Curran et al. 1999) and also it has been shown that migratory birds often use the movements of fronts to provide them with tailwinds (Liechti 2006). Obviously, IKS finds it difficult explaining how such phenomena can be linked to local conditions and only confined to a specific indigenous group. Roncoli et al. (2010) also found significant variation in the language that farmers use to discuss their weather observations especially in regard to appearance of clouds in the sky and other signs. In the case of clouds associated with arrival of rains, some local people simply refer to them as “black clouds,” while others employ more figurative language, such as “thick huge clouds,”

clouds looking mature holding water, clouds that are still heavy holding rains, and other local farmers use the term “nimbus,” referring to them as “rain-bearing clouds.”

Relatedly, the present study found a number of IKS used in both selecting planting seeds and storage/preservation. Their relevance notwithstanding, IKS used for selecting suitable planting seeds as well as those used for storing/preservation of seeds/crops harvested are diverse and also suffer from issues of standardization. Most of them, however, seem to be relevant and confined to this area. Therefore, unlike scientific knowledge, IK is not transferable across time, space, and social setting (DeWalt 1994), and, as it is very rich in contextual detail, it is immobile, having little utility outside particular places (Kloppenburg 1991, p. 531). And this can be seen as the main weakness of the IK in the context of main findings as documented by the present study.

The issue of adaptation and coping strategies to a changing climate is also a pressing one to most rural communities, especially those living in developing countries. As such, most local communities do employ IKS to enhance their adaptation and coping strategies. However, some of these strategies can be counterproductive. Some are simply reactive and carried out for survival purposes only. They deplete resource base of the community and are, therefore, not sustainable in long term in enhancing livelihoods security. For example, coping strategies such as opening up virgin lands for crop production each planting season and cultivating in wetlands to get adequate soil moisture for crops are just crisis-driven actions aimed at survival. Such practices are unsustainable, and they deplete resource base of the very community. Similarly, purportedly “punishing rain makers” in case of delayed rainfall in a given season can be equated to, in my opinion, “extra judiciary killing” and a “mob justice” motivated merely by superstitious beliefs. Such practices should never be allowed to recur in a modern society.

The “rich” and the “poor” in a community also tend to vary in their approaches of embracing a given form of a livelihood under a changing climate, primarily depending on access to and control over resources. These approaches may unfortunately involve adaptation or just coping strategies or both. It should be noted, however, that most often times, “adaptation” and “coping” in the study of climate variability and change have been used interchangeably, yet the two mean different things. And because of frequent confusion associated with use of the two terms Dazé et al. (2009) outline the following to illustrate fundamental characteristics between the two: Coping is generally short term and immediate, oriented towards survival, not continuous, motivated by crisis and is reactive, often degrades resource base, and is prompted by a lack of alternatives. On the other hand, adaptation is oriented towards longer term livelihoods security, a continuous process where results are sustained, involves planning, combines old and new strategies and knowledge, and is focused on finding alternatives. By and large, findings of this study revealed that local communities actually use both “adaptation” and “coping” strategies in reducing their vulnerability to climate change. However, community members endowed with reasonable resource bases tended to adopt adaptation measures much more than those without access to and control over resources within the same community. Such individual, therefore, resort to short-term, crisis management approach, hence depleting even further, the little resource base they may have. Therefore, it is extremely important to have interventions that will cater for the less privileged communities, especially emphasizing need for adaptations to changing climate in order to lessen their vulnerability in a long-term basis.

23.4 Conclusions

This study has revealed in depth, a wealth of local system and IKS that exist in subsistence agriculture to enhance climate risk management and mitigation of community vulnerability in a changing climate. The study has also revealed that climate variability and change has had severe impacts on local communities in Lake Victoria basin, but they seem to use rich stock of IKS to promote livelihoods security and mitigate vulnerability to climate variability and change. Generally, people are aware of trends in climate variability and change in Lake Victoria basin. The study has identified climate variability and change as one of the greatest risks facing agricultural activities in the area, a threat to local communities' livelihoods. However, as much as communities seem to have high awareness levels on trends of climate variability and change, their readiness to climate change adaptations remains wanting. Unfortunately, lack of funding and inadequate capacity are frequently cited as reasons for this and seem to be hampering better adaptation and mitigation measures. Nevertheless, communities in the area have also acted in their capacity to improve resilience and mitigate the negative impacts of climate variability and change mainly by use of IK and IKS in almost all aspects of their lives. Notwithstanding its inherent weakness to have meanings that cater across all cultural boundaries, IKS still remains a source of wisdom readily available to most rural subsistence farmers who continue to achieve tremendous results from its use in enhancing livelihoods security. It may, therefore, be important to incorporate IKS into scientific knowledge systems in an attempt to promote climate change adaptation and mitigation measures among vulnerable communities dependent on climate-sensitive resources.

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Part V
Water Accessibility, Institutional Setup and Policy

Chapter 24

Processes of Institutional Change and Factors Influencing Collective Action in Local Water Resources Governance in the Blue Nile Basin of Ethiopia

Tilaye Teklewold Deneke

Abstract In this chapter, processes of institutional change and factors influencing collective action for local common pool water resources governance in regions of the Blue Nile basin of Ethiopia were studied so as to understand and positively influence sustainable resources management. The study used qualitative case study methods. The results indicate that processes of institutional change are affected by characteristics of the actors involved. Actors with better bargaining power control institutional change in their favor. In addition to this, the opportunistic behavior of some actors leads to loss of trust among farmers which, in turn, leads to disintegrating governance structures. With regard to collective action, field evidences indicated that availability of exit options, inequality in farmland holdings, uncertainty, bargaining power asymmetry, and government-aid programs undermine the cooperative behavior of farmers. On the other hand, rich social capital, good leadership, and a strong link between formal and informal governance structures foster cooperation among farmers for local common pool resources governance.

Keywords Local common pool water resources · Institutional change · Collective action · Amhara region · Blue Nile basin

24.1 Introduction

In the Blue Nile basin of Ethiopia, where smallholder mixed farming systems dominate, there are numerous traditional and modern small-scale irrigation schemes, communal water harvesting ponds for livestock water, as well as communal domestic water points throughout the region which are being managed by farmers' groups. Modern schemes are river diversion or small dams with fully or partly cemented

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canals constructed by government or nongovernmental organizations (NGOs) with farmers' labor contribution. The traditional schemes are those constructed by the farmers themselves using mostly stream diversions made of uncemented headworks that need frequent repairs to irrigate farm areas that do not exceed 100 ha collectively. Farmers or local government bodies establish institutions and governance structures such as water users associations (WUAs) for the management of these resources. These institutions change from time to time based on local social dynamics. It is crucial to understand the processes of these changes so as to impact the sustainable management of local common pool resources as well as to shed light on what factors play important roles in such processes (Ostrom 1992; Agrawal 2003). Closely related to this, collective action by water-user farmers is very crucial for sustained use of these available communal water resources. Collective action, particularly farmers' cooperation for various activities concerning the operation and management of these resources, plays a make or break role in common pool resources management (Ostrom 1992).

This chapter seeks to address such questions as: How do processes of institutional change in local water resources governance take place? What factors hinder and foster farmers' collective action? This is done by analyzing processes of institutional change and problems of collective action in irrigation and other communal water resources governance in the Blue Nile basin of Ethiopia. The next section elaborates the theoretical framework for the analysis of collective action and processes of institutional change in local common pool resources governance. The third section deals with the research methods utilized and briefly describes the case study areas. The fourth section presents the results and discussion. Finally, conclusions are drawn from foregoing discussions.

24.2 Theoretical Framework

In this section, theories of institutional change and collective action are discussed briefly so as to serve as a theoretical framework for subsequent discussion. Institutional change implies change of existing institutions or establishment of new institutions where there was none previously. Institutional change can be spontaneous, unintentional, and from below or it might be designed, intentional, and from above (Vatn 2005). In the literature, there are different conceptions of the causes, mechanisms, and effects of institutional change. Some theories indicate efficient institutions as results of change while others predict not necessarily efficient institutions but only outcomes that reflect power structures among actors. Based on the actors and effects of institutional change, Allio et al. (1996) classified theories of institutional change into three categories: efficiency theories of institutional change (Demsetz 1967; Williamson 1985; North 1995), public choice theories of institutional change (Downs 1957; Sened 1997), and distributional bargaining theories of institutional change (Libecap 1989; Knight 1992).

In the economic theories of institutional change, the basic driver of this change is change in the exogenous variables which lower transaction costs, such as production, monitoring, and exclusion technologies. If existing institutions are not efficient with respect to such changes, then new ones which are more efficient will emerge gradually. The process of institutional change envisaged is one in which competitive pressure eliminates inefficient forms of organizations.

The distributional bargaining theories are generally based on the assumption that each actor in an action situation has different interests and power which leads them to be engaged in conflict of interests. The conflict will be resolved in such a way that will ensure the interest of those actors who are powerful because of possession of resources such as capital, information, and political power. The resulting institutional arrangement may not be socially optimal, as the aim of such change is individual interests rather than collective efficiency. According to Knight (1992), institutions are the product of social actors engaged in the process of seeking distributional advantage in the conflict over substantive benefits. In other words, bargaining among actors involved in a social interaction establishes rules that have distributional consequences. There are diverse sources of bargaining power such as resource ownership, attitude towards risk, sanctioning power, and information asymmetry.

The distributional bargaining theory of institutional change by Jack Knight is more comprehensive than the other theories as it gives a probable explanation not only for informal institutions but also for formal ones. It also gives sufficient emphasis to the role of power in institutional change realizing that social interaction does not take place in a level playing field where actors engage in cooperative relations only.

Early theoretical works on collective action (Olson 1965; Hardin 1982) were pessimistic in their view. They implied that with regard to governance of common pool resources, voluntary community-based collective action is not possible without external coercive intervention or privatization. However, later on, numerous case studies confirmed that groups can overcome the “tragedy of commons” and problems of organization and contribute to sustainable use of common pool resources through collective action by establishing provision and appropriation rules, monitoring the condition of the commons, and sanctioning non-compliance to rules (Ostrom 1992; Ostrom 1990; Agrawal 2003; Wade 1994; Baland and Plateau 1996). These authors suggest that factors like homogeneity of groups managing resources, inequality, degree of dependence of the group on the resource, availability of exit options, autonomy, trust, reciprocity, power asymmetry, and leadership determine the success and failure of collective action for common pool resources management.

24.3 Research Methods and Case Study Areas

The study makes use of qualitative case study analysis. The cases were irrigation systems, domestic water points and their user groups, and communal rainwater harvesting ponds and the user groups. It involves multiple cases, where both within-case and between-cases comparisons are carried out. Two groups of villages (*Kebele*s, the lowest administrative unit, constitutionally) in the *Fogera* and *Gubalafto* districts (*Woreda*s, an Amharic word meaning district) located in the *Amhara* region,

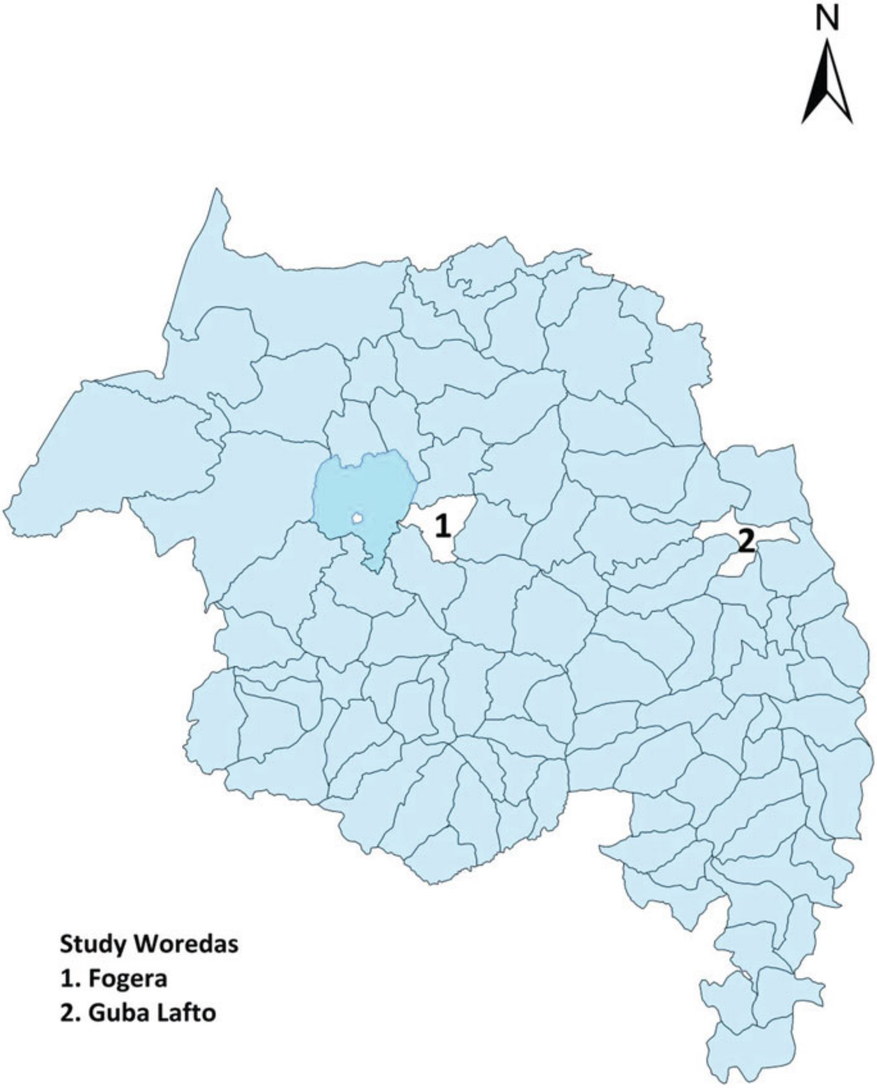

Fig. 24.1 Map of Amhara region and case study districts (*woreda*s)

which is almost entirely in the Blue Nile basin, were studied. The two *Kebele*s were *Quhar-Michael* (QM) *Kebele* from *Fogera Woreda* and *Lenche-dima*(LD) *Kebele* from *Gubalafto Woreda* (Fig. 24.1).

These two sites were purposely selected to represent water-sufficient and water-scarce crop–livestock mixed-farming systems, respectively. Contrasting cases were selected with the justification that the problems, institutions, and governance structures may vary depending on relative water availability. The local water resources under scrutiny in the two case study *Kebele*s were irrigation schemes,

Table 24.1 Case study irrigation schemes. (Source: composed from WUA and *Woreda* offices of agriculture)

	Name of scheme	Irrigation area (ha)	Number of households using the schemes	*Woreda* (district)
1	Alewuha modern scheme	360	1,017	Gubalafto
2	Alewuha traditional scheme	80	665	Gubalafto
3	Guanta-lomidur modern scheme	102	1,170	Fogera
4	Mesno traditional scheme	40	138	Fogera
5	Berengua traditional	40	121	Fogera

communal domestic water points, and communal water harvesting ponds. Five irrigation schemes and multiple communal rainwater harvesting ponds were studied. Communal ponds were selected from LD *Kebele* only as there are no such ponds in the relatively water-sufficient QM *Kebele.*

At the LD area, there are both traditional (about 80 ha) and modern (about 360 ha) irrigation schemes nearby and both are known as Alewuha schemes as they use the same Alewuha River for water source. A diversion structure constructed on Alewuha River diverts water for irrigation in two partly cemented canals to irrigate plots located at both sides of the river.

At QM *Kebele,* there is a traditional scheme known as *Mesno* (used mainly for supplemental irrigation of rain-fed crops). A modern irrigation scheme known as Guanta-lomidur and its tail-end traditional scheme are found in *Berengua* village located in a separate adjacent *Kebele* called Shina. The *Mesno* traditional schemes covers about 40 ha, while the *Guanta-lomidur* and the *Berengua* schemes cover about 102 and 40 ha, respectively. Table 24.1 depicts irrigation schemes, land area, and number of households.

In the water-scarce and drought-prone areas of the eastern Amhara region, communal water harvesting ponds for domestic and livestock water are widely utilized. In the LD area, every village has one or more communal water harvesting ponds with average water-holding capacity of 500–1200 m^3. These ponds are used for livestock water supply during the dry seasons. These ponds become full after a few rainy days and remain full until September. Beginning in October, they start depleting. They can be used until the end of December and dry up in January. They fill up again if it rains in February and they can be used for livestock water until the end of May and again they dry up in June (Table 24.1).

Village water points are the source of domestic and livestock water supply in many villages. These are mostly shallow wells with hand pumps constructed by the *Woreda* office of water resources with financial support from the government or NGOs. At QM, only two of the villages have communal water points. Farmers in the other villages use hand-dug wells, springs, and streams. At LD, there are five community water points served from a deep well using a diesel motor pump. Almost all households have access to water for domestic and livestock use from these water points.

The study used qualitative data collected from the above case study sites employing focus group discussions, key informant interviews, and participant observation. As part of a larger project, 32 group discussions with farmers and 61 key informant interviews with local officials, experts, and farmers were held. A formal survey of 130 households was also conducted to collect general household-specific data. The data were collected between April 2009 and March 2010. The data collected were analyzed using qualitative data analysis techniques which include transcription, coding, abstraction, and drawing generalizations and contrasting generalizations with theories.

24.4 Results and Discussion

24.4.1 Local Water Resources Governance Structures

Modern small-scale schemes are administered by WUAs established by the initiative of *Woreda* Office of Cooperatives Promotion. In the *Amhara* region, WUAs are normally known as irrigation cooperatives (ICs) and are established with the aim of not only operation and maintenance of schemes but also supply of agricultural inputs and marketing of outputs. They are established based on the regional cooperative establishment proclamation and irrigation cooperatives establishment directive. There is a model bylaw prepared by the Amhara Cooperatives Promotion Agency (ACPA), with some blank spaces on certain rules and procedure left to be filled by individual associations based on farmers' consensus which give minor room for possible adjustment. According to the WUA rules prepared by ACPA, in the modern schemes, every farmer with a landholding or with a legally recognized land lease contract in the scheme lasting for at least 5 years is entitled to irrigate his land and become a member of the WUA. This is with the condition that he is willing to be a member and pay the membership and registration fee of 20 and 5 Ethiopian Birr, ETB, respectively (US$ 1.08 = 20 ETB, 20 April 2013).

The Alewuha WUA was established in 2002. It is administered by a committee composed of 11 members. Every member of the committee is a section leader (called Qetena-meri in Amharic, is a water distributer for a command area served by a secondary canal). Under a section head, there are two to three groups of irrigators led by a "water judge" who is responsible for water allocation and conflict resolution among individual farmers. On average, there are 30–35 irrigators under a "water judge." The Guanta-lomidur WUA was established in 2006. It is administered by a committee composed of nine members. Like that of the Alewuha, it has nested organizational structure, with section heads and "water judges."

In the modern schemes, all irrigators ought to contribute labor for canal clearing and other maintenance work in the scheme. Failure to contribute labor for scheme maintenance is punishable by fees or denial of the culprit's turn in rotational water allocation. Priority in water allocation is given to farmers who have contributed labor for canal clearing and other maintenance activities. The rules for free riding also levy monetary fines of 5 ETB. Many indicated that this fine is too small to be a deterrent to free riding. These rules are partly enforced in the Alewuha modern scheme, while at Guanta-lomidur, they are not enforced at all as the WUA is virtually nonexistent.

The traditional irrigation schemes are managed by traditional water-user groups headed by one or more water distributers often called "water fathers." Generally, there are no written rules in the traditional schemes. There are only a few unwritten rules determining the amount of fine one has to pay in case of violating rules regulating water allocation, labor contribution, or control of grazing animals. The rules in the traditional schemes are freely negotiated ones, with the exception of the *Mesno* traditional scheme where a powerful farmer has been able to influence water allocation rule in his favor. In the traditional schemes, membership is open to all irrigators. Everyone who has a holding in the traditional scheme is a member by default.

In the traditional schemes, in addition to canal clearing, labor contribution for maintenance of water diversion structures after every flood or rainy season is mandatory. In the Alewuha traditional scheme, there is no monetary fine as such for not contributing to collective action; however, the culprit will be denied of his turn for water for one time. These rules are effectively enforced in the Alewuha traditional scheme only. In *Berengua* traditional schemes, the same rules exist. However, rules are rarely enforced so that free riding is found to be prevalent.

24.4.2 Process of Institutional Change

The following cases illustrate changes in operational rules at local levels. These changes indicate improving operation of the WUA at *Alewuha* and deteriorating situations at *Guanta-lomidur* related to the ability of groups to control opportunistic behaviors, availability of water resources, as well as the availability of exit options. At *Alewuha*, where water is relatively scarce and exit options are nonexistent, farmers strongly depend on irrigated agriculture as compared to the *Guanta-lomidur* scheme and hence have a stronger WUA. On the other hand, at *Guanta-lomidur*, where water is relatively abundant and farmers have exit options such as the use of motor pumps, the WUA was found to be functioning weakly. Prevalence of opportunistic behaviors among farmers, traders, development agents (DAs), and local administration led farmers to lose faith in the WUA. It is also observed that powerful farmers at QM block institutional changes that farmers deemed necessary as evidenced by the case of motor-pump regulation in the *Guanta-lomidur* scheme. Moreover, local institutional change evidence indicated that farmers preferred negotiated property rights rather than the formal government sanctioned one, as they think the former is more secure.

24.4.2.1 Negotiating Property Rights

In May 2008 and again in May 2009, violent conflicts with threats using guns happened between the Alewuha traditional scheme water-user farmers and those of the traditional scheme on the Qobo *Woreda* side of the river. The reason for the conflict was water scarcity. The traditional schemes on both sides of the river use water that flows over the diversion weir for the modern scheme. There are five traditional diversion structures, two used by farmers on the Gubalafto *Woreda* side and the other three used by farmers on the Qobo *Woreda* side of the river. The diversion canals of the Gubalafto *Woreda*-side traditional scheme are a little bit upstream and those of the Qobo *Woreda* are downstream. In times of water scarcity, April, May, and June, the downstream farmers from the Qobo *Woreda* side breach the diversion headworks made by the upstream Gubalafto *Woreda*-side traditional-scheme water users so as to allow more water flow downstream which they can divert.

Due to the increasing frequency of these violent conflicts, a general meeting of all water users on both sides of the river was called by the WUA of the modern scheme (that was because the majority of water users in the traditional schemes have plots in the modern scheme also). The meeting was attended by water-user farmers, WUA officials, *Kebele* leaders, local police, and DAs from both adjacent *Kebele*s found in the two adjacent *Woreda*s. The agenda for discussion was the issue of water rights, water allocation among the traditional water users, and conflict management in the future. During this meeting, the researcher witnessed that the *Kebele* leaders and WUA (there are overlaps between the two) and the local DAs from both *Kebele*s confirmed that the primary water-use right is that of the farmers in modern schemes and farmers from the traditional schemes have only secondary water rights. They try to justify it indicating that the government invested much money in the modern scheme; hence, it should have priority over the traditional schemes.

With regard to water allocation, after heated discussions which took half a day, consensus was reached to reduce some water from the modern scheme and let farmers in the tail-end traditional scheme get additional water as their crops would fail otherwise in that season. The farmers also reached at an agreement to establish a joint committee composed of representatives from the modern and traditional schemes found on both sides of the *Alewuha* River. The committee was supposed to meet every Friday at a time of water shortage and once in a month when there is no such a shortage. It was given the mandate to determine future water allocations in a manner that would be mutually beneficial. This would let increased water to be available for the tail-end traditional schemes located on both sides of the river. Agreement was also reached that breaching the main traditional diversion canals will be punishable by 300 ETB and nobody should carry guns in the irrigated areas. The joint committee will monitor the enforcement of resolutions and deal with conflicts among irrigator farmers.

This incidence indicates that although the government supports water rights of farmers in the modern scheme, farmers preferred negotiated rights to formal property rights systems so as to secure their claims, which they think the formal system cannot ensure. Moreover, the existence of rich social capital among farmers who lived together for a long time as well as an overlap of interest (the fact that farmers in the modern scheme have also plots in the traditional one) facilitate negotiations and peaceful coexistence among them.

24.4.2.2 Power and Regulating Pump Irrigation

Local governments in the *Amhara* region promote increased use of water harvesting (rainwater, stream diversions, and groundwater) for irrigation by individual farmers. The *Woreda* Office of Agriculture provides motor pumps to individual farmers on credit. The local elites such as *Kebele* administrators and better-off farmers take advantage of this program and irrigate their plots which are close to but outside the command area of the schemes both at *Alewuha* and at *Guanta-lomidur*. At *Alewuha*, 11 motor pumps are being operated while at *Guanta-lomidur* scheme there are about 38 motor pumps. The introduction of these motor pumps has created problems of water scarcity in both case study modern schemes.

At the *Guanta-lomidur* scheme, powerful farmers such as *Kebele* leaders block the main diversion canal so that water will flow through the natural stream which makes it suitable for them to pump much water and irrigate fields located far from the command area of the scheme. This creates serious water shortage at the tail-end traditional scheme known as *Berengua*. No regulation has been made so far at *Guanta-lomidur* regarding the use of motor pumps, despite the fact that sometimes it leads to total dry up of water for the tail-end farmers. Group discussant farmers at the tail-end *Berengua* scheme indicated that past efforts to influence the regulation of motor-pump use by head-end farmers were blocked by *Kebele* leaders (who are the most powerful actors at the local level) at QM who are pump irrigators themselves. This is an account of what Knight (1992) refers to as the effect of power asymmetry on institutional change. Pump irrigator farmers with positional power in the local administration use their power to impose their preferences over those using the traditional gravity irrigation scheme at the tail end. On top of this, the fact that motor-pump users are viewed by *Kebele* DAs and *Woreda* agriculture experts as “progressive farmers” who take up and apply government extension advice has made it very difficult for the tail-end farmers to exert sufficient pressure for regulation of the use of these pumps. The DAs give priority in water rights to motor-pump users so that the farmers will be able to produce and pay back the credits in time.

At *Alewuha*, the scarcity of water prompted the regulation of the use of motor pumps to pump water from the primary canal of the scheme. No *Kebele* official has got motor pumps as they have a modern gravity-irrigated scheme. They did not want to take the pumps on credit because either they do not have plots that can be irrigated using motor pumps or they do not want to get indebted in case of failure of the machine which happened to one farmer in the locality. They also indicated that fuel for the motor pumps is expensive. Only those farmers who do not have plots in the modern scheme and who were willing to take the risk got motor pumps on credit from the *Woreda* Office of Agriculture. Due to increasing water scarcity, WUA officials decided to allow only two pumps per day and those motor-pump-user farmers were obligated to contribute labor for canal clearing as well as pay an annual water fee. WUA officials indicated that they could not deny the pump irrigators the right to take water because the program is supported by the government and because many of the pump irrigators are young landless farmers trying to get a living by sharecropping previously rain-fed farms.

24.4.2.3 Opportunistic Behaviors Leading to Disintegrating WUA

At the *Guanta-lomidur scheme,* a trader based in Bahir-Dar town supplied farmers in the WUA with poor-quality onion seeds that led to crop failure. Another trader from Addis Ababa disappeared without paying the cost of onions he bought from the WUA. These problems left many farmers in the *Guanta-lomidur* scheme with loss of a lot of money as well as trust in the WUA and its officials. Prolonged lawsuits are going on the regional and *Woreda* courts, so far in vain, sparking suspicions among farmers that the WUA officials have negotiated with the traders and have forsaken them. As a result of such opportunistic behaviors and lack of trust, the WUA has virtually been disintegrating in that it no longer supplies seeds, sells outputs, or collects water fees from water-user farmers. Neither does it allocate water among irrigators.

An irrigator farmer who is also a deputy *Kebele* leader indicated that:

> Now that the WUA is disintegrating water allocation is not regulated, nobody consults the water judges and the powerful will take water by force or threat. The water judges or team leaders cannot do anything. (6 September 2009)

Group discussant farmers have indicated that conflict incidences have been on the increase at times of relative water scarcity due to the absence of organization, much pumping activities carried out by head-end farmers, and prolonged dry seasons. This has been exacerbated by the opportunistic behaviors of *Kebele* leaders, who are the most powerful actors, as they need to irrigate their fields using motor pumps.

24.4.2.4 Introduction of Locks at the Division Boxes

As indicated earlier, farmers at *Alewuha*, as well as other schemes do not coordinate the type of crop they cultivate and the time of planting. They plant the same type of crops at the same time, mostly onions or tomatoes, resulting in similar water needs. On top of this, scarcity of water due to prolonged dry seasons or upstream water abstraction leads to long water rotation schedules (3 weeks or more). These situations lead to fierce competition among farmers to get water at the right time and it increases the incidence of water theft. In order to deal with problems of water theft, the *Alewuha* WUA introduced locks at division boxes and also increased the fine for water theft from 20 to 50 ETB with the consent of member farmers. WUA officials indicated that the introduction of locks has decreased the problem of water theft but it could not stop it all together as most of the canals are not cemented and can be breached at any place which makes monitoring cost very high as most thefts occur at night.

24.4.2.5 New Governance Structure to Control Free Grazing

With the disintegration of the WUA in the *Guanta-lomidur* scheme, it became increasingly difficult to control the free grazing of animals in and around the irrigated area. This caused increased crop damage by livestock and increased incidence of conflict among farmers. Some farmers located in marginal areas of the scheme indicated that they left their fields fallow because they were tired of preventing free grazing of animals. Hence, controlling free grazing became an issue of discussion during the general *Kebele* meetings often held on Sundays at the local church, after mass, where the majority of the household heads attend. Controlling free grazing is a government policy being promoted vigorously by the DAs and the *Kebele* leadership by delivering extension advice of decreasing stock and adoption of stall feeding. A project called Improving Productivity and Market Success (IPMS) being conducted by the International Livestock Research Institute (ILRI) also promoted temporary closure of grazing lands during the rainy seasons and control of free grazing.

Following this, a group of farmers known as *Edir-committee* was assigned to protect communal grazing lands from encroachment by adjacent farmers, control free grazing, and solve local conflicts. Letting animals into other farmer's fields was decided to be punishable by 10 ETB per livestock let in to graze on crop fields. The *Edir-committee* was also given additional responsibility to punish with fines those who do not observe Ethiopian Orthodox Christian holidays. However, free grazing persisted; no one has ever been punished for letting animals into farmlands. This can be related to the fact that monitoring costs are high. Moreover, the *Edir-committee* does not have real authority and acceptance by the farmers as it is outsider initiated. Yet, rarely do farmers violate the observance of holidays because they have a deep-rooted belief that if someone does not observe the Sabbath or other holidays, hail storms will damage the crops. If one does not observe the holidays he/she will be fined with money, and if one is a repeated offender he/she will be socially sanctioned by isolation from the community. This provides strong evidence that shared norms are very stable and self-enforcing institutions while outsider-initiated institutions and governance structures are ineffective in many instances.

24.4.3 Explaining Collective Action for Local Water Resources Governance

24.4.3.1 Factors Hindering Collective Action

Collective action by water-user farmers is very crucial for sustained use of the available communal water resources. Here, collective action is mainly viewed from the perspective of farmers' cooperation for various activities concerning the operation and management of irrigation schemes, communal ponds, and domestic water points. Collective action is mainly observed through farmers' material and labor contributions for activities such as canal clearing, diversion structure repair, and protection and maintenance of communal ponds and domestic water points.

The majority of the canals in the modern schemes and all of the canals in the traditional schemes are not lined with cement. Hence, irrigation canals often get blocked with grass growing in and around them. There are also problems of siltation which necessitate canal clearing every now and then. In all the case study schemes, farmers needed to clear primary canals collectively. Clearing secondary and tertiary canals is left to the collective work of water-user farmers in a section and water-user groups, respectively. Often canal clearing is called by WUA officials in the case of the modern schemes and "water fathers" in the case of the traditional schemes.

These collective action activities are very crucial, especially for the *Alewuha* modern scheme and traditional schemes. In the case of the *Alewuha* modern scheme, large amount of silt gets accumulated in the primary and secondary canals during the rainy seasons due to lack of cutoff drains. In the case of the *Alewuha* traditional scheme, traditional diversions weirs built across streams are weak structures made of stone and mud susceptible to damage by floods and animals. Hence, they need repair every year at least once at the start of the rainy season and several times if there are rains in the upstream highlands that cause floods downstream.

Hence, in both cases, every year the irrigation season starts with heavy works of canal clearing and head-end maintenance. Beginning in October, after the rainy season, WUA officials call for the first major canal clearing and maintenance work. Farmers bring with them shovels, digs, and other materials. The section heads and "water judges" assign groups tasks to clean and maintain parts of the canals. At the end, WUA committee members keep record of attendance. Generally, scheme infrastructures are better maintained in both *Alewuha* traditional and modern schemes as compared to the schemes in QM *Kebele*.

Not all farmers participate in these canal clearing and maintenance activities according to the WUA rules or that of the traditional water-user groups. Often, delays are caused in commencement of irrigation in November and December because of labor shortage, as many farmers want to free ride and have a high opportunity cost of participating in these activities because they are usually engaged in harvesting and threshing of rain-fed crops at this time of the year.

Collective action for canal clearing is less regarded by farmers in the *Guanta-lomidur* scheme of QM as they are head-end farmers enjoying sufficient water even without proper canal clearings undertaken. Canals are generally in such poor conditions that some of them are damaged and are out of use. In fact, according to key informants, the destruction was deliberate to correct design mistakes which left some areas out of the command area of the scheme and made it unsuitable for others. According to WUA officials, only few individuals come out for collective canal clearing in the *Guanta-lomidur* scheme; despite the existence of rules that prohibit free riding, no one is sanctioned. On the other hand, farmers in the tail-end *Berengua* area need the canals in the head-end areas as well as those in their scheme to be cleared to get sufficient water for irrigation. The canals in their schemes are also very poorly maintained.

In the case of the *Mesno* traditional scheme, the small size of the scheme and number of users make collective action for canal clearing easier. It only takes a few days' work for them to clean the canals and there are no headworks, just diversion canals which only need clearing silt and weeds. Moreover, the local tree nursery which uses the same water source and is run by the *Woreda* Office of Agriculture and the *Kebele* administration order water-user farmers to clean the canals in time. Farmers turn out for the works almost entirely and would get sanctioned by the *Kebele* leader, who is also a water user, if they preferred to free ride.

Collective action in the communal water pond, domestic water points governance, and maintenance and protection of ponds and water points require cooperation among user farmers. Maintenance activities are not routine and are undertaken only when the infrastructures deteriorate. Yet, protection of communal ponds from unauthorized persons is a routine activity during the dry seasons when there is water in the ponds; protection of water points does not demand labor as they are often fenced and are opened twice a day in the mornings and late in the afternoon.

A number of factors were found to be important in explaining the collective action behavior of farmers with regard to local water resources governance. Some of these factors such as inequality in land holding, exit options, bargaining power, corruption, and uncertainty were found to deter collective action and encourage free riding. On the other hand, leadership and linkage between the formal and traditional governance structures and social capital in the form of shared norms and reciprocity were found to foster cooperation and contain free-riding behavior.

Inequality in Land Holding and Collective Action

In the *Alewuha* area, land redistribution was carried out in 1996, where all the arable land was divided into two categories: *yebereha meret* meaning wilderness to refer to rain-fed cropland which was shrub land and *Mesno* meaning irrigated (referring to the *Alewuha* traditional scheme). The majority of farm households were allocated land from both categories; rain-fed plots were parceled in larger sizes than the irrigated ones. The irrigated land was fragmented, to a great extent, in order to allocate a plot for everyone. Those plots located in the rain-fed area were larger and highly unequal because of measures taken to account for fertility variations and family size. Later on, the *Alewuha* modern scheme was constructed and a portion of plots which were previously rain-fed was included in the irrigated area. However, no further reallocation of land was carried out after the introduction of the irrigation infrastructure. Therefore, the variation in average plot size in the modern scheme is higher than the corresponding figures for the *Alewuha* traditional scheme.

At the *Guanta-lomidur* scheme also some farmers leased out part of their lands for sharecroppers because they lack labor to cultivate all their plots as irrigated farming, particularly for onion production that is labor intensive. Others leased in because they do not have sufficient land to cultivate or have required the surplus family labor or capital (oxen, seed, fertilizer, motor pumps).

Comparison of average plot sizes and variation thereof was carried out based on sample survey data. Accordingly, in the modern *Alewuha* scheme, the coefficient of variation in plot size was found to be 0.77, and the average plot size was 0.61 ha; whereas in the adjacent *Alewuha* traditional scheme, the coefficient of variation in plot size and average plot size were found to be 0.32 and 0.08 ha, respectively. The corresponding figures for the schemes at QM indicate that the coefficient of variation in the *Guanta-lomidur* modern scheme was 0.57 and the average plot size was (excluding pump-irrigated plots) 0.49 ha. These figures are higher than the traditional schemes both at *Mesno* and at *Berengua*. The average irrigated plot size at the *Mesno* traditional scheme was 0.35 ha with a coefficient of variation of 0.53. At the tail-end traditional scheme of *Berengua*, the average plot size was 0.25 ha, with a coefficient of variation of 0.46.

The variation in plot size was found to have negative implications for collective action. Inequality is an important factor negatively affecting maintenance of irrigation systems (Bardhan 2000; Dayton-Johnson 2000). This is evident from the *Alewuha* scheme where farmers with small plots are not willing to contribute labor as much as other farmers who hold larger plots. As a result, according to WUA officials and group discussion with water-user farmers, labor contribution by water-user farmers is very low and the majority of the farmers are free riders at the expense of those few who hold larger plots. The same effect has been observed in *Berengua* village as indicated by key informant farmers from the *Berengua* scheme:

> I have only 0.25 ha while some farmers have over 3 ha of land in the scheme; hence, I am giving unfair service to them. (A farmer from Berengua, 6 June 2009)

WUA officials at the *Alewuha* modern scheme indicated that it is a small group of individuals who always take the initiative for the early mobilization of farmers for the annual canal-clearing activities at the outset of the irrigation season. These are individuals who have larger plots in the scheme and depend much on irrigated farming as well as those who have sharecropped plots of lands other than their own. They are also involved in production of cash crops such as onions and tomatoes. These farmers urge the WUA officials for early mobilization of canal-clearing activities.

Availability of Exit Options: Communal is Cluttered

Availability of exit options impairs cooperative behavior among farmers in the governance of local communal water resources. In the case of irrigation schemes, the possibility of use of motor pumps to irrigate fields close to *Gumara* River and *Guanta* stream curtails the cooperative behavior of farmers threatening the very existence of the WUA and traditional water-user groups. In the *Guanta-lomidur* scheme, in addition to dissatisfaction with WUA the other reason for lack of cooperation among farmers for collective primary canal clearing was found to be the availability and low cost of exit (the use of motor pumps). It is less costly for some farmers to irrigate their fields using rented motor pumps and water from the nearby stream or irrigation canal than engage in the difficult task of mobilizing farmers for canal clearing and maintenance of irrigation infrastructure.

In the case of communal ponds of LD, farmers indicated that since the establishment of the deep well water points for domestic and livestock water, cooperation among farmers for maintenance of the communal ponds has decreased very much. They indicated that they used to maintain and protect the communal ponds largely because the ponds were the only source of domestic and livestock water. In some villages, communal ponds are abandoned altogether. In others, which are far from the nearest alternative sources of livestock water, the local *Kires* (mutual assistance associations to bury the dead and comfort survivors) are still actively engaged in coordination of farmers for maintenance and protection of communal ponds used for livestock.

The same is true in the case of domestic water points that the availability of exit options impaired collective action. For instance, in QM *Kebele*, many farmers have private hand-dug wells for domestic and livestock use which they find a better option than communal water points. In group-discussion sessions, farmers indicated that everyone prefers private hand-dug wells and private irrigation options than engaging in communal ones if there is an available exit option. Responding to a question why farmers prefer private hand-dug wells even in villages where there are communal domestic water points, a key informant farmer from QM indicated eloquently in Amharic "*Yegara Wengara!*" meaning "communal is cluttered!"

Bargaining Power and Cooperation

Field evidences suggest that actors in head-end areas are in a better bargaining position than those in the tail ends. The fact that the head-end farmers can get water even without proper canal-clearing efforts gives them better risk tolerance than those in the tail ends. Hence, farmers in the head-end *Alewuha* modern scheme are in a better bargaining position than those in the tail end of the same scheme. Likewise, farmers in the head-end *Guanta-lomidur* scheme have better bargaining power than those in the tail-end *Berengua* traditional scheme in terms of participation in collective action such as canal clearing.

WUA officials in the *Alewuha* modern scheme indicated that those participants in head-end areas are less enthusiastic to participate in collective canal clearing than those in the tail ends. The same is also true in the case of the *Guanta-lomidur* scheme. However, in the case of the *Alewuha* traditional scheme, water-user farmers as well as "water fathers" indicated that both the tail-end and head-end farmers are equally enthusiastic to cooperate in collective action for the maintenance of the traditional diversion weirs. This is because no one can irrigate his or her field unless the diversion headworks are properly maintained which creates little bargaining power asymmetry between head-end and tail-end farmers. Besides, farmers have long years of experience living and working together which led to a strong sense of solidarity among them.

Another similar negative effect of asymmetric power relations on collective action is also observed in the case of the tail-end *Berengua* scheme. Farm plot-owning farmers in the *Berengua* scheme have the exit option of leasing out their land and cultivating pump-irrigated larger plots located outside the scheme by the banks of the nearby *Gumara* River. They prefer to sharecrop their plots to landless young farmers. The sharecropping young farmers from *Berengua* village often engage in primary canal clearing in the head-end *Guanta-lomidur* scheme and protect the diversion canals from being breached by head-end farmers during peak irrigation time.

Uncertainty Hindering Cooperation

At Berengua scheme, farmers' uncertainty about the availability of sufficient water for irrigation was observed to have negative implications for their willingness to participate in collective action such as canal clearing. Group discussant farmers indicated that many farmers are uncertain about availability of sufficient water as the head-end farmers in *Guanta-lomidur* scheme make use of much water for irrigating fields far from the command area of the scheme using motor pumps. Moreover, the prevalence of corrupt practices for water allocation among farmers creates uncertainty among farmers regarding water availability. As a result, many of the farmers do not participate in collective action activities. Rather, many of those who have other plots of land by the banks of *Gumara* River prefer irrigating their fields using motor pumps than engaging in collective action in *Berengua* scheme. Many of these farmers sharecrop-out their lands to young landless farmers who have few alternatives other than engaging in the contentious irrigation water-user groups.

The same is true in the case of *Mesno* traditional scheme in that group discussant farmers indicated that many farmers abandon irrigation in the scheme and refrain from collective action for canal clearing and maintenance because of the uncertainty in the availability of sufficient water. The uncertainty is created by unfair water sharing as a certain powerful farmer described the excessive water use by the local tree nursery belonging to the WOA (*Woreda* Office of Agriculture).

Food-For-Work Program and Collective Action

Since 2005, the government launched a nationwide household-level food security program known as Productive Safety-net Program. It aims at transferring food or cash to food-insecure households (found in selected food insecure households which are drought prone and with history of food problem) where households participate in food or cash for work in local public work activities such as watershed management, afforestation, rural road construction, and soil and water conservation activities. It is intended to enable food-insecure households to gradually accumulate assets so that they will be able to withstand future drought-related food shocks on their own.

Gubalafto Woreda, where LD *Kebele* is found, is one of the food-insecure *Woreda*s in *Amhara* region. As in other food-insecure *Woreda*s, there is a Productive Safety-net Program being conducted by the regional and *Woreda* governments. In LD *Kebele*, a number of households were included in the program based on the criteria of lack of productive assets such as oxen, land, or other assets such as livestock. Farmers included in the program obtain mainly cash transfers for works in the maintenance of the local elementary school, rural road and terracing, and afforestation of degraded hillsides in their localities. Many farmers are not included in the program and indicated that there is much corruption and nepotism in the selection of beneficiaries. They indicated that there are many households which should not have been included in the program and many which should have been. The role of *Kebele* leaders in selecting beneficiary households is pivotal and gives them an important bargaining power in various action arenas.

This created grievances among farmers and made them abandon their age-old collective action for the maintenance of communal ponds with the hope that they will be included in the program to repair it. Group discussion sessions with farmers revealed that they are reluctant to maintain the ponds unless they are paid. *Kire-Asadaris* also indicated that they are not able to call *Kire* members for pond repairs while similar public works are done by government sponsorship in the form of the Safety-Net program. They indicated that no one is willing to contribute free labor anymore. A United States Agency for International Development (USAID)-sponsored project aimed at rehabilitating degraded hillsides by construction of terraces, tree planting, and closure from human and animal access had used a similar food-for-work approach to get the community to participate. According to key informant farmers and *Kebele* officials, it had a negative effect on farmers' willingness to participate in free labor contribution for the maintenance of communal ponds and other public works.

Outsider Sharecroppers and Collective Action

Sharecropping is a common practice in both case study sites. Old, poor, and women farmers who lack labor or oxen for plowing and are unable to buy inputs such as fertilizer, pesticides, and fuel for motor pumps usually engage in sharecropping arrangements. Young and landless farmers in the villages or traders and out-growers who come from the nearby towns are also sharecroppers.

Sharecropping farmers, particularly, traders and out-grower farmers who come from the nearby towns, often do not contribute labor for irrigation scheme maintenance. Either they are mostly absent or they deliberately avoid those events. They also evade such duties by engaging in corrupt relationships with WUA officials, *Kebele* leaders, or "water fathers" of traditional water-user groups. Such relations have been reported by key informants from *Guanta-lomidur* and *Berengua* schemes in QM *Kebele*.

24.4.3.2 Factors Facilitating Cooperation

The action arena in local common pool resources governance is not only a hotbed of contest and conflict, it is also one of consensus and cooperation. Field evidences suggest that certain community characteristics such as shared norms, reciprocity, and the overlap between formal and informal institutions and governance structures pave the way for cooperation among farmers in the management of local communal water resources.

Social Capital

Self-enforcing shared norms were found to be very crucial factors fostering cooperation among farmers. These shared norms include what are normally regarded as proper behavior in a community, individual farmers' expectation from fellow farmers, and what they think others expect from them. In answering to the question why they are contributing labor for canal clearing while others free ride, a group of farmers that the researcher met clearing canals at *Alewuha* modern scheme indicated that it is abominable to "ride on others' back." Some of them referred to free riding as tantamount to "plowing using humans as oxen." Asked about what kind of people free ride, they answered that it is only careless and shameless people who are free riders.

Reciprocal relations which develop through repeated interactions over a long and indefinite time span create credible commitments among farmers which facilitate cooperation. Many farmers in the *Alewuha* modern schemes have some plots in the traditional schemes or they rent in land in the traditional schemes, and vice versa. This gives a signal of credible commitment for cooperation that farmers in the traditional schemes participate in canal clearing in the modern scheme and those in the modern scheme do the same to help the repair of diversion structures for the traditional scheme. Mostly, they start the annual routine scheme repair with repairing damaged diversion headworks of the traditional schemes; then, they move on to clearing the canals in the modern scheme.

Reciprocal labor-sharing arrangements *Debo* (a festive labor-sharing arrangement for agricultural or other activities) and *Wonfel* (a reciprocal labor relationship where two or more farmers arrange reciprocal labor support for each other at times of peak agricultural labor demand) are deeply rooted cultural heritages which also serve as mechanisms of mobilization for collective action. Particularly, the rich social capital in LD area makes free riding a dishonorable behavior making the majority of the farmers in *Alewuha* traditional scheme cooperative for collective action.

Leadership

Baland and Plateau (1996) indicated that appropriate leadership as characterized by young, familiar with changing external circumstances, and connected to local traditional elites is among the critical enabling conditions for sustainability of the commons. In the case study areas, it was found that leadership is an important factor determining group solidarity and cooperation for collective action.

Effective leaders who are well regarded and able to mobilize the people for collective action are found to have the following characteristics. They have some formal education (can read and write). They are mostly members of the ruling party and are economically better off or are not poor as compared to local fellow farmers. They have similar livelihoods as the majority of farmers they represent or lead. They are eloquent and they serve as bridges between government and community. Party officials and *Kebele* leaders also rely on them to get things done. They use their influence and informal networks to get things done. They have a number of responsibilities and engage in a number of committees both in the formal and informal structures. In LD area, *Kire* leaders have such qualities and are able to mobilize the people for maintenance of communal ponds. The leaders of the *Alewuha* schemes (both the traditional and modern schemes) have also similar leadership qualities and can effectively mobilize water users for collective action.

On the contrary, poor leadership plagues all the schemes at QM as evidenced by the prevalence of corruption and opportunistic behavior among the leaders of water-user groups. According to key informant farmers, the WUA officials of the *Guantalomidur* scheme as well as that of the *Berengua* traditional scheme were elected by water-user farmers themselves. Yet, they turned up to be corrupt and opportunistic. Farmers were unable to change these corrupt leaders due to the latter's network of client farmers and the lack of sanctioning support from third parties such as the *Kebele* or *Woreda* administration. The cases at QM show the fact that charismatic leaders can turn into dictators and be difficult to replace in a circumstance where corrupt leaders engage in patronage relations with some clients or with higher level entities.

Formal–Informal Linkage

The overlap between formal and informal governance structures is an important mechanism used for mobilization of the community for various collective actions and enforcement of rules. At QM, some members of the *Kebele* administration are also members of the WUA committee or the traditional water-user groups. Similarly, some of the *Kebele* leaders at the LD area are also *Kire-Asadaris* (*Kire* leader). For instance, the leader of the *Alewuha* WUA, Ato Bihonegn Sisay, is also a *Kire-Asadari*. These overlaps make it possible to mobilize the people for collective action and enforce rules using the *Kire*.

At *Alewuha* modern scheme, WUA officials decided to use the local *Kire*s for mobilization of water users for canal clearing. They gave a portion of the work for each *Kire* in their villages. Since everyone respects *Kire* calls and resolutions, it proved to be an effective way to mobilize water users. According to WUA officials, only few farmers used to appear for canal clearing and it used to take them more than 4 months to finish canal clearing and commence irrigation; now, it only takes not more than 5 days. According to WUA officials of the *Alewuha* modern scheme, sharecropping farmers, who mostly free ride, were forced to contribute labor for canal clearing as they are also members of the local *Kire* and abide by *Kire* rules and if they are from other villages, it was decided that they have to contribute labor or pay a fine of 30 ETB.

24.5 Conclusions

The case studies provide evidence that the process of institutional changes is affected by characteristics of actors. Actors with better bargaining power control institutional change in their favor. This is clearly evidenced in the *Guanta-lomidur* scheme where head-end farmers and *Kebele* leaders blocked institutional change to regulate pump irrigation. In addition to this, opportunistic behavior of some actors has, on the one hand, led to tighter rules to control such behaviors as in the case of introducing locks at division boxes and raising the amount of fines for canal breaching. On the other hand, opportunistic behaviors by traders and WUA officials and the consequent farmers' loss of trust have led to disintegrating WUA at the *Guanta-lomidur* scheme.

These cases also provide evidence that government policies undermine traditional water rights in favor of modern ones. This deprives peasants in the traditional schemes of their livelihoods and it becomes a source of conflict among farmers. Yet, the *Alewuha* water rights negotiation among farmers indicated above suggests that if given the autonomy to solve their own problems, farmers can forge viable institutions of property rights which will avoid conflicts and also secure water rights more effectively than the formal system.

The case studies provide evidence that inequality in the distribution of irrigable farmland deters the smooth functioning of irrigation WUAs and consequently reduces the potential benefit that could be gained from cooperation among water-user farmers. Moreover, field evidences indicated that availability of exit options, uncertainty, and bargaining power asymmetry undermine the cooperative behavior of farmers. The government safety-net program to help the poor also had negative effects on farmers' willingness to freely contribute labor for the collective good. On the other hand, rich social capital in the form of mutual help and reciprocity are crucial assets facilitating collective action among farmers. Good leadership and the link between the formal and informal governance structures were also found to foster collective action.

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Chapter 25
Water Governance in the Nile Basin for Hydropower Development

Marit Kitaw and Muluneh Yitayew

Abstract Water governance in the Nile basin and, in general, in Africa faces technical, social, environmental, economic, and political challenges. Power shortage is a factor in limiting development and growing food shortage. The Nile basin countries have an estimated 140,000 MW of hydropower potential, but a small fraction is exploited except for Egypt. Increasing population in the Nile basin countries is increasing the demand for water and power. By 2025, Burundi, Rwanda, Egypt, Ethiopia, and Kenya are projected to face shortage of per capita water availability (1,000 m^3 per person per year). Nile countries are facing tremendous challenges with regard to food security, adapting to climate change, and shortage of energy. But, they are not yet able to settle legal and political disagreements on a proposed agreement for cooperation. Lack of water agreements that are timely, equitable, and acceptable by all riparian countries could result in constant conflict and mismanagement of the water resources of this transboundary river basin. There are several examples of best practices in governance of transboundary water resources.

Keywords Nile basin · Nile countries · Hydropower · Transboundary rivers · Water governance

25.1 Introduction

Generating sufficient power to unlock economic potential is among the main challenges faced by Africa. While the continent is blessed with natural resources, food insecurity continues to prevail with millions of people struggling to survive the relentless hunger and poverty for the past several decades. Among the number of critical

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factors contributing to food insecurity and limited agricultural productivity are the ever-increasing population and the associated water and energy demands exacerbated by changing weather patterns and climate change. Water is a vital strategic natural resource for all economies mainly in food production, domestic use, and in the production of renewable energy. For this reason, its governance is a necessary condition for sustainable development and for meeting the Millennium Development Goals (MDGs). Attaining food security by raising agricultural productivity will inevitably involve increase in energy inputs for water supply and management, plant nutrient and agro-processing, community lighting and drinking water, and for cultivation. What is important to note is the fact that for all practical purposes, water and energy are interdependent. Water is used in hydroelectric generation while energy is used to pump water for domestic use, irrigation, and industrial uses.

25.1.1 Water Resources and Energy Development in the Nile Basin

The Nile basin countries have huge bodies of water to comanage from Lakes Victoria and Tana to several numbers of rivers and streams that flow across and between the borders of the countries. The basin has the potential for competition and conflict driven by a growing population and the subsequent rise in demand for water and hydropower energy production for development. Presently, the Nile basin countries have a severe energy shortage that has proved to be costly to the region's economy and sustainable development goals. Lack of reliable energy has rendered efforts to develop the economy across the subregion as fruitless, despite its significant number of perennial rivers with the potential to generate more than enough energy for the region and beyond. The main energy challenges faced by the subregion and Africa as a whole are low-level energy access, heavy dependence on biomass for energy, low per capita consumption, and lack of energy infrastructure.

Transition towards a stage where households, services, and farming activities use a variety of sustainable and diversified energy is needed. Moving away from the present levels of subsistence energy usage based on human labor and fuelwood resources is needed for Africa to increase energy access. The obvious benefits are greater resilience in the production system, higher productivity, improved efficiency, and higher incomes to farmers and greater availability of both water and energy for industrial and domestic uses. Moreover, environmental degradation that is driven primarily by poverty would be reduced.

The underlying themes that need to be stressed in Africa for increasing energy access are country-led efforts, regional projects, and strengthened partnerships. The emphasis should be electricity growth, powering sustainable development, and meeting basic needs. In order to achieve these goals, there should be an effective governance of the resources with improved institutional performance within the region. More deliberative water governance is, thus, needed for informed transboundary water and energy utilization.

Given the increasing demand for clean, reliable, and affordable energy, the role of hydropower is gaining importance, particularly as a means to reduce poverty and attain sustainable development. Hydropower can be used not only to provide electricity access but can also effectively contribute to regional cooperation and development through the judicious and optimal allocation of increasingly scarce energy resources. Hydropower has a great role to play in solving Africa's energy security and addressing economic, social, and environmental issues. It should be addressed through considerate application of lessons learnt and best practices through a bottom-line approach to achieve sustainability.

25.1.2 Africa's Hydropower Potential

Africa has a number of rivers running through eastern, western, central, and southern regions which provide excellent opportunities for hydropower development. There is an enormous exploitable hydropower potential in the continent, particularly in the sub-Saharan countries. The hydropower resources in sub-Saharan countries account for about 12 % of the world's hydropower potential. Only 17.6 % of these resources has been harnessed which is one of the world's lowest figures.

The continent has a technically exploitable capability of 1,888 TWh/year of which 41 % (or 774 TWh/year) is in one country, the Democratic Republic of Congo (DRC), from the Congo River. Ethiopia, with its highlands, has a technically exploitable capacity of 260 TWh/year and Cameroon 115 TWh/year. Madagascar also has substantial potential capacity at 180 TWh/year. In terms of installed capacity, Egypt with the Aswan Dam leads with 2,810 MW, followed by the DRC (2,440 MW) and Mozambique (2,180 MW). Mozambique (11,548 GWh) and Egypt (11,450 GWh) are the leading producers of hydroelectricity based on 1999 data (WEC 2003). Figure 25.1 shows estimates of the hydropower potential for the continent.

The current geographic distribution of hydropower in Africa demonstrates the following pattern: North Africa (23 %), West Africa (25 %), and southern/central/eastern Africa (51 %). Despite this potential which is enough to meet all the electricity needs of the continent, only a small fraction has been exploited and Africa has one of the lowest electricity utilization rates in the world. Presently, 20 % of this potential has been harnessed (FAO 2008).

In the Nile basin, as mentioned earlier, a number of countries have faced power shortages that have caused power supply rationing. The origin of the crisis is the decrease of water level in rivers and lakes that are feeding the hydropower plants and lack of investments in power generation. Countries in the region have responded to the challenges by embarking on aggressive measures in the production as well as transmission of energy, interconnecting countries, and sharing available capacity. The creation of the Eastern Africa Power Pool (EAPP) in 2005 is one of the major steps undertaken in this regard.

Hydropower has long been the pillar of East Africa's energy production capabilities. The majority of electricity produced in the region comes from hydropower, and it

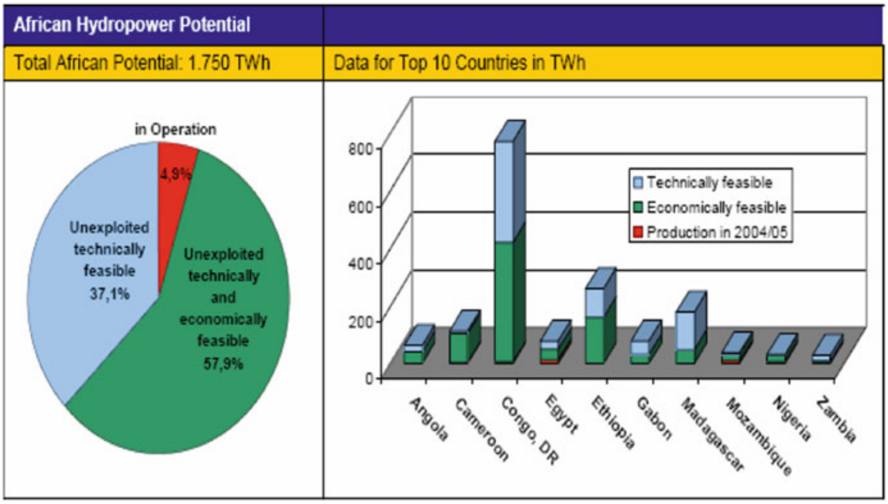

Fig. 25.1 Africa's hydropower potential. (Source: FAO 2008)

is expected to provide 79 % of East Africa's total new additional generation capacity (Quirte 2012). However, environmental and institutional challenges to harnessing the region's hydropower production potential remain. This includes drought, the need for capital investment, lack of technical expertise in formulating energy plans and feasible projects, and focus on large-scale projects.

On the other hand, hydro projects have benefited and can continue to benefit from private-sector investment and foreign donors. The Nile basin countries are attractive areas for such investment. The region has maintained a fast growth trajectory despite experiencing severe drought and famine. The region registered 5.8 % gross domestic product (GDP) growth in 2011 and 6 % in 2010 (UNECA 2012). Much of Uganda's growth came from increased foreign direct investment (FDI) in its energy sector (UNECA 2012). Furthermore, Africa's hydroelectricity production costs are the lowest in the world (WEC 2003).

25.2 Nile River and Hydropower Development

The Nile is the world's longest river. It flows for 6,850 km, covering 11 countries: Burundi, the DRC, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. The Nile river system has the White Nile arising from Lake Victoria in the south, or in Burundi if rivers that feed into Lake Victoria are taken into account, and the Blue Nile which originates from Lake Tana in Ethiopia. The two Nile rivers merge near Khartoum in Sudan and enter Egypt as one river. The term Nile is used to include the entire Nile system including the White Nile, the Blue Nile, and tributaries.

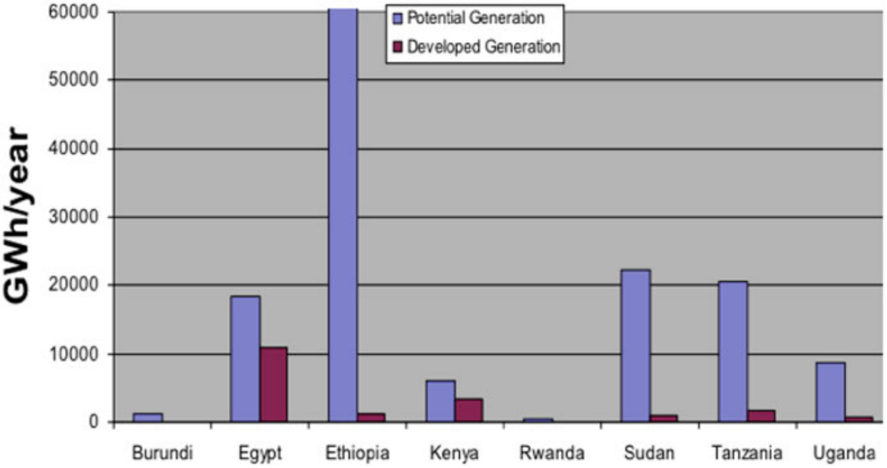

Fig. 25.2 Energy potential and realized in the Nile basin countries. (Source: Kanangire 2008)

Some countries, such as Burundi, Rwanda, Uganda, Sudan, and Egypt are totally dependent on the river, while for others, such as the DRC, the Nile's water constitutes only a small part of their resources. Egypt and Sudan use the Nile's water mainly for agricultural purposes; 80 % of water in Egypt is directed to this sector. The Nile is not only a water reserve for its riparian states but also a fundamental waterway. In Sudan, it is the only practicable transportation during the flood season from May to November. Nile water is also used for production of hydroelectric power by Sudan, Egypt, Uganda, and Ethiopia (Sinnona 2007).

If all the Nile basin countries are taken into account, their hydropower potential is estimated to be 140,000 MW. The DRC alone is considered to have a potential of 100,000 MW, with approximately 40,000 MW concentrated in the INGA complex from the Congo River; Ethiopia has a hydropower potential of 45,000 MW. Figure 25.2 shows the energy from hydropower for the Nile basin countries excluding DRC.

Two important factors contribute to the hydropower potential of any river system: the hydraulic head, which is a function of the topography, and the flow rate of the river system. The flows of the Nile as measured at Aswan on the border of Sudan and Egypt experience very high degrees of fluctuations, making the governance of transboundary water very difficult.

In the past 150 years, the lowest recorded flow at Aswan was at 42 billion m^3 in 1913–1914 and the highest was 150 billion m^3 (1878–1979). The flow oscillated between 117 to under 50 billion m^3 from 1960 to 2010 (see Fig. 25.3). The fluctuations in the flow of watercourses have the potential of increasing in the twenty-first century. Most climate change models agree that inconsistent patterns of rainfall and concentration over fewer days would affect productivity in agriculture as well as energy. As witnessed by Ethiopia, Kenya, and Sudan recently, depletion of water resources during crucial seasons can lead to a decline in agricultural production by as much as 50 %.

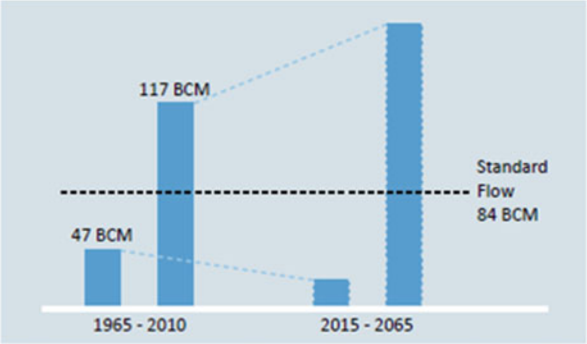

Fig. 25.3 Oscillations in Nile flow. (Source: Blue Peace for the Nile, March 2013)

While the regional hydropower potential is considerable, especially for DRC and Ethiopia, the current situation is that each country is attempting to develop its hydropower resources autonomously. They face challenges for collaboration. But, there are examples of countries jointly building hydropower plants such as the one on the Ruzizi where Burundi, Rwanda, and DRC collaborated. Small hydropower developments are important to rural power supply. Most of the countries have energy policies and strategies in place on rural electrification through small or mini-hydropower development. But, progress has been limited for the most part. The reasons cited mostly are lack of access to relevant technologies and limited financial resources.

25.3 Governance of Transboundary Water Resources in the Nile Basin: Challenges and Opportunities

25.3.1 Dimensions of Water Governance

The central water and energy management issue for the Nile River basin, as in many other river basins throughout the world, is sustainability of water supply in the context of intense population growth, recurring droughts, and increasing competition for water (see Fig. 25.4).

The issue gets complicated as a result of global climate change that is being realized in the region. As a result, the demand for the Nile water is going to increase significantly. Some of the basin states such as Ethiopia, Kenya, Tanzania, and Uganda are already experiencing critical water shortage due to some extreme events such as recurring drought while some have occasional dosage of excess water. Shortage of water occurs when the needed amount and quality is not available at the right time and place of need. Shortage due to drought represents physical shortage. On the other hand, shortage can happen due to degradation in water quality. In this case, the water can become degraded to an extent it is not safe for human consumption. Considering a threshold value of 1,000 m^3 per person per year, it is projected that some of the Nile basin countries: Burundi, Rwanda, Egypt, Ethiopia, and Kenya will

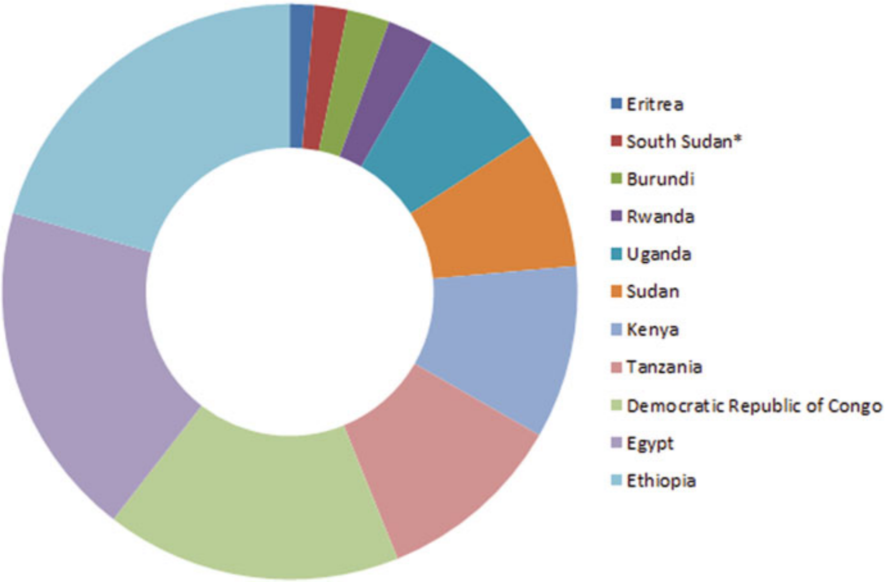

Fig. 25.4 Population of Nile riparian countries. (Source: CIA World Factbook 2012; *South Sudan Government 2008 census)

all be considered as water "scarce" by 2025. This is based on a continuous population growth of the basin. If the present trend continues, water shortage is likely to happen, and because of that socioeconomic development is going to be restrained and the potential for water conflict will increase (Yitayew and Melesse 2010). Strains on the Nile water resource are displayed by unilateral actions such as Egypt's development of new areas as the Toshca project to expand irrigated areas to establish claims for prior appropriation rights and Ethiopia's construction of the Renaissance Dam.

Historical hydro-climatology studies show the variability in flow of the Nile flow both in time and in space. Unless there is a way to regulate this flow condition, it is difficult to plan a meaningful sustainable water resources and energy development program. This is particularly true when one considers hydropower development. It is also apparent that in a basin as big as this, a concerted effort to gather data that can be used to forecast the hydrologic and climatologic variables is absolutely necessary. Any effective Nile water governance must consider integrated basin-wide hydraulic cooperation in parallel with the rest of the effort to bring the riparian countries to work together with a shared vision of benefiting socioeconomically and politically.

Until recently, most of the agreements on the Nile basin were either agreements made between colonizers or bilateral agreements between Sudan and Egypt. The 1990s has been one where substantial effort has been invested by the riparian countries and the donor agencies to develop confidence and vision for the future which is based on cooperation, consideration for the environment, and the efficient use of water. Even now, despite the intense pressure for cooperation driven by demographics, sustainable development needs, water and food security, economic integration,

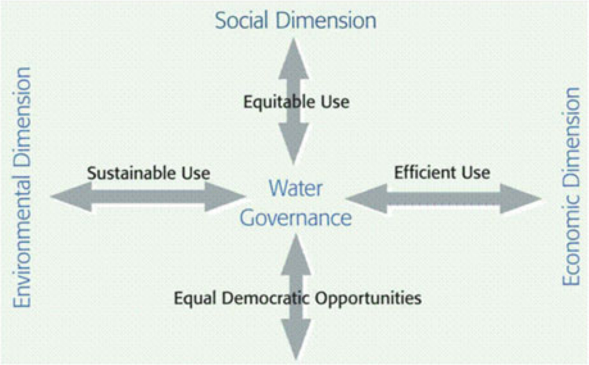

Fig. 25.5 Dimensions of water governance. (Source: UNDP) (http://www.watergovernance.org/why, accessed 20 April 2013)

and climate change, there is no reliable established framework for governance of the water and energy resource of the basin that is accepted by all the riparian countries. The present challenge for cooperation stems from conflicting agricultural water demands mainly from the eastern Nile countries. All have yet to agree on equitable and reasonable use of the water without causing significant harm to each other.

Optimum management of water resources to meet the MDGs requires effective governance of the resource, especially along transboundary lakes and river basins. Water governance refers to the different political, social, and administrative mechanisms that must be in place to develop and manage water resources and the delivery of water services at different levels of society. It is the framework of political, social, economic, and legal structures within which societies choose and accept to manage their water-related affairs. Efficient water governance requires transparency and accountability, participatory mechanisms appropriate to regional realities, needs, and wishes, and equitable and fair water agreements that signatories comply to.

The social dimension of water governance deals with equitable use of water resources while the economic dimension draws attention to the efficient use of water resources and the role of water in overall economic growth. The political empowerment dimension addresses granting water stakeholders and citizens at large equal democratic opportunities to influence and monitor political processes and outcomes. The environmental sustainability dimension shows that improved governance allows for enhanced sustainable use of water resources and ecosystem integrity. Figure 25.5 illustrates the relationships of these dimensions of water governance.

Water governance capacity also reflects a society's level of competence to implement effective water arrangements through policies, laws, institutions, regulations, and compliance mechanisms. Without a clear policy, it is difficult to develop a coherent system of laws. Without a clear established legal structure, it is difficult for institutions to know how to operate. Without effective institutions, compliance and enforcement are likely to be lax (Iza and Stein 2009). This is particularly true when dealing with water as a transnational resource that is to be shared for sustainable development of a region such as the Nile basin.

While water governance is a complex subject that needs an extensive treatment, this chapter focuses on water governance in the context of energy production with particular attention given to hydropower production in the Nile River basin. Good water governance along transboundary lakes and river basins is a necessity for achieving the MDGs. Equitable governance of water resources implies finding a balance between citizens' needs and the demands from stakeholders in the agricultural, industrial, and other fields. While water is considered a national resource by governments, it is not demarcated by borders that are political by nature. By connecting people and creating interdependence among local users from different countries, transboundary rivers and lakes pose governance problems and can become a great challenge at the political level. While transboundary water resources hold considerable potential for conflict and escalation, they also offer a variety of different possibilities for transnational cooperation.

For most regions such as the Nile basin, in the 1980s and 1990s, concerns were greatly raised about water shortage-related conflicts in various regions given the rising consumption of water and the asymmetrical power relations between riparian countries. A much-cited example was conflict among the riparian countries along the Nile. The relations between the riparian countries of southern Africa were likewise seen as a potential source of conflict. The United Nations Development Programme (UNDP) Human Development Report (2006) affirms that water could foster conflicts, but more frequently, it has been a bridge for cooperation. However, these somber predictions have not materialized. Experience shows that transboundary water resources are far more likely to serve as the motor of transboundary cooperation than of violent conflict between nations. Since the end of the apartheid regime in South Africa, it is precisely southern Africa—a region with an exceptional number of transboundary rivers—that has a number of positive developments to show in this regard. Also, in other subregions, Africa's heads of state and government have opted for a cooperative management that has been affirmed in many declarations and bi- and multilateral agreements.

25.3.2 Transboundary Rivers

Transboundary water resources management (TWRM) in Africa is addressed in various international documents with guideline charter. These include the G8 Africa Action Plan, the New Partnership for Africa's Development (NEPAD) Action Plan, and the Abuja Declaration of the African Ministers Council on Water (AMCOW). These efforts also have reference to the work of the UN Secretary-General's Advisory Board on Water and Sanitation and the International Water for Life Decade proclaimed by the UN General Assembly (2005–2015).

There are many shared water basins in Africa, the Nile basin being geographically the largest with 11 riparian countries and complex upstream and downstream issues to be dealt with. In the South African Development Community (SADC) alone, there are 13 transboundary rivers shared by two or more riparian states. As many local, national, and international stakeholders are involved, TWRM) cannot be conducted purely on a state-by-state basis. Multinational dialogue and negotiations are the basis of wide-ranging agreements between riparian states. The need for cooperation and information sharing is an essential element. This can be facilitated by the creation of transboundary-basin institutions or agreements—such as the Congo-Oubangui-Sangha International Basin Commission (CICOS), the stillborn Zambezi Basin Commission, or the Nile Basin Initiative (NBI). The NBI is established to monitor the policies of riparian states and ensure equitable utilization of water resources, create development strategies, and monitor the implementation of national integrated water resource management (IWRM) plans. In most cases, however, such institutions have faced severe challenges impeding their ability to get off the ground.

As indicated above, governance of countries that are riparian along the Nile present both challenges and opportunities. While at the national level different institutions have been created to settle disputes over water allocation, at the international level there is no institutional structure with power on national governments that is able to force the countries to take actions that do not correspond to their national interests.

While progress made with regard to conventions is commendable, a sustainable regional framework is absent. Governments have a preference for bilateral agreements to settle disputes over transboundary water resources. At the international level, there are few international water laws such as the United Nations Economics Commission for Europe (UNECE) "Convention on the Protection and Use of Transboundary Watercourse and International Lakes," signed in Helsinki 1992 and in force from 1996, and the UN "Convention on the Law of the Non-Navigational Uses of International Watercourses," adopted in 1997, but still not in force (Sinnona 2007). The 1966 Helsinki Rules on the Uses of the Waters of International Rivers (International Law Association, ILA) that outlines the principles related to the "equitable utilization" of shared watercourses and the commitment not to cause "substantial injury" to co-riparian states (the no-harm principle), the 1997 United Nations Convention on the Law of Non-Navigational Uses of International Watercourses (International Law Commission, ILC), the 2004 Berlin Rules on Water Resources (ILA) are the most important water laws that are being used at present. Principle of reasonable and equitable utilization, obligation not to cause significant harm, principle of duty to cooperate, and prior notification and negotiation on planned measures are fundamental principles that are used to establish legal framework and water governance for most of the river basins globally.

25.3.3 The Political Economy of the Nile and Implications for Water Governance

Transboundary water management is mainly a political process. This is the reason why cooperation and conflicts on water resources are determined by asymmetries in power among riparian states. It is not without good reason that the example of the Nile is again and again cited in the popular discourse on "water wars." Egypt is wholly dependent on the waters of the Nile for its economic development, and for this reason, Egypt has declared a secure supply of water from the areas beyond its border to be a vital national security interest. In the past, there have been repeated conflicts between Egypt and the upstream Nile riparian countries over the allocation of the waters of the Nile, and these conflicts have even led to threats of war in times of particular stress as in periods of drought. It is important to point out that while there are 11 riparian countries, only three of these are in the most critical position for peaceful, cooperative sharing of Nile water—Ethiopia as the primary supplier and Egypt and Sudan as the dominant consumers.

Among riparian states, Egypt is the one with the highest Nile's water demand. It is subjected to water management of the upstream riparian states. In 1979, it was declared that at the beginning of 2000, Egypt would face a water deficit of 4 billion m^3 due to the huge population growth (one million every 9 months) and agricultural needs. Still in the 1990s, Lake Nasser, because of the high evaporation, could not meet the population's demand, so that 50 % of food was imported from abroad (Swain 1997). These occurrences caused high internal instability and a strong political and economic dependence on other countries' policies, threatening Egyptian national security. In order to face these political problems, Egyptian diplomacy has strongly promoted regional cooperation. Sudan and South Sudan (secession with the referendum of January 9, 2011), as well, are strongly dependent on the river.

The first important Nile Waters Agreement (NWA) over the allocation of its waters between Egypt and Great Britain (which represented Uganda, Kenya, Tanganyika—now Tanzania, and the Sudan) was concluded on November 7, 1929, in Cairo by an exchange of letters between the Egyptian prime minister and the British high commissioner in Egypt. After the Second World War, with independence, the river became the scenario for power games and disputes related to the Cold War. In 1956, when Sudan obtained independence, it requested a renegotiation of the 1929 water agreements with Egypt. Sudan accepted the Aswan High Dam construction by Egypt, in exchange for sharing the water of the dam. The two countries signed in 1959 the Nile water agreements to allocate the resource and to share costs and benefits of future projects on the river. From that year, cooperation between Sudan and Egypt more or less continued. This agreement between Egypt and Sudan, which increased the water allocations to themselves while completely ignoring the interests of the other riparian countries such as Tanzania, Kenya, and Ethiopia, has, in retrospect, weakened the Egyptian argument about inviolability of the 1929 agreement (Sinnona 2007).

In the past few decades, population pressures, frequent droughts, and increasing soil salinity have intensified the demands by the Nile basin countries to renegotiate the 1929 agreement. Not deterred by Egyptian reluctance to negotiate the agreement, or even Egyptian threats of financial hardships, some Nile basin countries such as Ethiopia are determined to implement projects that tap into sources of the Nile. To avoid the possibilities of conflict over the Nile water and instead to forge some sense of cooperation, some of the Nile countries were able to meet and agree on some noncontroversial issues starting in the mid-1960s.

The Hydromet Agreement was signed in 1967, originally among Egypt, Kenya, Tanzania, Uganda, and Sudan with the collaboration of the UNDP and the World Meteorological Organization, and later joined by Rwanda, Burundi, DRC, and Ethiopia, increasing cooperation. Hydromet lasted for 25 years, terminating in 1992. In the same year, the water resource ministers from Egypt, Sudan, Rwanda, Tanzania, Uganda, and DRC created a new organization, the Technical Committee for the Promotion of the Development and Environmental Protection of the Nile Basin (TECCONILE). The rest of the four riparian states participated as observers. To further reduce the potential for conflict, and with the help of the World Bank, the NBI guided by a shared vision “to achieve sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources” was launched in February 1999 with members that included all riparian countries, except Eritrea (The World Bank 2009). As a result, in September 1999, the NBI Secretariat replaced TECCONILE in Entebbe, Uganda. The NBI is considered as a transitional arrangement until a permanent framework and a permanent Nile River Basin Commission is in place (Sinnona 2007).

This positive development is a good indication that the constellation outlined above also offers incentives for international cooperation. Decision makers throughout the world, and precisely in Africa, have come to recognize in principle that transboundary waters call for cooperative transboundary management. This has found expression in numerous bi- and multilateral declarations and agreements on individual water bodies as well as in framework agreements that lay down general principles governing the management of transboundary river basins.

Cooperation is often extended to other benefits. The UNDP Report (2006) claims that more than 40 % of transnational water treaties include provisions on financial investments, energy commerce, and peace negotiations. This approach could facilitate agreements, because it provides governments national justifications and it promotes financial flows, capable of opening cooperation on a variety of matters. Moreover, it offers a bargaining power to weaker countries that could grant something in return to an equitable water management. Transnational cooperation is influenced by asymmetries in power. In this framework, transnational relations for the management of common water resources become a matter of interactions more than just a problem of conflict or cooperation. Conflicts and cooperation coexist in all situations where a resource is shared.

While Nile basin countries are facing tremendous challenges for their future in terms of food security, climate change, and lack of energy, they are involved in legal and political disagreement on the proposed Comprehensive Framework Agreement for cooperation in the basin which was drafted in 2010. The formation of South Sudan as a sovereign state could also add some elements to the legal challenges. These differences over legal and political issues pose the risk of depriving people in the basin of the opportunity to achieve economic development and realize their full potential.

25.3.4 Public Participation in Water Governance

In many respects, civil society participation in water resources management and water supply and sanitation is the key to successful sector governance, encompassing management, quality service provision, and sustainability. This has been recognized in the Dublin-Rio Principles, which are clear in their statements that water development and management should be based on a participatory approach, involving users, planners, and policymakers at all levels, and that women play a central part in the provision, management, and safeguarding of water. This calls for a sharing and balance between stakeholders (both top down and bottom up) in their planning and management. It has also been recognized that service provision functions should be delegated to the "lowest appropriate level" at which stakeholders involved in management need to be identified, resourced, and mobilized. It follows that in the water sector the beneficiary needs to be involved at all stages of the project cycle from monitoring and needs identification right through maintenance and basin and system management.

In order to manage water equitably, governments must solicit stakeholders' involvement. Involvement of stakeholders at the transboundary scale is key to ensuring adaptive water management which is being able to respond to challenges before they become problems (Kranz and Mostert 2010). Principle 10 of the 1992 Rio Declaration on Environment and Development affirms that environmental issues are best handled with the participation of all concerned citizens. The Declaration exhorts nations to facilitate public participation through methods to increase transparency, participatory decision-making, and accountability. The International Association for Public Participation (IAPP) defines public participation as "any process that involves the public in problem solving or decision making and uses public input to make better decision." As mentioned by Kranz and Mostert, there is public participation when the involvement is direct. This form excludes elections that are a form of indirect involvement, and it includes financial contributions (Kranz and Mostert 2010).

Inadequate public participation, or even worse, the exclusion of people in decisions that affect their welfare, often lead to a violation of basic human rights and possibly to public protests and obstruction to the implementation of decisions (idem). "Ending global thirst depends upon providing the public with a voice in water resource decisions that directly affect them" (idem).

25.3.5 Best Practices in Governance of Water Resources

The NBI has undertaken in the past a "knowledge exchange study tour" to the Senegal River basin to learn the role of the Senegal river basin organizations (OMV) and identify certain best practices. The Nile basin countries should use the auspices of the African Ministerial Council on Water and International Network of Basin Organizations to establish access to some of the countries and determine where they wish to undertake learning tours.

Some countries, regions, and areas are known for best practices in different aspects of national governance of transboundary cooperation of water, such as:

1. Senegal River for transboundary water management
2. Rhine River for transboundary water management

3. SADC for regional cooperation principles
4. European Union (in context of Directive Framework 60) for cooperation in quality control
5. South Korea for restoration of rivers
6. Singapore for urban water management and wastewater treatment
7. Indus Water Commission for arbitration mechanism in case of disputes
8. Israel for drip irrigation and mitigation of conveyance losses
9. Mekong for cooperation in data management

The Mekong River Commission, an intergovernmental agency that works directly with the governments of Cambodia, Laos, Thailand, and Vietnam, established under the 1995 Agreement on Cooperation for the Sustainable Development of the Mekong Basin, provides one of the most highly developed examples of an international river basin organization founded to facilitate transboundary water cooperation. Currently, the MRC Secretariat administers a range of joint programs, including: the Basin Development Plan; the Water Utilization Program; the Environment Program; the Flood Management and Mitigation Program; the Fisheries Program; the Agriculture, Irrigation and Forestry Program; the Navigation Program; the Hydropower Program; the Information and Knowledge Management Program; and the Integrated Capacity Building Program.

As one of the world's largest and most complex efforts at TWRM, the NBI could be considered as best practice as its objective is to develop water resources in a sustainable and equitable way and to ensure efficient water management and optimal use of the Nile's water resources. Major achievements have been to facilitate cooperative action, build confidence and capacity in riparian states, and pursue cooperative development opportunities.

In the SADC Region, the SADC Water Protocol was prepared in 1995 to encourage the establishment of appropriate institutions for monitoring, ensuring equitable utilization, and strategizing for water resources development. The Protocol also provides for essential data and information exchange between riparian states. Progress has been made in forging agreements in some shared basins, such as the Zambezi, Orange-Senqu, and Incomati basins, and some water monitoring networks have been established that are now providing information to riparian states. Efforts to get the Zambezi Watercourse Commission (ZAMCOM) up and running 5 years after an agreement was signed by seven of eight riparian states continues to be bogged down by political disputes.

Civil Society Participation in Practice: Burkina Faso, Senegal, and South Africa use decentralization approaches to ensure the enhanced participation of target communities in program design and implementation and come closest to what could be defined as best practice. Benefiting from decentralization and democratic systems that avail responsive representation and local governments, these approaches center on participatory planning in the development of local development plans (LDPs) and, commensurate with them, local water and sanitation plans (LWSPs). The LWSPs are a platform for the identification of specific projects that are prepared in concept and budget estimates for approval by local or municipal councils and forwarded to regional and national levels. The LDPs and LWSPs constitute a useful framework for sector planning that is based on community and community organization participation. They successfully integrate community involvement and local government ratification with regional and national planning and budgeting processes.

25.4 Way Forward for the Nile Basin

River water does not stop at administrative or political boundaries, so the best way to develop, use, protect, and manage it is by forging cooperation between all the countries within the natural geographical and hydrological boundary of the river basin. All the interests of both upstream and downstream countries have to be considered in a transparent, responsible, and comprehensive manner.

Transboundary water resources represent a situation in which water governance is complicated by issues of politics and competition for scarce resources between two or more countries. The literature on the subject notes that TWRM cannot be conducted purely on a state-to-state basis, since many other stakeholders from the local to the international level typically need to be involved. Furthermore, weak legal and regulatory frameworks, a lack of basin-wide institutional arrangements for joint development and management of transboundary water resources, poor water resources information systems, poor financing, and a lack of stakeholder participation also affect the success of TWRM.

Two basic principles discussed widely in the literature and considered prerequisites for good water governance are transparency and accountability, which are closely related to one another within the context of governance systems. For instance, transparency necessitates strong sector performance-monitoring systems, which will enhance accountability for the use of resources by service providers. Decentralization not only provides an opportunity for the introduction of transparency and accountability measures but also introduces threats to the same if community and civil society voices are not well articulated.

Moreover, corruption in the water sector results from a lack of transparency and accountability. Corrupt practices are endemic to most institutions and transactions in Africa, leading to increased costs to users for service provision. With regard to civil society participation in sector governance, the involvement of all users in the process of developing appropriate policies and regulations for water resources management and use is essential for effective water sector governance. Participation of civil society and the permanent mechanisms that will enable it are essential in every aspect of governance, from project and program selection and planning to budgeting, policy, and regulation. This not only improves sustainability of services but also improves transparency, accountability, and regulatory enforcement.

The ongoing changes in the world economy and the shift from geopolitics to globalization are being complemented by a move away from special treatment for individual countries in mitigating their systemic development failures and structural weakness to accelerate their integration into the world economy. This is expected to help manage common problems, which stem from rapid global integration. Regional energy cooperation and integration offer one of the most promising and cost-efficient options for Africa, eastern Africa in particular, to further develop their energy sectors, in order to gain the environmental, social, and economic benefits from a more efficient use of resources. Four major benefits are associated with regional energy integration: improved security of supply, better economic efficiency, enhanced environmental quality, and development of renewable resources. It can enhance peace and stability. Historically, the first two factors have been the driving forces behind power interconnections and regional trading throughout the world. However, with the increasing concern and awareness of the need to integrate environmental considerations in development planning, power interconnections are being considered as a means to develop alternative clean or more environmentally sound energy resources.

The way forward for the Nile basin is to establish effective water governance based on the principles of equity and efficiency in water and energy resources allocation and distribution. The countries in the region must come together and formulate, establish, and implement water and energy policies with appropriate legislative and institutional frameworks. There has to be clearly defined roles of governments, civil society, and the private sector in terms of their responsibilities regarding ownership, management, and administration of the water and energy resources. Transnational dialogue and coordination, conflict resolution, price regulation, and subsidies must be clearly defined and agreed upon by all parties. Also, the region has to focus on benefit sharing rather than water sharing, multilateralism instead of unilateralism, and enhancing a more cooperative approach. Establishing effective water governance and the NBI legal and institutional framework agreement with full consideration of the hydro-politics of the region is urgently needed if the countries are to overcome their differences and attain a sustainable water and energy development. To this end, NBI has to be replaced by the Nile Basin Commission with an absolute power to make basin-wide decisions even if some of the member states oppose on the basis of their own national interests. The Nile Basin Commission should have a new framework that will bring together politics, law, regulations, civil society, water, and energy policies for optimum utilization of these resources. It should insure that sufficient energy and water supplies are available to secure long-term economic viability and provide a high quality of life for the present and future generations of the basin. The commission must develop a broad portfolio of solutions to meet the myriad of challenges that are inherent in this diverse, variable, and complex basin.

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Chapter 26
Managing Rainwater for Resilient Dryland Systems in Sub-Saharan Africa: Review of Evidences

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Abstract Rainfed agriculture will continue to play an important role in achieving food security and reducing poverty in sub-Saharan Africa (SSA). But it is threatened by a combination of technology, policy, and institutional failures. Effects of recurrent drought and future climatic changes would affect rainfed systems and it would be most felt in SSA systems, where local institutions are not yet well prepared to respond to emerging climatic shocks. Rainwater management (RWM) is one strategy that could minimize drought effects through mapping, capturing, storing, and efficiently utilizing runoff and surface water emerging from farms and watershed for both productive purposes and ecosystem services. The extra water saved could be used to grow long maturing crops, producing more than one crop per season or diversify production systems. Enabling wider adoption of RWM interventions would improve the profitability of smallholder agriculture by increasing crop and livestock yield by factors of up to fivefold, while net returns on investment could double. However, adoptions of these interventions demand supportive policies and institutions, to enable farmer innovation, multi-institutional engagements, and collective action of actors at various levels. This is particularly critical in semiarid river basins, for instance the Nile basin, where because water availability is seasonal, upstream

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water towers are threatened by land degradation and deforestation and competition for surface water is becoming severe and could ignite regional conflict. This chapter contributes to the ongoing discussion on rainfed agriculture by not only inventorying the available RWM technologies and practices that could be used by small-scale farmers under various drought scenarios but also reviewing the challenges of technology uptake. It suggests institutional arrangements and policy recommendations required to improve uptake of RWM interventions at local, national, and regional levels.

Keywords Interventions · Rainwater · Management · Uptake · Policy · Sub-Saharan Africa

26.1 Water and Agriculture in Sub-Saharan Africa

Rainfed agriculture, which feeds more than 90 % of the population in sub-Saharan Africa (SSA), will continue to play an important role in achieving food security and reducing poverty (Rockström et al. 2007). It is practiced under a wide variety of climatic conditions, with rainfall amount ranging from 300 mm per annum in the Sahel to 2,000 mm per annum in East African highlands. At the same time, recurrent drought and rainfall variability have been causing food insecurity, reduction of export commodities, and aggravated poverty, which are expected to worsen with climate change (IPCC 2007). The impact of recurrent drought has been already felt in East Africa in the past three decades (as recent as in 2011, Somalia) and reflected in terms of change in the length of growing periods, the onset of rainfall, seasonality, intensity, variability of dry spells, and subsequent crop failures and livestock mortality, each of which had implications on people's livelihoods. Even in good years, crop yield rarely exceeds 1.5 $\mathrm{t\,ha^{-1}}$ compared to 5–6 $\mathrm{t\,ha^{-1}}$ under dry but well-managed environments (e.g., Australia). The current yield level is 2–4 times less than the achievable yield (Rockström et al. 2007). With the majority of smallholder farmers depending on rainfed agriculture (green water), the consequence of recurrent drought on food security and livelihoods could be a disaster unless responsive adaption mechanisms are in place at farm, landscape, and basin scales. It requires an investment in the often untapped potential of upgrading rainfed agriculture (Sharma et al. 2006), using water as an entry point (CA 2007). Not only the current water scarcity but also the water needs of SSA for food and livelihoods would triple by 2025 (Rockström et al. 2004). On the other hand, 75 % of the additional food required over the coming decades could be met by bringing the production levels of the subsistence farmers up to 80 % of those of high-yield farmers, mainly through improved water management (CA 2007).

According to FAO (2009), the demand for water for farming, industrial, and urban needs in Africa in 2030 will increase by 40 %. Climate change is likely to intensify the current challenges of water scarcity and water competition within and between communities and nations, particularly in those countries linked by transboundary rivers. The ongoing debate between upstream and downstream countries, particularly Ethiopia and Egypt, in the use and management of the Nile River is a case in point. The threat of water scarcity is real, due to expanding agricultural needs, recurrent drought, and inappropriate land use (Amede et al. 2009a, b). IPCC (2007) indicated that climate change, mainly as a result of human action, is impacting SSA more than any other continent because its economies are largely based on weather-sensitive crop–livestock commodities and agro-pastoral production systems. The poor and vulnerable communities with low adaptation capacity will likely face the greatest risk. The negative effects are aggravated by land degradation, poor water management practices, and limited institutional capacities to store and efficiently utilize the available water resources at various scales (Rockström et al. 2007; Wani et al. 2009).

On an annual basis, there is generally enough amount of rainfall in SSA to support full-season crops, but variability in temporal and spatial distribution calls for improved rainwater management (RWM). RWM system is an integrated strategy to systematically map, capture, store, and efficiently use runoff and surface water emerging from farms and watershed in a sustainable way for both productive purposes and ecosystem services (Amede et al. 2011). It has three major components namely water storage, water distribution, and water productivity. Interventions aim to decrease unproductive water losses (runoff, evaporation, conveyance losses, deep percolation) from a system, as well as improve the water productivity of the respective enterprises to increase returns per unit of water investment. In order to ensure yield increase and minimize drought risks in rainfed areas, the most potential strategy appears to harvest small parts of the available runoff and utilize it for supplemental irrigation at rainless critical crop growth stages (Sharma et al. 2006). There is a huge water loss that could be converted to productive use (Rockström et al. 2010). For instance, Derib et al. (2011) reported that in Woreta, the Blue Nile basin, the average canal water loss from the main, the secondary, and the field canals of a small-scale irrigation scheme was 2.58, 1.59, and 0.39 $l\,s^{-1}$ $100\,m^{-1}$ canal length, representing 4.5, 4.0, and 26 % of the total water flow, respectively. Most of this water was lost through evaporation and canal seepage, which could have been converted to productive use of the crop–livestock systems.

African farmers have been experimenting with various forms of indigenous land and water management practices (Critchley et al. 2006; Awulachew et al. 2005). Mati (2010) observed that the productivity and profitability of smallholder agriculture with water management technology increased crop yield levels by factors ranging from 20 % to more than 500 %, while net returns on investment increased by up to tenfolds. Also, it was observed that these gains were linked to poverty reduction, employment creation, and environmental conservation. In most cases, these practices reduce farmers' vulnerability to annual rainfall variability, increase agricultural production per unit of land, water, and labor investments (Mati 2010; Kajiru and Nkuba 2010; Gezahegn et al. 2006), enable communities to produce high-value enterprises in their farms (Hagos et al. 2007; Ngigi 2009), and strengthen collective action for broader land and water management (German et al. 2012; Amede et al. 2012). In fact, the greatest potential increases in yields are in rainfed areas, where many of the poorest rural people live and where managing water is the key to such increases (CA 2007). However, major trade-offs are forecasted in water use between agriculture and ecosystem services, including trade-offs between increasing food security on the one hand and safeguarding ecosystems on the other hand (de Fraiture et al. 2007; Bossio 2009), particularly in SSA.

Limited adoption of water management technologies in SSA costs farmers low crop yield, recurrent crop failure, livestock mortality and morbidity, continual expansion of farmland in search of fertile plots (commonly at the expense of environmental services), elimination of fallow periods, converting valley bottoms and wetlands to agricultural fields, and encroaching pasturelands and protected areas. Recognizing this challenge, the 2005 Commission for Africa report called for an improved water resources management (Wichelns 2006). Various authors have underlined the importance of rainfed management for reducing drought risks, improving agricultural water productivity, and increasing crop yield and food security (CA 2007; Awulachew et al. 2005; Wani et al. 2009; Rockström et al. 2007). The Challenge Program on Water and Food (CPWF) of the Consultative Group on International Agricultural Research (CGIAR) centers have been promoting RWM systems in the upper Nile basin through developing improved land and water management interventions, creating local and national innovation platforms, and assessing upstream and downstream interactions (Amede and Haileslassie 2011). This chapter contributes to the ongoing discussion on rainfed agriculture by not only inventorying the available RWM technologies and practices that could be used by small-scale farmers but also reviewing the challenges of technology uptake. It suggests institutional arrangements and policy recommendations required to improve uptake of RWM interventions at local, national, and regional levels.

Are there suitable RWM interventions to minimize drought effects? While acknowledging the presence of a wide variety of water management strategies in the continent, the following section presents selected RWM technologies and practices widely tried and validated in SSA for increasing agricultural productivity and minimizing drought risk. However, the effectiveness of these water management interventions varies depending on local circumstances (Kundzewicz et al. 2007; Gezahegn et al. 2006).

26.2 Rainwater Harvesting Systems

Lal (1991a, b) reported that the primary limiting factor for crop-yield stabilization in semiarid regions is the amount of water available in the crop rooting zone. Rainfall intensity in SSA could more often be greater than the infiltration rate and the soil water holding capacity, which triggers an overflow of runoff. Moreover, rainfall amount in most SSA countries is so low that rain and water control and management have very special place in the overall water availability and access. Rainwater harvesting (RWH) is about capturing and storage of seasonal excess runoff (Critchley et al. 1992;

Sharma et al. 2006) diverting it for household and agricultural uses using traditional or improved structures for possible farm, livestock, and household use. In SSA where rainfall amount is low and unpredictable, which is also predicted to decline further with impacts of climate change, rain water storage in farm ponds, water pans, subsurface dams, and earth dams is gaining prominence for supplemental irrigation (Ngigi 2009) and watering livestock. It is also an effective strategy to manage floods, particularly in high-rainfall areas. It could be used to satisfy water demands during dry spells and create opportunities for multiple uses (domestic uses or for human and animal drinking). This is particularly critical for eastern and southern Africa, where about 70 % of the land falls within arid, semiarid, and dry subhumid zones and periodic excess runoff is available.

RWH provides enough water to supplement rainfall and, thereby, increases crop yield and reduces the risk of crop failure (Oweis et al. 2001; Mitiku et al. 2006; Malesu et al. 2006) and also supplies drinking water for livestock. Enhancing and stabilizing crop yield and livestock production for farmers in these crop–livestock systems would encourage farmers to invest in RWH and accompanied nutrient management at plot, farm, and landscape scales. It has been also strongly promoted as a key strategy to improve water access in drought-prone agricultural systems (Critchley et al. 1992; Sharma et al. 2006; Mati 2010). Quantitative studies in a drought-prone district in southern Ethiopia (Alaba) showed that RWH improved the adaptation capacity of communities to recurrent drought (Amha 2006). Using RWH, farm households have started to diversify the cropping systems, introducing new vegetables and perennial crops, and increased their household income to invest on their farms as a result of water availability from the water harvesting ponds. Adopting water harvesting structures has improved irrigation access and impacted a considerable income improvement of households in the Sahel. There are many RWH technologies for which the farmer can survey, lay out, and construct using own labor at the farm level with minimum training and facilitation (Critchley et al. 2006). For climate change adaptation, the focus should shift to increasing water storages and supplemental irrigation of crops. This can be achieved by storing water in ponds, pans, tanks, and subterranean aquifers, including sand-bed storages. Some of these technologies are described below.

26.2.1 In situ Rainwater Harvesting

RWH includes in situ water harvesting methods that would concentrate soil water in the rhizosphere for more efficient use by plants. In situ water harvesting denotes that rainwater is conserved on the same area where it falls, whereas water harvesting systems involve a deliberate effort to transfer runoff water from a "catchment" to the desired area or storage structure (Mitiku et al. 2006; Critchley et al. 2006). Land and water conservation interventions on sloping lands include bench/fanya juu terraces, retention ditches, stone lines, vegetative buffer strips, contour bunds, and all activities that reduce loss of runoff water. They are primarily promoted to reduce soil erosion and to improve rainfall infiltration and conservation in the soil profile

(Bossio et al. 2007). The main limitation of these interventions includes high labor demands especially on very steep slopes where proper structural measures are required. Some level of training and site-specific design/layout is also needed. In one example from the Nile basin, Anjenie watershed of Ethiopia (Akalu and Adgo 2010), long-term terracing increased yields of barley by threefold. In contrast, cultivation on the steep unterraced hillsides had negative gross margins. Similarly, Vancampenhout et al. (2006) obtained positive results for the use of stone bunding on the yields of field crops in the Ethiopian highlands associated with increased soil water holding capacity. Fox and Rockstrom (2003) reported that the in situ RWH had a significant effect on grain yield, and by using this system in Burkina Faso they were able to increase the yield of the sorghum from 715 kg ha^{-1} to 1,057 kg ha^{-1}. Micro-basin water harvesting structures (half-moons, eyebrow basins, trenches) are also proven to be effective in improving production in degraded lands. Experiences from northern Ethiopia showed that these structures improved tree survival and growth significantly compared to non-treated landscapes (Derib et al. 2009). The seedlings grown on micro-basins were thicker, taller, and more productive than those grown on normal pits, implying the need to integrate tree planting with soil water management.

Some of these interventions are indigenously developed and used by communities in Africa for centuries, including the Konso tribes in southern Ethiopia and communities in Burkina Faso. Zai is a traditional practice developed by farmers in Burkina Faso and adapted widely in the Sudano-Sahelian zone for rehabilitating degraded fields, which have been eroded and completely crusted, with an infiltration rate too low to sustain vegetation (Roose et al. 1999). Zai pits lead to water and nutrient concentrations around the root zone (Amede et al. 2011). Roose and Barthes (2001) from an experiment in the semiarid Yatenga region of northern Burkina Faso (400–600 mm annual rainfall) showed that water harvesting by runoff concentration produced higher benefits, with even higher benefits when mineral fertilizer was applied. Similarly, in a different agroecology in eastern Africa, Amede et al. (2011) reported that Zai pits have significantly increased crop yield (up to 500 % for potato) including in high-rainfall hillsides, where runoff is very high but water infiltration is low because of slope and soil crust. The benefit was particularly apparent in outfields, where the management and application of farm inputs by farmers are limited.

Conservation agriculture is another intervention used to improve resource-efficient agricultural production based on an integrated management of soil, water, and biological resources combined with external inputs (Biamah et al. 2000; FAO 2008). Baron and Rockstrom (2003) also observed that maize yield can be tripled by employing conservation agriculture, which facilitates water infiltration and reduces evaporation. To achieve this, CA (Comprehensive Assessment) is based on three principles that are believed to improve the water holding capacity of the soil, reduce erosion, and enhance biological processes above and below the ground (FAO 2008; Giller et al. 2009). These are: (1) minimum or no mechanical soil disturbance; (2) permanent organic soil cover (consisting of a growing crop or a dead mulch of crop residues); and (3) diversified crop rotations. It is one of the most effective interventions to improve in situ soil water management (Biamah et al. 2000) and has been adopted by farmers in southern Africa, particularly by those who own only few numbers of livestock.

26.2.2 Water Storage in Ponds, Pans, and Underground Tanks

Ground-level storages offer scope for water harvesting for large areas of SSA. The water is used for drinking, livestock rearing, as well as for supplemental irrigation especially in the dry areas. Runoff harvesting could be done from open surfaces and paths, roads, and rocks, and storage could be done in structures such as ponds or underground tanks (Nega and Kimeu 2002; Mati 2005). Flood harvesting is done from valleys, gullies, and ephemeral streams as well as its storage in ponds, weirs, and small dams. Pans and ponds are particularly popular in community-scale projects, as they can be made cost effective using local materials and community labor (Malesu et al. 2006). The main difference between ponds and pans is that ponds receive some groundwater contribution, while pans rely solely on surface runoff. Thus, pans, which range in size from about 5,000–50,000 m^3 (Bake 1993), can be constructed almost anywhere as long as physical and soil properties permit. In areas where seepage is a problem, small storages can be lined with clay grouting, concrete, or geo-membrane plastics. Water harvesting with small storage ponds (Fig. 26.1) could make major contributions to household incomes and rural poverty reduction (Box 1). For instance, in Ethiopia, water harvesting and storage in small ponds for supplemental irrigation of vegetables and seedlings at Minjar Shenkora obtained average net incomes of US$ 155 per 100 m^2 from onion seedlings, while incomes from bulb onions provided equivalent of US$ 1,848 ha^{-1}, adding up to US$ 2,003 ha^{-1}, from onion crop alone (Akalu and Adgo 2010). In other studies, Gezahegn et al. (2006) and Nega and Kimeu (2002) assessed small-scale water harvesting technologies in Ethiopia and found that returns on investment were high and reduced poverty levels (Awulachew et al. 2005). The benefits of water harvesting go beyond water use for irrigation. Amha (2006) reported that households with RWH technology use more labor and seed but less oxen power compared with those households who have not adopted the technology.

In a recent case study, Bond (2012) reported that by investing in a water harvester, farmers are now able to irrigate crops through the dry period with the stored water. This allows them to achieve a bigger yield and to sell at a time when the price is good. One water harvester has increased the farmers' income tenfold. This has the additional effect of safeguarding the farmers' livestock, which are invaluable to the mixed-farming system (http://www.raw.info/latest/when-water-is-scarce). Moreover, strategic allocation of livestock watering points could improve livestock water productivity and increase returns per animal by up to 100 %. For instance, in the drought-prone areas of Ethiopia, reducing the distance of livestock walking from 12 km to 3 km increased milk gains by 250 l per lactation period per cow (Descheemaeker et al. 2011).

Fig. 26.1 Small ponds for supplementary irrigation in Ethiopian highlands

26.2.3 Small Earth Dams and Weirs

When larger quantities of water are to be stored, bigger dams are more appropriate. This could be in the form of an earthen dam constructed either on-stream or off-stream (Fig. 26.2), where there is a source of large quantities of channel flow (Gould and Nissen-Peterssen 1999). The volumes of water storage range from thousands to millions of cubic meters.

Due to the high costs of construction, earthen dams are usually constructed through donor-funded or government-supported projects. However, there have been cases of smallholder farmers digging earthen dams manually as in Mwingi District of Kenya (Mburu 2000). Earthen dams can provide adequate water for irrigation projects as well as for livestock watering. Low earthen dams, called "malambo," are common in the Dodoma, Shinyanga, and Pwani regions of Tanzania (Hatibu 2000).

It involves dam construction to collect water from less than 20 km^2 for a steep catchment to 70 km^2 for a flat catchment. Some of these are medium-scale reservoirs used for urban or irrigation water supply. Sediment traps and delivery wells may help to improve water quality but, as with water from earthen dams, it is usually not suitable for drinking without being subject to treatment.

Fig. 26.2 Small reservoirs in Burkina Faso

Box 1: Water Harvesting for Rice Production in Shinyanga, Tanzania

In Tanzania, farmers make excavated bunded basins, locally known as 'majaluba', which hold rainwater for supplemental irrigation of crops. This system is practiced in the semi-arid areas where rainfall amounts range from 400 to 800 mm yr^{-1}. About 35 % of the rice in the country is produced this way under smallholder individual farming Shinyanga, Dodoma, Tabora and the Lake Regions. In many cases, majaluba utilize direct rainfall, but sometimes, farmers combine the system with runoff harvesting from external catchments. Generally, rice yields are higher, attaining 3.43 t ha^{-1} with the use of harvested water for irrigation as compared to 2.17 t ha^{-1} obtained without supplemental irrigation. These systems have increased household incomes by 67 % from US$ 430 ha^{-1} without runoff harvesting to US$ 720 ha^{-1} with the technology (Kajiru and Nkuba 2010). The main constraint was that with or without runoff harvesting, the majaluba system is predominantly rainfed with water storage in the soil profile (green water). Consequently, climatic uncertainties and prolonged dry spells could adversely affect the system unless it is augmented by other storage infrastructure e.g. ponds.

Fig. 26.3 Terracing for soil and water conservation in Tigrai, Ethiopian highlands

26.2.4 Sand and Subsurface Dams

The semiarid zones of Africa are commonly subject to occasional but intense flooding during the peak rainy season, providing an opportunity for RWH. Where seasonal rivers carry a lot of sand (sand rivers or “lugga,” “wadi,” and “khor”), the sand formation can be used to store water for use during the dry season (Nissen-Peterssen 2000). The most convenient way to harvest water in a sand river is by either sand or subsurface dams. Local materials for construction are usually available and the only extra cost is that of cement and labor. It is a cost-effective method for providing water for drinking and irrigation. Because the water is stored under the sand, it is protected from significant evaporation losses and is also less liable to contamination. Another advantage of sand river storage is that it normally represents an upgrading of a traditional and, hence, socially acceptable water source. Nissen-Peterssen (1996) distinguished between three types of subsurface dams: (1) sand dam built of masonry, (2) subsurface dams built of stone masonry, and (3) subsurface dams built of clay. The construction of river intakes and hand-dug wells with hand pumps in the riverbank can further help to improve the quality of water.

26.2.5 Bunds and Ridges for Run-off Diversions

This involves runoff harvesting from land, roads, and paved areas and channeling it to specially treated farmlands for storage within the soil profile (Fig. 26.3). The cropped area may be prepared as planting pits, basins, ditches, bunded basins (majaluba), semicircular basins (demi-lunes), or simply ploughed land (Mati 2005; Ngigi 2003).

Storing rainwater in the soil profile for crop production is sometimes referred to as "green water" and forms a very important component for agricultural production (Box 1). The design of a run-on facility depends on many factors including catchment area, volume of runoff expected, type of crop, soil depth, and availability of labor (Hatibu and Mahoo 2000). The source of water could be small areas or "micro-catchments" or larger areas such as external catchments. The latter involves runoff diversion from larger external catchments such as roads, gullies, and open fields into micro-basins for crops, ditches, or fields (with storage in soil profile) including paddy production where the profile can hold water relatively well (Box 1). Water harvesters these systems are usually prepared in different shapes and designs, such as trapezoidal bunds, semicircular and contour bunds, planting pits, and T-basins, and has various types of channeling methods for the conservation of runoff (Critchley et al. 1992; Mati 2005).

26.3 Spateflow Diversion and Utilization

Spate irrigation or floodwater diversions involve techniques in which floodwater is used for supplemental irrigation of crops grown in low-lying lands, sometimes far from the source of runoff. Spate irrigation is primarily practiced in the dry countries of the northern Africa and the Sudano-Sahelian region (Franken 2005). It has a long history in the Horn of Africa and still forms the livelihood base for rural communities in the arid parts of Eritrea, Ethiopia, Kenya, Somalia, and Sudan (SIWI 2001; Negasi et al. 2000; Critchley et al. 1992). For instance, in Tanzania, spate irrigation increased rice yield from 1 to 4 t ha^{-1} under RWH systems (Gallet et al. 1996). Although spate irrigation has high maintenance requirement, its applicability is valid for large areas of the Sahel and the Horn of Africa, where other conventional irrigation methods may not be feasible. In terms of climate change adaptation, spate irrigation holds promise considering that rainfall events are expected to get ever more erratic with flush floods, which can be harnessed and used wherever possible. However, users of spateflow irrigation have to improve the local diversion structures, soil moisture management, field preparations, crop genotype, and land and water tenure. In the absence of surface flow, groundwater has also been used in some countries (e.g., Zambia) as an adaptation option to minimize drought effects (Kundzewicz et al. 2007).

26.4 Drip Irrigation

Micro-irrigation systems are designed to reduce water loss and improve water management using low-head, drip irrigation kits for smallholders (Sijali 2001). Many types of drip irrigation systems are in use in many parts of SSA (Ngigi 2008; Sijali and Kaburu 2008). The kits range from 20-liter bucket kits to 200-liter drums or mini-tank systems and operate at 0.5–1.0 m water head. A majority of them target market gardens and vegetable production. This type of irrigation integrates the fertigation for achieving high efficient use of water and fertilizers in crop production by bringing them at the right amount and at the right place. In an on-farm experiment in Niger, Woltering et al. (2011) found that total labor requirement on a 500 m^2 garden was on average 1.1 man hours per day for drip irrigation systems against 4.7 man hours per day for the Farmers Practice (water buckets). Returns on labor are at least double for drip against the other treatments. For instance, the returns on land from eggplant were found to be US$ 1.7 and 0.1 per m^2 for the drip and farmers practices, respectively.

26.5 Integrated Watershed Management

Farm innovations, including water harvesting, drip irrigation, precision agriculture, and conservation farming technologies, which aim at improving water productivity (increasing water use efficiencies), are generally applied at the field scale but fail to improve productivity due to the limited biophysical and socioeconomic linkages and missing interactions at the larger watershed or river-basin scales (Rockström et al. 2004).

Water scarcity is commonly aggravated by land degradation, deforestation, and expansion of croplands to vulnerable hillsides (e.g., the Kabale hillsides in Uganda, Rwenzori's in Rwanda, and the fragile Ethiopian highlands). Estimates from a national-level study in Ethiopia indicated that the total soil loss due to erosion is about 2 billion t yr^{-1} (FAO 1986), which is estimated to cause an annual onsite productivity loss of 2.2 % of the national crop yield (Bewket 2003). FAO (1986) has also reported that soil erosion was causing about 30,000 ha of croplands in Ethiopia out of production annually. The highest rate of soil loss occurs from cultivated fields estimated to be on an average about 42 t ha^{-1} yr^{-1} (Hurni 1993). These landscape-level land and water issues could be treated only through integrated watershed approaches.

Integrated watershed management, which is a strategy to manage agricultural landscapes taking into account the processes and interactions of naturally occurring biophysical resources, social institutions, and human activities (German et al. 2007, 2012), has been successfully used to improve landscape hydrology and minimize resources in East African highlands (Mitiku et al. 2006). It was also a strategy to address resources management issues that could not be addressed by a single farmer or a community, and to integrate different disciplines (technical, social, and institutional; Reddy 2000; German et al. 2007) or production objectives (conservation, food security, income generation) for improving livelihoods and ecosystem services.

Box 2. Watershed Management in Southern Ethiopia

Farmers in Areka, Southern Ethiopia rated soil erosion as one of the major landscape problems, decreasing productivity and increasing vulnerability to climate variability. Despite earlier attempts to curb soil erosion by the government and other development actors, there was little change on the ground until a regional programme called African Highlands Initiative (AHI) arrived in the district. The shortcoming of the earlier approach was that it was seen as imposed initiatives. AHI and Areka research centre, Ethiopia organized consecutive community meetings to create awareness and sought solutions together. Then soil bund was selected as practical solution for minimizing erosion and reducing removal of seed and fertilizer from the farmlands. Farmers' research groups (FRG), which were established to test interventions, were used to organize farmers and collectively constructed bunds, experimented on fodder crops and established by-laws for sustainable maintenance of the conservation structures. Farmers started to get more crop yield and dry season fodder for their livestock. This was further expanded by grazing management and landscape water management interventions, which has developed overtime as integrated watershed management programme, which is now used a learning site for the district officers and regional governments.

German et al. (2007) identified different forms of integration within a watershed namely (a) managing interactions between various landscape units and benefits of diverse landscape-level components (trees, water, livestock, crops, soils) and (b) adopting a multidisciplinary approach to integrate biophysical, social, market, and policy interventions. From the water management perspective, watershed management encompasses strategies that would decrease unproductive water losses (runoff, evaporation, conveyance losses, deep percolation) from a landscape and increase landscape productivity (increased returns per unit of water, land and labor investments) through adapting integrated and multidisciplinary approaches and facilitating interaction among various landscape components (Amede and Haileslassie 2011). Managing water at watershed scale brings an accompanied benefit of managing runoff, controlling soil erosion, and improving vegetative cover (Rockström et al. 2010). For instance, within watershed management interventions, there is a strong interaction between physical structures and vegetation management (WOCAT 2007) that may dictate the amount and quality of water in the landscape that could be used to minimize the effects of climate variability within a locality. Increasing the vegetation cover will result in higher biomass production, higher rates of converting locally unproductive water to economical and productive water use, and increased carbon sequestration at all levels, from farm to landscape scales (Amede and Haileslassie 2011). Better water and nutrient management using watershed approaches could capture more CO_2 from the atmosphere and contribute to mitigating many of the negative effects of climate change and increasing weather variability.

Some SSA countries, e.g., Ethiopia (Tigrai), have been achieving a considerable success in watershed management, mainly through the "SafetyNet" programs. This is a program designed to improve the food security of the poor while facilitating the engagement of the local communities in improving land and water resources through food/money for work arrangements. The institutional structures of the program heavily rely on the existing local arrangements including community representatives/leaders, disaster prevention committees, local byelaws, and local governments (Box 2). It also considers assets, income, and livelihood criteria for household selection and their ability to physically work. The work includes soil and water conservation structures, planting trees in degraded slopes, protecting landscapes from livestock grazing through "area enclosure" and creating local institutions to sustainably manage the landscapes. Although the success rates of adoption vary, the benefits of upper catchments protected in the late 1990s in selected sites of the Ethiopian highlands could be seen clearly. In irrigation schemes where extensive soil conservation was done, erosion and siltation have been considerably reduced—head works and canals continue to serve without the need for frequent maintenance (Awulachew et al. 2005). The greatest benefits are found in situations where physical measures were accompanied by innovations that bring short-term benefits in terms of fodder, fuelwood, water, and other resources. Introducing and promoting multipurpose legume trees, in farm niches including farm borders, soil bunds, and farm strips are becoming an important driver for sustainable watershed management (Amede and Haileslassie 2011). It increases the vegetation cover, minimizes erosion, and improves watershed functions. Farmers' groups were found to be effective approaches to identify farm and landscape niches where trees could be integrated in the watershed without competing with other enterprises (Box 2). Through implementing integrated watershed management, various water management technologies could be combined in a variety of ways at various scales ranging from covering one technology such as pits to combination of groundwater well, water harvesting, and drip irrigation.

26.6 Why RWM Interventions Are Not Widely Adopted?

Although most RWM interventions are technologically effective and proven to improve water access and productivity of small-scale farmers, it has worked only in certain localities, with few communities, commonly due to very strong financial support and external facilitation (Amede et al. 2009a, b). In a survey of nearly 15,000 household ponds (and a few shallow wells) in the Amhara region, Ethiopia found that only 22 % were functional, 70 % not functional, and the balance had been destroyed; this was attributed to major technical, social, and environmental problems (Wondimkun and Tefera 2006). Most often lack of uptake is not due to technical problems of the new options but it occurs because farmers are constrained in resources, which involves trade-offs with other activities from which the farmers generate their livelihood (Giller et al. 2009). Another bottleneck of uptake was targeting. Kassahun

(2007) and Segers et al. (2008) found that targeting is a problem: Women-headed and generally poor households were not benefiting from RWH ponds. Moreover, Merrey and Gebreselasssie (2010), after reviewing the wide range of literature in Ethiopia, concluded that low performance of water harvesting structures was related to differences in implementation strategies including top-down quota-driven programs, failure to identify proper location at farm and landscape scales, failure in design, huge water loss through seepages due to use of inappropriate base materials, open excess surface evaporation, and lack of water-lifting technologies.

Farm-level water utilization from groundwater or water harvesting ponds is commonly hampered by lack of water-lifting, affordable technologies (Namara et al. 2010). The main types of water-lifting device and the framework for consideration of appropriate water-lifting technologies depend on the supply side (technology specific) and demand side (place specific). The commonly used methods like the furrow and small-basin methods have higher water losses, while the improved water-lifting technologies (motorized pumps, wind and solar pumps) require the rarely available energy.

The net impact of RWM interventions on poverty may depend individually or synergistically on the working of these technologies (Namara et al. 2010) and institutional arrangement and policies to be able to reach wider communities. In general, scaling-up has remained to be a challenge for various reasons (Table 26.1; Amede et al. 2009a, b):

a. Scaling-up of land and water management technology is a resource- and knowledge-intensive duty, which requires the participation and serious engagement of multiple actors at various scales. It demands the engagement of technology developers, technology multipliers, traders, local policy makers, law enforcement institutions, and community mobilizers. Creating collective action and a functional partnership for promoting RWM practices remains to be a challenge.
b. Going to scale of RWM interventions is of less interest to politicians, while their priority is promoting fast-track technologies and interventions that would bring about immediate benefits, so that farmers will support their political campaign and win elections.
c. While farmers are keen to test and adapt technologies and good practices that would bring immediate benefits, RWM technologies commonly take longer time to appreciate the impact and reap benefits. Moreover, the benefits are usually visible more at landscape scales than at individual household scales. A farmer in Kaseko watershed in Uganda stated that “I have no time, no money and no interest to think about scaling up; if it works I will be very pleased in my farm; it is the responsibility of the officers to take it elsewhere” (personal communication).
d. RWM is a complex agenda that could not be solved by a single technology or practice. It requires linked technologies and flexible working approaches. Scaling this complex knowledge requires intensive engagement, resources, and time.

Table 26.1 Major RWM technology uptake barriers in SSA

	Major uptake barriers	References
1	Recurrent siltation by erosion, reducing storage capacity	Critchley et al. 2006; Gezahegn et al. 2006
2	Weak extension services to display evidence and create capacity	Merrey et al. 2007; Deneke et al. 2011; Amede et al. 2009a, b
3	Labor intensive for continual maintenance	Lundgren 1993; Mitiku et al. 2006
4	Reduce farm size, particularly in land-scarce countries	Negasi et al. 2000; Gezahegn et al. 2006
5	High initial and maintenance cost, particularly for large reservoirs	SIWI 2001; Hagos et al. 2007
6	Commonly small volume of water, high water loss	Ngigi 2008
7	Water not available during dry periods	Amha 2006
8	Lack of water-lifting facilities	Namara et al. 2010
9	Market incentives/disincentives	Bond 2012; Hagos et al. 2007
11	Lack of collective action, leadership, and local byelaws	German et al. 2012; Deneke et al. 2011; Merrey et al. 2007
13	Limited short-term benefits	German et al. 2007, 2012
14	Policy enforcement and support mechanisms	German et al. 2012; Merrey and Gebreselasssie 2010
15	Soil, crop, and location specific	Critchley et al. 2006; Awulachew et al. 2005
16	Unpredictable/depends on occasional flooding	Awulachew et al. 2005
17	Knowledge and information intensive	Ngigi 2003, 2008
18	Biomass shortage and associated low soil carbon (for in situ management)	Amede et al. 2012; Giller et al. 2009

26.7 What Type of Policy Interventions Are Required?

26.7.1 Developing Complementary Policies

Lack of enabling environment for sustainable management and use of water resources is another feature common to most African countries. There is an enormous stake in shifting the focus from relief to development, from short-lived and quick-impact objectives to long-term, all-encompassing, environmentally sustainable, and consciously monitored interventions. Recurring needs in recent years, such as in the horn of Africa, seemed to have made NGOs and community-based organizations (CBOs) to lose sight of long-term development objectives. There exists limited coordination role in guiding local organizations towards integrated land and water resources management (German et al. 2012). Generally, the existing sectoral policies within the African continents (e.g., food security, irrigation development, and watershed management) rarely integrate the broader development agenda (CA 2007). Comprehensive and integrated policies that consider water management at all scales are desirable to improve the productivity of water and minimizing recurrent drought effects by clearly understanding their interactions and trade-offs. However, the social engineering panaceas of the past 30 years in agricultural water management and use have failed to achieve their objectives (Merrey et al. 2007).

A review on organizations, policies, and institutions indicated that the organizational setup affecting agricultural water management stretches from national-level policy/strategy-making ministerial offices to local micro-planning and implementing offices (Merry and Gebreselassie 2010). In most countries, there are national policies that support water development for agriculture, albeit most countries are in the process of reviewing their policies. For instance, Mati et al. (2007) examined 78 policies from Eritrea, Kenya, Madagascar, Malawi, Mauritius, Rwanda, Sudan, Tanzania, and Zimbabwe that were deemed to have implications on RWM in these countries. However, these policies lack detailed implementation plans and the required personnel and investment to convert them to action. There is also very limited match between policies of the respective countries in terms of use and management of the common land and water resources (Mati et al. 2007).

At a local level, community institutions within a landscape would include traditional water master, modern water user associations (WUAs), and water cooperatives (Deneke et al. 2011). In some cases, these different organizations exist side by side and play competitive roles. Strengthening community organizations to manage and use water efficiently has been proved to be an important policy strategy to sustainably use water resources (Amede et al. 2012).

26.7.2 Repair Institutional Disconnect

A review of various water-related policies in SSA (Mati 2006) showed that there is no specific policy document that addresses water management in its broad sense in any of the nine countries. Instead, existing policies had statements on water management scattered across different ministries or sectors. The scattering of RWM issues across several sectors had resulted in unavoidable overlapping of policies, duplication of efforts, and inefficient use of resources, as well as the lack of clear ownership of critical issues (Merrey et al. 2007; Mahoo et al. 2007). A wider policy and investment arena needs to be opened by breaking down the divides between rainfed and irrigated agriculture and by better linking the various commodities and practices to water management (CA 2007). This calls for supporting SSA countries in their efforts to fast-track their policy reforms and improve their infrastructural and institutional frameworks so as to make them responsive to dwindling water resources (Mahoo et al. 2007) by adopting suites of RWM technologies. Indeed, there is also institutional disconnect between research and development, and lack of institutional arrangements that may recognize the complexity of resources degradation and drought management. A new approach is highly needed, which will place poor men and women farmers at the center of the natural resources management. This also demands wider interaction and mutual collaboration among key stakeholders at local and higher levels through action research (Amede et al. 2009a, b). These positive impacts could be realized if water management policies align with investments on market infrastructure.

26.7.3 Introduce Incentive Mechanisms

In the agricultural water sector, technology uptake has been constrained by many sources of market failure, including the existence of market monopolies (Merrey et al. 2007). Poor market opportunities are commonly identified as disincentives for improving the productivity of irrigation schemes and water harvesting structures (Hagos et al. 2007). Lack of functional market linkages and saturation of markets with similar seasonal agricultural products are two critical marketing constraints.

While the current capacity of farmers in most African countries is weak to financially sustain the operation and maintenance of water infrastructure, it is unsustainable to fully rely on funds emerging from governments or development partners (e.g., International Fund for Agriculture Development, IFAD, Asian Development Bank, ADB). This calls for strategies for additional income sources, including value addition of agricultural produces. Agricultural subsidies could also play an important role to support income generation by smallholder farmers (CA 2007).

Improved access to rural credit schemes also plays an important role in facilitating adoption of water management technologies (IFAD 2005). For instance, the Lesotho Agricultural Development Bank, Tanzania, which was established in the mid-1970s to extend credit to farmers, has played a very important role in facilitating adoption of livestock technologies (Amede et al. 2012). Microfinance schemes have been also expanding in Malawi, Ethiopia, Kenya, and other countries but the very high interest rate is repelling farmers from taking credit unless reliable markets assure them.

Water pricing in irrigation fields is a potential incentive to improve water-use efficiency and institutional performance at local and regional scales and create the sense of community ownership of water investments within the landscape. While building the local capacity in optimizing irrigation water use and effective distribution, water pricing is a key foundation for enhancing local capacity and improving irrigation efficiency and water productivity of agricultural systems (Molle and Berkoff 2007). In this modality, beneficiaries pay irrigation charges or fees for accessing water and related service—based on area sizes and volumes supplied. The fee could be used for water pricing to pay for extension, operation, and maintenance of infrastructure, covering costs of WUAs and modernization of the irrigation facilities.

26.7.4 Improving Rural Infrastructure

Many regions in SSA with water investments are not accessible during the rainy season. Intensified cropping requires fertilizer input, while diversification requires new seeds. The inaccessibility to these inputs can possibly impact the farm sustainability. In many cases, farmers are currently almost entirely dependent on the government for input delivery (Merrey et al. 2007). Construction of all-weather roads to improve market connectivity of remote areas would certainly increase market participation, enable the formation of collective cooperatives to increase produce volume, and improve negotiation capacity of communities in selling their goods and services (Gezahegn et al. 2006; Merrey et al. 2007). It will also help to avail rural credit for farmers to improve storage and marketing of produces at the time of their choice, particularly by linking producers and processors. Moreover, the expansion of mobile phone connectivity and radio stations to reach isolated highland communities would create local capacity, facilitate input–output markets, and link farmers to diverse livelihood opportunities including off-farm jobs.

26.7.5 Build Institutional Capacity

The major constraints affecting water management in SSA relate to policy and institutional capacity at local, country, and regional levels in planning, facilitation, and policy implementation (Mati et al. 2007). The current institutional arrangements in the Ministries commonly lack the required manpower and facility to be engaged beyond occasional workshops and management of donor funds. There is a need to establish strong national and regional water institutions, with multidisciplinary teams that could regularly support and capacitate irrigation and RWM experts at district and ward/kebele levels (Mati 2006). Moreover, the current extension support on irrigation agronomy is far from responding to farmers' needs. One key intervention promoted by some development partners (donors) is the establishment of farmer research groups to promote farmer-led research on key water management, pest and disease management, spot application of chemical fertilizers, management of perishable seeds and related issues. This is best done through the support of the agricultural research institutions. The participatory experimentation would give farmers and practitioners opportunities to try out interventions and develop water, crop, and livestock management skills. However, the challenge requires a more comprehensive approach than the "educate-the-farmers" attitude (Merrey et al. 2007).

26.8 Conclusion

While the potential effect of recurrent drought, climate change, and variability on rural livelihoods and the national economy in SSA is well established, there is very limited institutional capacity in the region to respond to these emerging drivers of change. Weak institutional linkages, sectoral police, and fragmented investments have affected cross-institutional learning, local action, and policy implementation in managing water resources for resilience economy. Moreover, where there are good water management experiences in the various parts of the continent, they are commonly inaccessible to the wider users. RWM strategy would enable communities and local actors to systematically map, capture, store, and efficiently use runoff and surface water emerging from farms and watershed in the soil, farm, and landscape for both agricultural and domestic purposes. It will not only increase production and productivity but also decrease unproductive water losses (runoff, evaporation, conveyance losses, deep percolation) from a system, as well as reduce potential negative effects on downstream communities and countries. It will be an effective strategy to manage the consequences of climate change (e.g., floods and drought) in the Nile basin and beyond by combining water management with germplasm, land, and vegetation management at landscape scales. RWM could satisfy water demands during dry spells and create opportunities for multiple use by capturing and storing water in the rhizosphere, and in the landscape. This is particularly critical for SSA, where about 70 % of the land falls within drought-prone arid, semiarid zones.

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Part VI

Transboundary Rivers, Water Sharing and Hydropolitics

Chapter 27

Impact and Benefit Study of Grand Ethiopian Renaissance Dam (GERD) During Impounding and Operation Phases on Downstream Structures in the Eastern Nile

Asegdew G. Mulat, Semu A. Moges and Yosif Ibrahim

Abstract The Government of Ethiopia has undertaken the implementation of the 6,000 MW Grand Ethiopian Renaissance Dam Project (GERD) located on the Blue Nile just upstream of the Ethiopian–Sudan border. The GERD has an active storage capacity of 60,000 million m^3 (million cubic meter) which is greater than the yearly average flow of 48,770 Mm^3, thus acting as a multiannual regulating reservoir. The objective of this chapter is to analyze potential impacts and benefits of GERD on Eastern Nile, mainly on the High Aswan Dam (HAD) and reservoirs in Sudan. Simulations have been based on monthly flow data considering specific series of years as representative of a possible near-future scenario during GERD filling and operation. For the GERD impounding stage, average sequences of inflows are selected according to a 6-year (planned period to fill GERD reservoir) moving average on HAD yearly inflows time series. The scenarios were evaluated by comparing the current situation (HAD alone) and with GERD. More regular and constant flows will be released to downstream of GERD. At the Sudanese border, peak flows on the Blue Nile are controlled and reduced by GERD (reduction of 85 % of the maximum monthly flow) while low flows are significantly increased (+ 300 %). Evaporation losses are reduced by 12 % comparing to the current situation. Egyptian irrigation water demand is always satisfied during the simulated period.

Keywords Easter Nile · Grand Ethiopian renaissance Dam · Water resource modeling · Reservoir impounding impact and benefit · The Nile River

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27.1 Introduction

The Nile represents a crucial resource for the economy of eastern and northeastern Africa. Water is a critical resource for all countries that share the basin. Water will be even more critical in the future as these countries face larger populations and, therefore, an even greater demand for water. Most part of the Nile catchment is located in the arid and semiarid region. Rainfall in this area is highly seasonal and the base flow contribution is also low resulting in the need for reservoirs to meet the agricultural demand during the dry season. El-Raey et al. (1995) identified water resources as one of the three most vulnerable sectors to climate change in the region.

The Nile River Basin has several water users that could face conflict with one another in the near future. The major water users are irrigation and hydropower. These uses have resulted in the commitment of a large percentage of the catchments' mean annual runoff. The intense agricultural practices and absence of reasonable and basin-wide water resources management have led to an increase in water demand competitions in the region.

The rainfall is highly erratic, and the population pressure on Ethiopia's land has made the system of extensive cultivation unsustainable. The seasonality of the flows in Ethiopia is very high. This means that very considerable regulation would be necessary for their full utilization. The upper Blue Nile is very rich in water resources. The annual runoff amount is more than 48 billion m^3 (BCM) that flows to the neighboring countries, contributing to 62 % of the Nile River water flow.

The water resources are, however, hardly used in Ethiopia for economic development and poverty alleviation in the basin. The total potential for hydropower generation in the basin is at about 13,000 MW, which is many times the existing installed capacity. One of these projects which have been undertaken by the Ethiopian Government is the implementation of the 6,000 MW Grand Ethiopian Renaissance Dam Project (GERDP) located on the Blue Nile just upstream of the Ethiopian–Sudan border and other hydropower projects at the upper part of GERD. The GERD has an active storage capacity of 60,000 Mm^3, greater than the yearly average inflows (48,770 $Mm^3 year^{-1}$), thus acting as a multiannual regulating reservoir. Therefore, it is necessary to assess the impacts and benefits of these projects during filling and operation. The objective of this analysis is to evaluate potential impacts on the High Aswan Dam (HAD) and reservoirs in Sudan. During impounding and operation phases, results of water resources management simulation without and with GERD are evaluated.

27.2 The Eastern Nile

There are two major basins within the Nile Basin. These two major basins are the Eastern Nile that is composed of Abay (Blue Nile), Tekeze (Atbara), Baro Akobo (Sobat), and the Nile Equatorial Lake that is composed of mainly Lake Victoria Basins and Sudd Swamp.

The Sobat River is a result of two main tributaries: the Baro River from the Ethiopian Highlands and the Pibor River from southern Sudan and northern Uganda. However, one of the main tributaries which join the Pibor River is the Akobo River (originating from the Ethiopian Highlands). The area of Sobat Subbasin is about 186,275 km^2. Many of the tributaries of the Sobat River tend to overflow and form large swamp areas when they reach the flat plains of Sudan; the river enters a marshy area and water is also lost to the Machar Swamps. Sutcliffe and Parks (1999) estimate the loss between Gambela and the mouth of the Baro at 2.8 BCM year^{-1}.

The Atbara River is the most northern tributary to join the Nile River. Its headwaters originate in the northwestern Ethiopian Highlands. The nature of the river is extremely torrential. The entire Atbara subbasin is quite large. It is estimated to be 166,875 km^2. The majority of the river discharge is derived upstream of the Khashm El Girba reservoir which was constructed in 1964.

The Blue Nile Basin (BNB) is characterized by highly rugged topography and considerable variation in altitude. The total area of the basin is 311,437 km^2, of which approximately 63 % is in Ethiopia and 37 % is in Sudan (Hydrosult et al. 2006). Rainfall varies significantly with altitude and is considerably greater in the Ethiopian Highlands than on the plains of the Sudan. The main rain occurs in the summer, between June and September. Interannual variability in rainfall is considerable and several consecutive years with below average rainfall is common. Rainfall in the region is highly seasonal and the Blue Nile possesses a highly seasonal flood regime with more than 80 % of annual discharge occurring in the 4 months from July to October.

The Dinder and Rahad Rivers are the main tributaries of the Blue Nile. They rise to the west of Lake Tana (Ethiopian Highlands) and flow westward across the border joining the Blue Nile below Sennar dam. They are seasonal streams and generally cease to flow during the dry season. They are nearly equal in length, about 750–800 km. The effective catchment areas of Dinder and Rahad are about 16,000 and 8,200 km^2, respectively. The average annual flows of the Dinder River is about 3.0 BCM, while for the Rahad River it is about 1.0 BCM, with a combined estimated annual average flow of s 4.0 BCM.

The upper catchment of the Blue Nile (Abay) extends from 7°45’ to 13° N and from 34° 30’ to 37° 45’ E. The Blue Nile is the most important tributary of the Nile as it contributes to about 60 % of the annual Nile discharge (Sutcliffe and Parks 1999). The Blue Nile leaves Lake Tana at Bahir Dar and flows to the southeast through a series of cataracts. The river then enters a canyon and changes direction to the south and then to the west and finally to the northwest forming a large open loop. Along its 940-km journey from Bahir Dar to Diem, near the Ethiopian–Sudanese border, the river is joined by several tributaries draining a large area of highlands in western Ethiopia. The main tributaries are Beshilo, Weleka, Jemma, Beles, Muger, Guder, Finchaa, and Didessa from the east and south and the Birr, Fettam, and Dura from the north and Dabus from the west. The elevation of the basin varies greatly from over 4,000 m in the headwaters of some tributaries to 700 m at the foot of the plateau.

The headwaters of all tributaries of the Blue Nile are in the highlands of Ethiopia. The bulk of their runoff (70 % on average), occurs between July and September. Among the tributaries of the Blue Nile, the Upper Blue Nile (Abay) (with drainage area 175,000 km^2) is the most important.

The highest point in Lake Tana is slightly above 1,800 meters above sea level (m.a.s.l.) and enters Sudan at a level of 490 m.a.s.l. at the border of the two countries. This has a gradient of approximately 1.5 m per km that is considered a very high slope. However, if we consider the whole reach from the highest point in the Ethiopian Highlands (4,250 m.a.s.l.) up to confluence at Khartoum (350 m.a.s.l.), the difference in levels is tremendous. However, on the contrary the average slope of the river from the Ethiopian frontier to Khartoum is about 15 cm per km, which is considered relatively flat.

27.3 Data Used

The Eastern Nile Technical Regional Office (ENTRO) is the main source for data. The major input data prepared for the model application were stream flow data at required points, irrigation water demand data for existing irrigation schemes, hydropower in the current state, and the future development.

27.3.1 Stream Flow Data

Catchment runoff represents locations in the model where water is introduced directly to the stream system. The hydrological analysis that will be undertaken during the study requires the collection and review of hydrometric data associated with the Eastern Nile River.

Historical hydrologic inflows were acquired from the WP II Stage I model. The five inflow locations into Lake Tana are Gilg Abay, Megech, Ribb, Gumara, and Tana ungagged flows. Inflow time series data from five tributary locations include Didessa, Dabus, Beles, Dinder, and Rahad. Incremental flows along the mainstream of the Blue Nile were extracted from a monthly flow spreadsheet from ENTRO. These monthly flows were developed through the scoping of the proposed reservoirs. These sites include Bahar Dar to Kessie incremental, Kessie to Karadobi incremental, Karadobi to Mandaya incremental, Mandaya to border/Renaissance incremental, Meleka, Kubur, Abara wade, Rahid, and Dinder. These incremental flows were available for the sites for the period from 1956 to 2003. They were developed from simple subtractions of mainstream gauges, therefore, incorporating flows from tributaries already known from gauged data. To maintain the maximum resolution of hydrologic inflows in the Blue Nile, flows from the first data set for the Didessa, Dabus, and Beles were subtracted from the corresponding incremental flows in the second data set and these tributaries were included in the model.

27.3.2 Water Users Data

The most common water use in the Nile River Basin is irrigation water demand. This activity is defined as a water user and added to the model as a water user node in the

Table 27.1 Irrigation water demand in Sudan and High Aswan Dam (HAD). (Source: ENTRO 2009, 2011)

Month	Sabo-loka (cms)	D/S Sennar (cms)	U/S Sennar (cms)	Gizira (cms)	Dongolo (cms)	Khashim (cms)	Jubial (cms)	HAD (BCM)
1-Jan	18.85	7.51	67.46	202.34	13.44	45.56	29.97	2.55
1-Feb	10.75	8.1	66.45	191.27	10.75	51.35	34.55	3.36
1-Mar	20.37	10.42	44.69	118.13	20.37	51.82	38.74	4.22
1-Apr	25.08	11.72	34.87	30.78	25.08	55.41	43.26	4.31
1-May	25.92	12.39	35.09	44.49	25.92	46.73	45.03	5.54
1-Jun	23.26	12.54	77.06	180.89	23.26	45.23	47.85	7.26
1-Jul	18.85	9.04	97.39	268.64	18.85	42.24	78.52	7.35
1-Aug	12.85	7.22	93.75	258.55	12.85	39.78	78.66	6.33
1-Sep	5.34	10.28	132.38	337.76	5.34	27.43	146.06	4.5
1-Oct	4.63	11.35	148.2	321.77	4.63	16.89	166.39	3.6
1-Nov	7.17	10.11	141.85	249.6	7.17	19.44	145.5	3.33
1-Dec	14.81	7.25	82.78	185.58	14.81	40.83	45.75	3.16

D/S downstream, *U/S* upstream, *HAD* High Aswan Dam

MIKE BASIN model. The temporal variation in the extraction of water is described by a time series file for each water user node. The temporal variation of return flow of water that is assumed not to be consumed at the water user node can be transferred back to one or more river nodes.

In the current situation, the water system retained for the purpose of this study will assume water requirements for irrigation purposes in Sudan and water requirements associated to HAD. HAD outflows aim to satisfy Egyptian irrigation water demand as priority over energy generation. A total of 55.5 BCM year^{-1} is allocated to Egyptian irrigation supply downstream of HAD. Sudan is allocated 18.5 BCM year^{-1} for irrigation supply.

This 18.5 BCM year^{-1} of water is tapped at two different points upstream of HAD in the water system model. A total of 9.3 BCM year^{-1} is deducted from the Blue Nile River to irrigate lands around Sennar; 9.17 BCM year^{-1} is deducted from the intermediary catchment (on the White Nile River and on the Atbara River). At HAD, as long as the water level is equal or greater than the minimum operating level (MOL) (147 m), water volumes for Egyptian irrigation are supplied at a monthly time step. The water volume allocated to Egyptian irrigation supply is previously turbined within the HAD installed capacity to generate energy. Table 27.1 shows irrigation water demands in Sudan and Egypt.

27.3.3 Hydropower Data

Hydropower generation is simulated by inserting a hydropower node and connecting it to a reservoir using the channel feature. Return flow back to the river is simulated by connecting the hydropower feature with a downstream river node. Hydropower

Table 27.2 Hydropower input data in MW. (Source: ENTRO power toolkit)

Merowe		HAD		Sennar		GERD		Rosaries	
Target	Installed	Target	Installed	Target	Installed	Target	Installed	Target	Installed
650	1,000	–	2,100	15	15	1,736	2,800	200	415

HAD High Aswan Dam, *GERD* Grand Ethiopian Renaissance Dam Project

data similar for each month are shown in Table 27.2. The time series file contains the following items:

- Target power demand and installed capacity (MW).
- Minimum head for operation of turbines. If the head (difference between the reservoir level and the tail water level) drops below this threshold, no water is routed through the turbines, regardless of power demand.

27.3.4 Reservoirs Data

Individual reservoir performance can be simulated for specified operating policies using associated operating rule curves. These define the desired storage volumes, water levels, and releases at any time as a function of existing water level, the time of the year, demand for water, and possibly expected inflows. Reservoirs can be inserted anywhere on the river branches except on river bifurcation nodes or the most upstream nodes. The reservoir dialog is used to describe the reservoir characteristics, operating rules, and upstream and downstream connections to users and control nodes are specified. Data required to simulate the reservoirs are available from the ENTRO power toolkit.

For the standard reservoir, the time series information required includes bottom, crest, spillway, top of dead storage, and minimum operation pool elevations; minimum and maximum valve releases; precipitation, seepage loss, and evaporation; and flood control and operational rule levels for any water users attached to the reservoir. Although not a time series, the height–volume area relationship describing the reservoir bathymetry is additional input information required by the model.

The Aswan reservoir characteristics required for the definition of the present water resources management of the Nile Basin are summarized here: normal water level (NWL) is 183 m.a.s.l. and the MOL is 147 m.a.s.l. The GERD water level is not constant during impounding; it varies from 560 to 640 m.a.s.l. However, during operation the NWL is 640 m.a.s.l. and the MOL is 610 m.a.s.l.

Losses/gains were placed at reservoir locations within the basin to account for reservoir gains due to precipitation and losses due to evaporation. These losses represent the difference between gross precipitation on the reservoir and natural losses due to evapotranspiration. Table 27.3 shows evaporation losses from reservoirs.

Table 27.3 Monthly net reservoir evaporation, mm day^{-1}. (Source: ENTRO 2011; Abbay Master Plan Study Sept 1998)

Reservoir	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
HAD	4.6	5.6	8.9	10.6	12.7	13.5	13.7	13.6	11.6	9.3	13.4	5.3
GERD	6.3	6.8	5.1	4.9	3.7	− 0.6	− 7.3	− 6.6	− 1.1	2.7	4.7	5.8
Khashim El-gibra	5.8	6.8	8.1	8.3	8.6	7.9	4.2	2.7	5.4	6.1	6.3	6.1
Jubil Aluia	6.1	8.1	7.5	7.4	7.4	7.5	3.8	3.7	4.5	4.9	5.8	5.7
Rosaries	5.8	6.4	7.3	7.4	6.1	2.1	− 0.9	− 0.8	0.7	4	5.2	5.6
Sennar	6	6.2	7.6	7.4	6.3	2.1	− 0.9	− 0.9	0.7	4.2	5.2	5.6
Merowe	6.4	7.7	9.5	11	11.8	11.3	10.1	9.8	10.6	9.9	7.7	6.6

HAD High Aswan Dam, *GERD* Grand Ethiopian Renaissance Dam Project

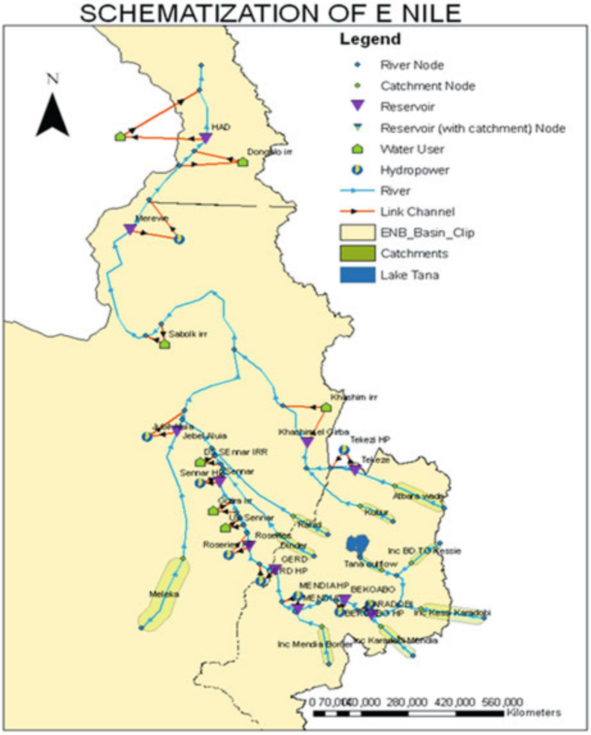

Fig. 27.1 Schematics of Eastern Nile River Basin

27.4 River Basin Modeling and Setup

The river system is represented in the model by a digitized river network that can be generated directly on the computer screen in geographic information system (GIS) software. The natural river system of the Eastern Nile River Basin was schematized and represented with a node–branch structure. A number of nodes and corresponding reaches were established based on the river network configuration (Fig. 27.1).

Branches represent the main river and its main tributaries and nodes represent major river confluences, reservoirs, and control points for off take. Off-take points were selected on the main river and/or tributaries to release water to cover downstream irrigation and hydropower water demands. In the simulation, only two major water demand sectors were considered, irrigation and hydropower.

There are four irrigation sites within the basin considered here. The major irrigation system in the basin is gravity flow (normally from reservoirs). The schemes were then allocated to the nearby nodes for their water withdrawals, and return flows from established schemes were directed to the immediate downstream nodes.

MIKE BASIN is a software developed by the Danish Hydrologic Institute (DHI). MIKE BASIN is an integrated water resource management and planning computer model that integrates GIS with water resource modeling (DHI 1997, 2001, 2003, 2008). MIKE BASIN addresses water allocation, conjunctive use, reservoir operation, or water quality issues. It couples the power of ArcGIS with comprehensive hydrologic modeling to provide basin-scale solutions.

In MIKE BASIN, the movement of water in and out of the river system is specified with time series data. Catchment, reach gain/loss, branches, reservoirs, and irrigation nodes require time series data in the model. The catchment node time series data are used to describe stream inflows. For each irrigation node, time series information is used to define irrigation demand, ground-water fraction (fraction of demand satisfied by ground water), return fraction (fraction of demanded water that returns to the stream at specified return locations), deficit carryover (in the event of a deficiency in the demand, the amount that can be made up in the subsequent time steps), and lag time (the linear routing of return flow from the irrigated fields back to the river).Reservoir nodes require physical characteristics and operational rules. At this phase, the Eastern Nile River Basin as represented in the schematization is populated with skeleton data sets, whereby all appropriate time series files have been created, formatted, and linked with the corresponding water users.

The following elements can be given as model input data (time series input data) for MIKE BASIN:

- Rivers represented by river reaches and nodes
- Catchment area
- Reservoirs
- Water users, including irrigation, represents any user that abstracts, consumes
- Returns surface and/or ground water
- Hydrologic information at different catchments as stream flow, rainfall, and reservoir

The first set of simulations investigates the performance of MIKE BASIN compared to the Nash–Sutcliffe coefficient (NS) and illustrates the effect of using calibrated parameters. Calibration and validation of the water allocation model (MIKE BASIN) were conducted to see the performance. The specific flow data without water abstraction were input data for the performance analysis of the model.

Model performance was evaluated with coefficient of determination (R^2). It is obtained by dividing the covariance of the two variables (observed and simulated

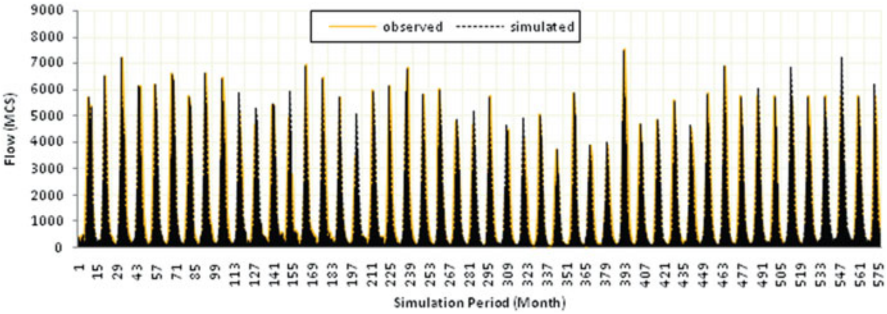

Fig. 27.2 Comparison of time series of simulated and input flow data at El Deim

data) by the product of their standard deviation. It ranges from $+1$ to -1. If R^2 is equal to 1, the relation between simulated and observed time series is a perfect linear relationship. If R^2 is equal to -1, the relation between simulated and observed time series is perfectly negatively correlated. Finally, if R^2 is equal to 0, both series are uncorrelated. Like for the Nash efficiency, the closer the R^2 is to 1, the more the model is accurate.

27.5 Result and Discussion

Simulation results consist of performance of reservoirs, hydropower units, and water balance at user nodes and river flows at each river node. Simulations have been based on monthly flows data considering specific series of years as representative of a possible future scenario. Simulations are realized at all reservoirs in future conditions (with GERD) based on monthly flows from January 1956 to December 2003. The model was used to simulate selected future scenarios. A baseline scenario is current state and the alternative scenario is considering GERD at filling and operation phases. The scenarios were developed using the demand data from 2020–2068 and simulated stream flow data from 1956–2003 assuming that a similar trend of stream flow situation will exist in the future. Agricultural demand and hydrological condition are assumed to be unchanged into the future. There is no restriction to meet water demand. There are two situations for discussing the impacts and benefits of GERD on downstream cascades, impounding period of GERD and operation modes of both reservoirs.

27.5.1 Calibration

Calibration was carried out by comparing the input data to the model with the results of the MIKE BASIN simulation at two sites (Eldiem and Khartoum) and the results are shown in the Figs. 27.2 and 27.3. The coefficient of determination is nearly 0.94 which shows good performance of the model.

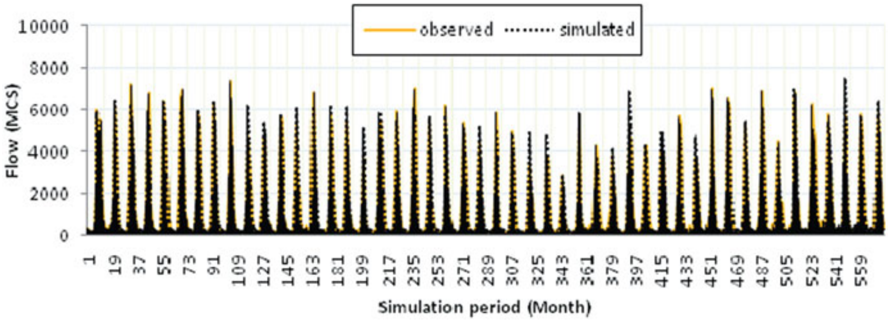

Fig. 27.3 Comparison of time series of simulated and input flow data at Khartoum

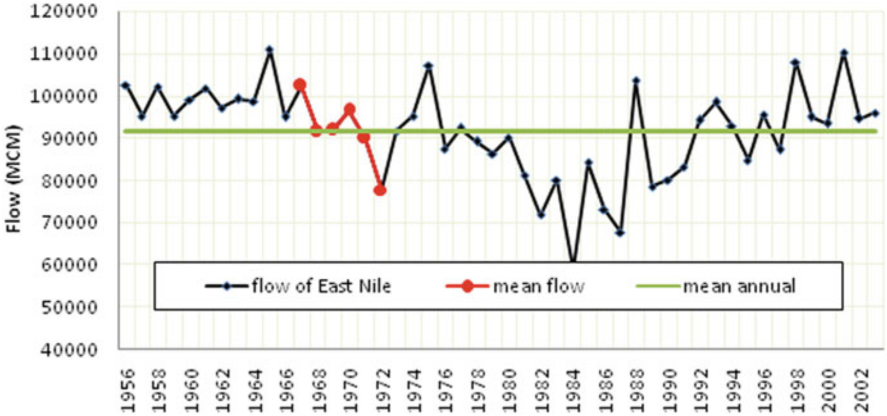

Fig. 27.4 Selected representative annual flows of Eastern Nile

27.5.1.1 Water Resources Management Simulation Studies During Impounding Stage of GERD

The impacts of GERD on downstream projects were simulated for mean sequences of Nile River flow data. Egyptian irrigation and Sudan water demands of 55.5 BCM $year^{-1}$ and 18.5 BCM $year^{-1}$, respectively (ENTRO 2009, 2011), were always satisfied during the simulated period. Volumes were distributed monthly in proportion to the current irrigation water use.

The normal case analysis for the GERD impounding stage and its downstream impacts and benefits on irrigation water demand and hydropower uses an average sequence of years of Eastern Nile flows. To select the sequence, the 6-year average curve on the Eastern Nile time series flow is used. The period of 6 years which presents the closest mean flows to the average Eastern Nile flows in the whole available period was selected. Figure 27.4 shows the selected sequence which is the period between 1964 and 1972. The average value of Eastern Nile flow during these 6 years has no difference (0 %) with respect to the mean value on the whole available time series (1956–2003).

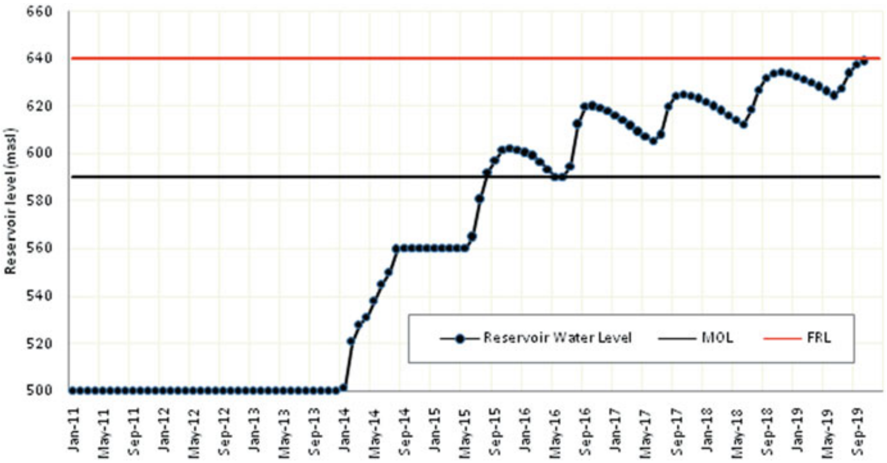

Fig. 27.5 Grand Ethiopian Renaissance Dam Project (GERD) water level during impounding

Thus, the reference case is based on a water management simulation modeled with a sequence of observed hydrological year's representation of the interannual inflows on all reservoirs. From the sequence of average inflows, the normal case assumes that the 2011–2013 flows are similar to the 1964–1966 flows from the available time series. During these 3 years, the GERD impounding stage will not start yet. The 2014–2019 flows are assumed to be equal to the 1967–1972 flows from the available series which corresponds to the sequence of average years. The water used for irrigation and hydropower generation starting from August 2014 with an MOL of 560 m.a.s.l. to August 2015 with an MOL of 590 m.a.s.l. were used for impounding of GERD.

27.5.2 GERD Impounding Results

Figures 27.5–27.8 summarize GERD impounding simulation results. As shown in Fig. 27.5, the GERD water level in the reservoir will reach 560 m.a.s.l. in August 2014 and can start generating energy and will reach its MOL (590 m.a.s.l.) in August 2015. Considering an average sequence of years, GERD water level will reach its NWL, or full reservoir level (FRL), (640 m.a.s.l.) at the end of 2019. Thus, 6 years may be required to fill GERD till its NWL. GERD minimum annual outflows during the impounding stage could be 26 BCM. Figure 27.6 depicts GERD inflows and outflows in million cubic meter (MCM) during impounding. Figure 27.7 depicts energy generation by GERD during impounding.

Energy generation will be limited during the impounding stage, especially in 2014 and 2015 because of the GERD water level (lower or close to the MOL). The evaporation loss from the reservoir will increase as the water level increases (Fig. 27.8).

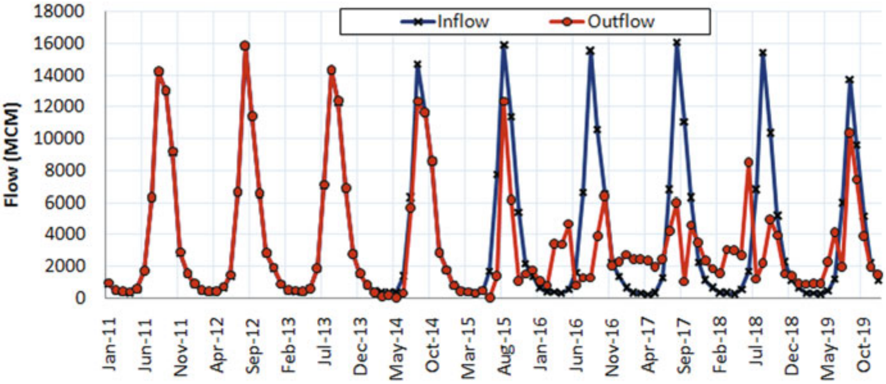

Fig. 27.6 Monthly inflow and outflow of Grand Ethiopian Renaissance Dam Project (GERD) during impounding

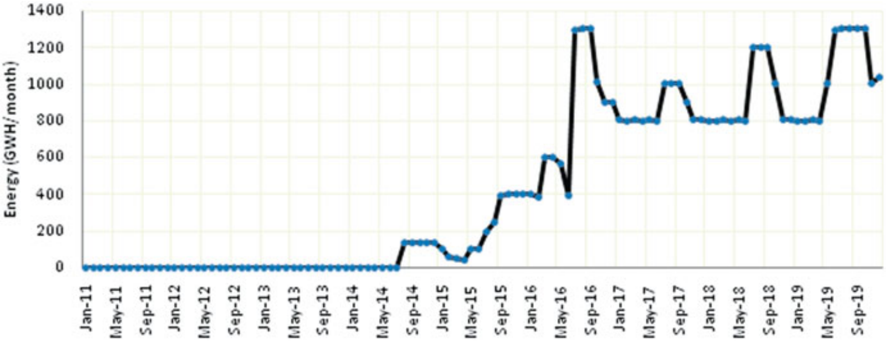

Fig. 27.7 Monthly generated energy of Grand Ethiopian Renaissance Dam Project (GERD) during impounding (GWh)

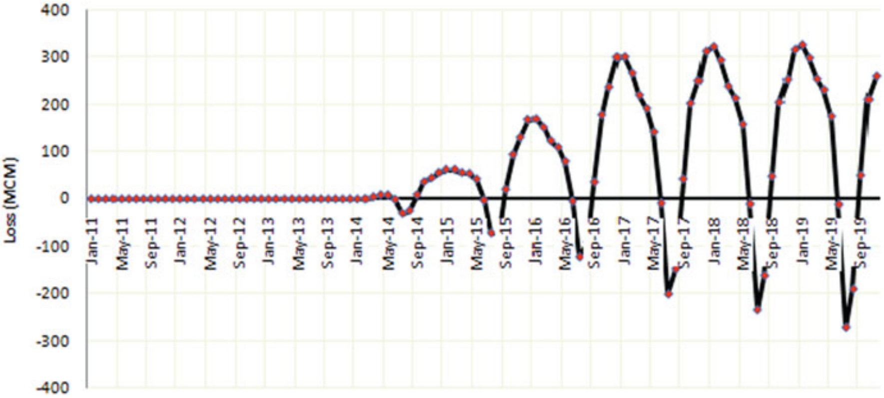

Fig. 27.8 Monthly loss or gain at Grand Ethiopian Renaissance Dam Project (GERD) during impounding

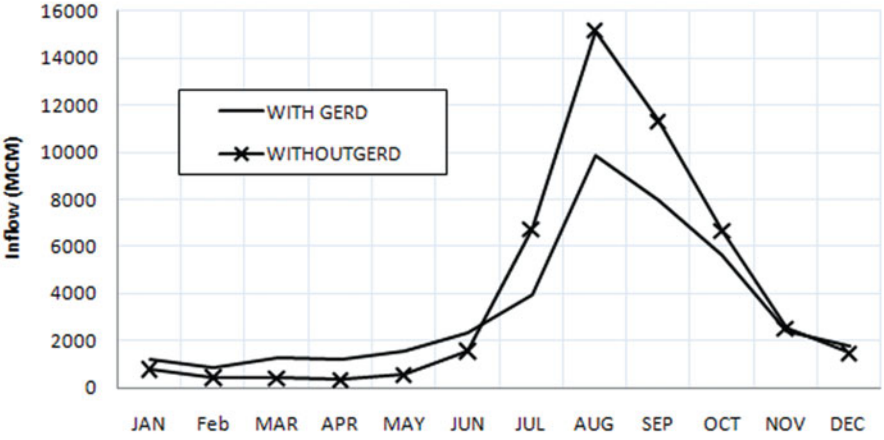

Fig. 27.9 Mean monthly inflow to Sennar reservoir during Grand Ethiopian Renaissance Dam Project (GERD) impounding million cubic meters (MCM)

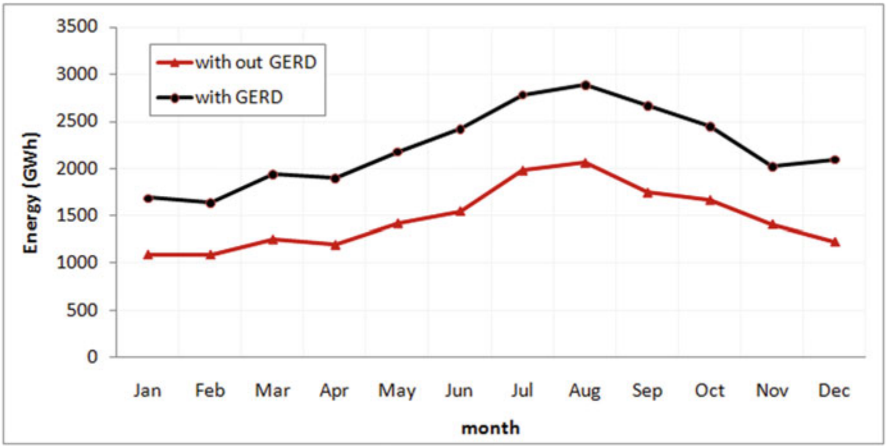

Fig. 27.10 Mean monthly cumulative Eastern Nile energy during impounding (GWh)

27.5.3 GERD Impounding Influence on Downstream Reservoirs

Figures 27.9–27.13 summarize downstream reservoir simulation results considering GERD to be upstream during its impounding period. Between January 2011 and January 2014, there is no storage of water in the GERD reservoir and this will not affect all the reservoirs located downstream of GERD. From January 2014 to June 2015, the HAD water level will be slightly affected (only 4.2 BCM will be stored in the GERD reservoir). From July 2015 to December 2019, the HAD water level will decrease because of GERD impounding. There will be full coverage of irrigation

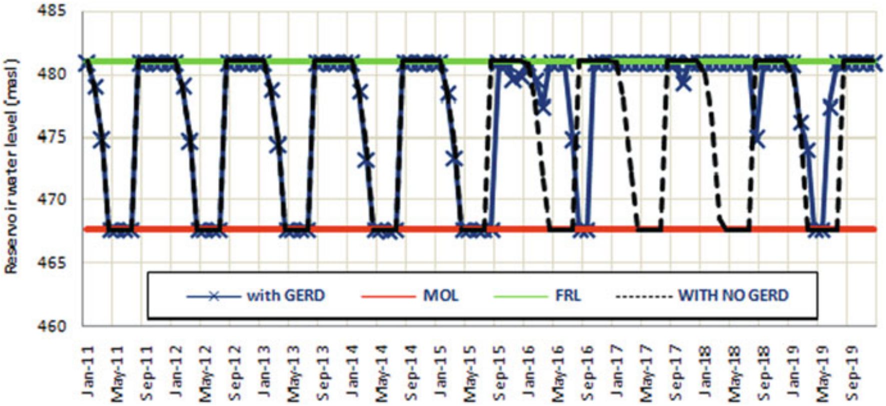

Fig. 27.11 Rosaries reservoir pool level during impounding

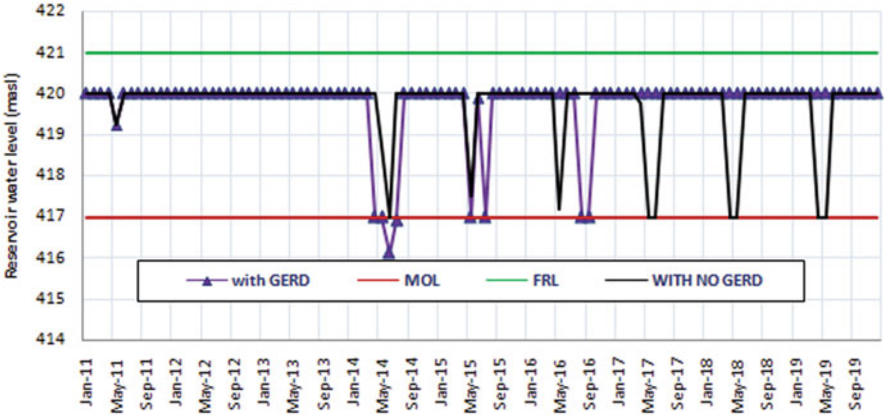

Fig. 27.12 Sennar reservoir pool level during impounding

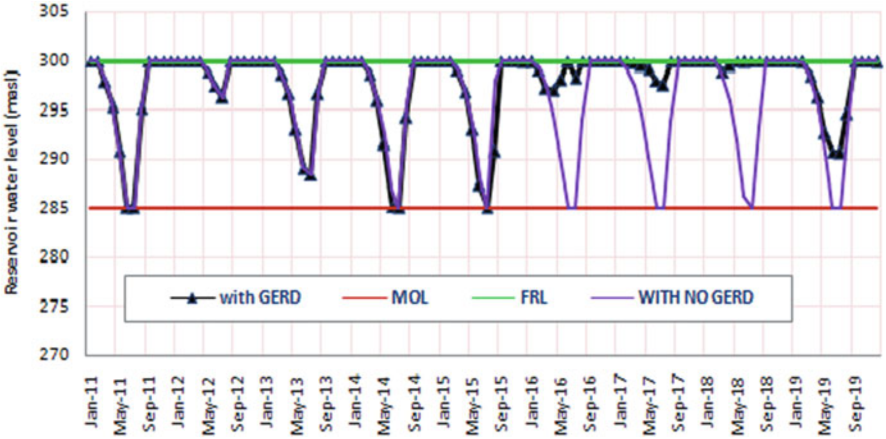

Fig. 27.13 Merowe reservoir pool level during impounding

Table 27.4 Water demand deficit during Grand Ethiopian Renaissance Dam Project (GERD) impounding with mean flow

	Number of months		Water deficit (MCM)		NS coefficient	
Irrigation site	With	Without	With	Without	With	Without
D/Sennar	2	0	0.53	0	1	1
Gizira	5	2	16	1.15	0.99	1
HAD	0	0	0	0	1	1

NS Nash–Sutcliffe, *HAD* high Aswan dam, *MCM million cubic meters*

water demand at HAD. Impounding of GERD has no impact on the other reservoirs which are located in Sudan; moreover, energy generation will increase.

HAD MOL (147 m) will never be reached. HAD annual energy generation will decrease from 3 to 17 % between 2015 and 2019 because of lower water level at HAD and consequent head reduction. HAD evaporation losses will be reduced in average by 18 % during the GERD impounding stage. Figure 27.9 shows a comparison of monthly average inflows into the Sennar reservoir with GERD upstream during impounding and without GERD. Dry season inflows to Sennar are higher and wet season flows are lower during impounding.

During impounding, the overall energy generation by the Eastern Nile will increase when compared to that without the GERD condition (Fig. 27.10). The elevations of the scenarios for Rosaries, Sennar, and Merowe reservoirs are essentially identical to the baseline due to the primary operational criteria being monthly elevation targets. As shown in Figs. 27.11, 27.12, and 27.13, the reservoirs' pool levels are maintained more regular. In addition, these reservoirs are minimally subject to shortages due to the high flows relative to the small storage volumes of these reservoirs; but even in the filling phase, they could get regulated flow. The inflow to these reservoirs will increase in dry months due to GERD being upstream (Fig. 27.9).

There will be 590 GWh/year energy uplifting in Sudan from the three reservoirs (Sennar, Rosaries, and Merowe) in the filling phase of GERD. The cumulative power generation and annual energy generation across all reservoirs or any subset of reservoirs provides statistics that can be compared across scenarios. Energy production in the Eastern Nile will increase by 4,860 GWh/year, which is more than 27 % of that without GERD. The cumulative energy generation during impounding is shown in Fig. 27.10.

Both scenarios' models assume the repeated patterns of future depletions of water at each irrigation node. The Sennar Dam is operated to supply direct diversions from the reservoirs. In addition, the Roseries and Sennar dams are operated to assure that demands are satisfied downstream. In the vast majority of the run, all demands are completely satisfied. The only instance that all demands are not met is for 2 and 5 months. These occurrences are within the accuracy of the model to represent actual conditions; therefore, the conclusion is that all demands assumed in the model are essentially met under both scenario conditions (Table 27.4).

Table 27.5 Inflow, outflow, losses, and energy production of GERD during operation phase

Month	Inflow (MCM)	Outflow (MCM)	Losses (MCM)	Total energy (GWh/month)
January	758	1,212	294	1,271
February	467	1,202	284	1,236
March	401	1,186	207	1,199
April	405	1,182	186	1,090
May	707	1,213	133	929
June	1,953	1,364	– 11	1,003
July	6,856	3,115	– 207	1,316
August	14,205	14,186	– 139	1,361
September	11,163	11,105	49	1,636
October	6,344	6,145	196	1,927
November	2,503	2,271	246	1,319
December	1,317	1,276	293	1,297
Annual	*47,081*	*45,458*	*1,532*	*15,583*

MCM million cubic meters

27.6 GERD Operation Simulation Results

27.6.1 Simulation Results at GERD Operation

GERD operation simulations are realized utilizing monthly inflows time series from January 1956 to December 2003. This is taken as a possible future hydrologic pattern and considering the GERD reservoir condition at the end of the impounding stage in the reference case (sequence of average years) in December 2019. The GERD water level is 639 m.a.s.l. and the water volume stored in the GERD reservoir is equal to 73 BCM.

As shown in Table 27.5, average annual GERD losses are equal to 1,532 MCM year^{-1}. Mean GERD water level during the operation simulation period is 615 m.a.s.l. It reaches its MOL (610 m.a.s.l.) 45 times in the simulation period. The minimum value (610 m.a.s.l.) mostly occurs in the months from April to July.

Annual outflows are equal to annual inflows once losses are deducted (approximately the difference in GERD water levels at the beginning and at the end of the simulated period). Compared to pre-GERD conditions, the monthly repartition of flows is modified with a smoothing effect; outflows decrease during the wet period (July to October) and increase significantly during the rest of the year. More regular flows are provided downstream of GERD (in Sudan and Egypt). The total energy generation is 15,330 GWh year^{-1}, with a firm energy generation equal to a guaranteed 95 % of the time.

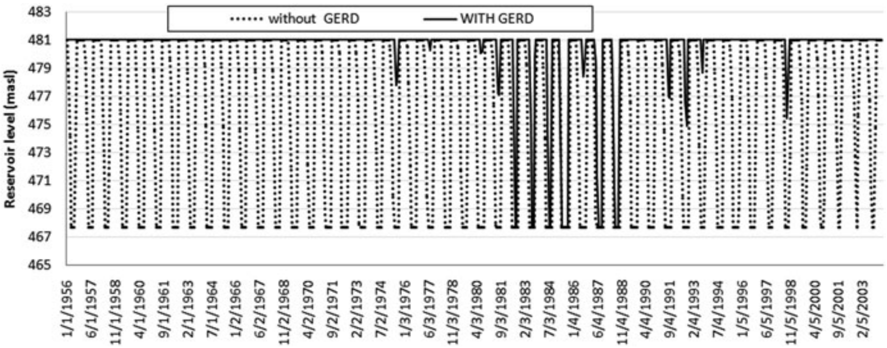

Fig. 27.14 Rosaries water level during operation of Grand Ethiopian Renaissance Dam Project (GERD)

27.6.2 Downstream Cascade Operation Simulation Results Considering GERD Upstream

Simulations are realized at downstream structures in future conditions (with GERD) based on historical monthly flows from January 1956 to December 2003. The irrigation demands have been simulated for the current irrigation demands. Current irrigation water demand results for the period 1956–2003 are taken as a possible future hydrologic pattern.

The fluctuation of water level is reduced compared to that without GERD simulation results. This is a consequence of the seasonal inflows regime regulation; more constant flows arrive at HAD all through the year. With GERD operating upstream, average annual HAD losses are equal to 14 BCM year^{-1} instead of 17 BCM year^{-1} in case of losses without GERD. Evaporation losses are reduced by 15 % comparing due to GERD. The Egyptian irrigation water demand of 55.5 BCM year^{-1} is always satisfied during the simulated period with more than 98 % performance (Table 27.4). This result highlights the benefit of GERD construction compared to the present situation.

HAD energy production will be around 7,381 GWh year^{-1}, that is to say 8 % less than the production considered without GERD. This reduction is a consequence of the average water level decrease at HAD, but it will be largely compensated by the additional energy produced by GERD.

GERD has no negative impacts on either of the Sudanese cascades; instead, in all reservoirs the inflow is more uniform, and the energy production increases. There is a significant increase in power generation for the reservoirs of Sudan. This benefit is the result of maintaining a higher level of consistency in the pool elevations of the Rosaries, Sennar, and Merowe reservoirs and reducing the inflows during the flooding period and hence reducing the probability of spills from the reservoirs (Figs. 27.14, 27.15, 27.16). There could be some improvement in satisfying irrigation water demand in Sudanese reservoirs (Table 27.4).

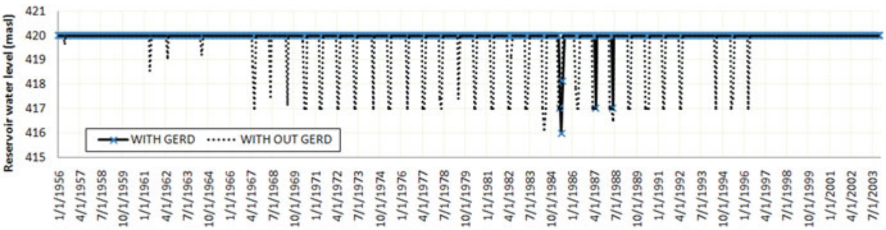

Fig. 27.15 Sennar water level during operation

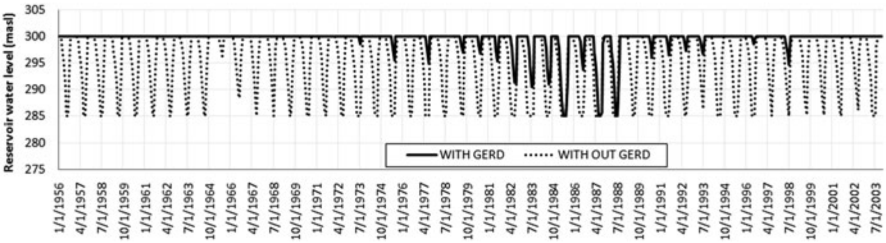

Fig. 27.16 Merowe water level during operation

Hydropower generation is a primary objective of the development of the Blue Nile Subbasin. The cumulative power generation and annual energy generation across all reservoirs or any subset of reservoirs provide statistics that can be compared across the two scenarios (Table 27.6). The cumulative energy generation in the Eastern Nile will increase by 108 % due to GERD being in operation (Fig. 27.17).

The GERD operation rules which will be applied in the future water management system will consider that the objective of GERD is energy generation. Energy will be generated satisfying the monthly demand as long as the GERD water level is above the MOL (610 m.a.s.l.). If the GERD water level becomes higher than 640 m.a.s.l., water volumes will be spilled downstream or possibly turbined (within the capacity of the installed power). Thus, to satisfy this objective of firm energy generation, GERD will turbine water at a rather regular rate all through the year. These operation rules will match the three countries' water uses requirements. In the Sudan, as it will be necessary to withdraw water downstream GERD, there will be no change in yearly water volume arriving from the Blue Nile. The major modification will concern the seasonal Blue Nile flows' distribution which will be more uniform along the year, therefore, beneficial to flood control in Sudan.

Figure 27.18 shows a comparison of mean monthly inflow to HAD under GERD and without GERD conditions. It is apparent that the GERD-modified flow has lower variation, with mean flow higher in the dry season and lower in the wet season. Figure 27.19 shows a comparison of mean monthly flow at Khartoum under GERD and without GERD conditions. It is apparent that the GERD-modified flow has lower variation, with mean flow higher in the dry season and lower in the wet season.

Table 27.6 Mean monthly energy production of downstream reservoirs (GWh/month) with and without Grand Ethiopian Renaissance Dam Project (GERD)

Month	HAD			Rosaries			Sennar			Merowe		
	Without GERD	With GERD	Difference (%)	Without GERD	With GERD	Difference (%)	Without GERD	With GERD	Difference (%)	Without GERD	With GERD	Difference (%)
Jan	392	358	– 9	144	299	107	11	11	2	484	707	46
Feb	503	463	– 8	131	289	120	10	11	4	468	599	28
Mar	619	571	– 8	66	282	329	7	11	53	453	604	33
Apr	623	584	– 6	34	266	685	7	10	38	408	589	44
May	795	739	– 7	51	237	367	10	11	5	313	581	86
Jun	1,027	938	– 9	128	246	93	11	11	0	292	582	99
Jul	1,007	930	– 8	296	290	– 2	11	11	0	492	687	40
Aug	867	817	– 6	305	305	0	11	11	0	736	732	– 1
Sept	658	603	– 8	303	306	1	11	11	0	732	738	1
Oct	543	488	– 10	302	305	1	11	11	0	727	735	1
Nov	505	455	– 10	257	303	18	11	11	0	622	729	17
Dec	480	434	– 9	157	301	91	11	11	1	517	725	40
Annual	8,019	7,381	– 8	2,174	3,430	58	123	131	6	6,244	8,007	28

HAD High Aswan Dam, *GERD* Grand Ethiopian Renaissance Dam Project

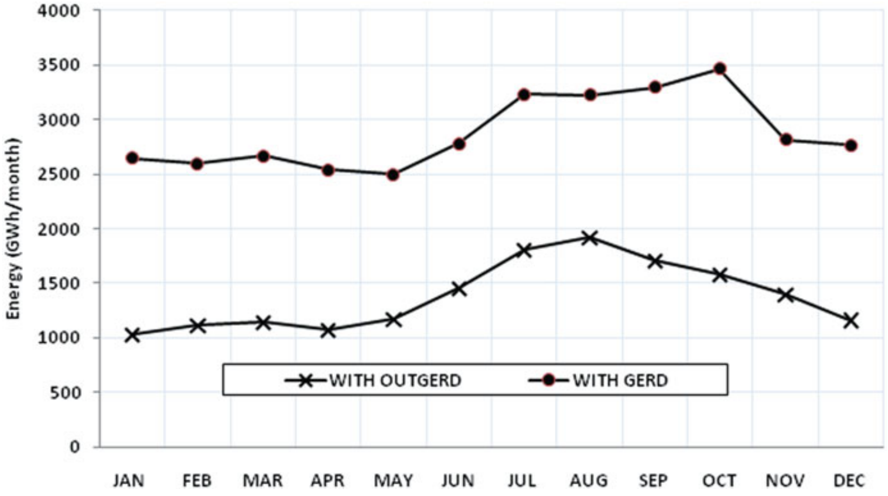

Fig. 27.17 Mean monthly Eastern Nile energy (GWh)

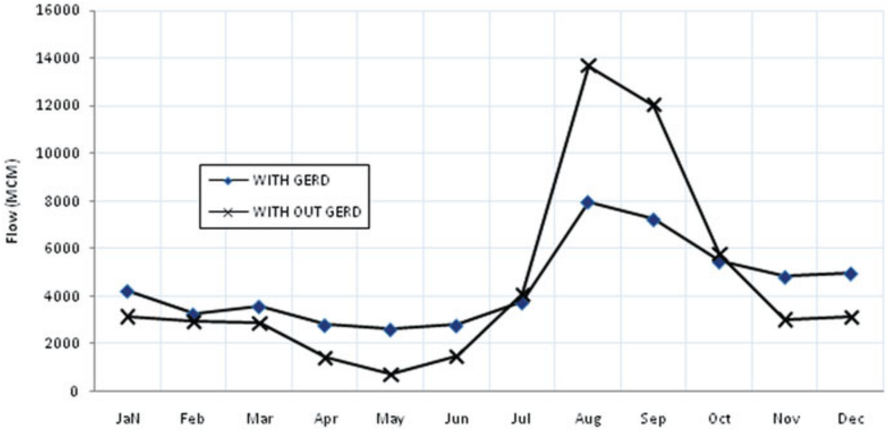

Fig. 27.18 Grand Ethiopian Renaissance Dam Project (GERD) impact on mean monthly inflow to High Aswan Dam (HAD) in dry seasons

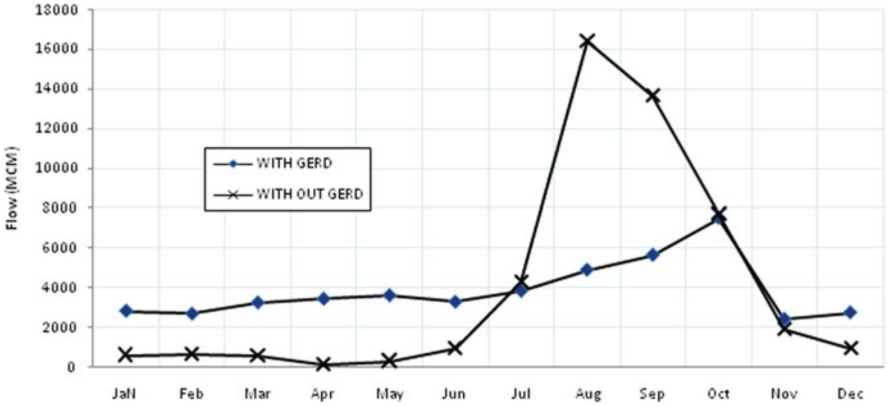

Fig. 27.19 Grand Ethiopian Renaissance Dam Project (GERD) impact on mean monthly inflow Khartoum in wet seasons

27.7 Conclusion

Simulations were undertaken to assess the impacts of GERD on downstream cascades during impounding and operation periods. All graphs and tables which are shown in the analysis section demonstrate changes in the Eastern Nile system. The changes have impacts and benefits in the system. Impacts and benefits are assessed based on the filling period and in the long run developments of the basin (operation of GERD), and by considering the local situations and by considering the basin-wide condition or the basin as a system. The impacts and benefits of GERD on downstream cascades are seen by comparing the changes on the water resource and water demand with and without GERD scenarios. The parameters compared are inflow to reservoirs, outflow from reservoirs, irrigation water demand deficit in Egypt and Sudan, energy generations, and losses of water from reservoirs.

Comparative analysis of HAD operation results for the current situation with GERD has some impact on the Eastern Nile Basin system. During the impounding period, the water level of HAD will decrease. Decrease in head (reservoir level) has impact on the energy generation, that is, energy will decrease by 9.2 % as compared to current situation. There will be no impacts of GERD on HAD in irrigation water demand requirements.

Reservoirs in Sudan will not be affected during filling of GERD. Since these reservoirs have less storage capacity, they are minimally subject to shortages due to the high flows in the current scenario. Due to this, they release little water in the dry months and the energy production is less as compared to the future scenario (with GERD condition). During the impounding of GERD, the amount of energy in the Eastern Nile will increase by 50 % (from 17,718 to 26,655 GWh year^{-1}).

Benefits and impacts of GERD operation on downstream cascades are also assessed based on the parameters indicated above (flows, water demand, energy, and loss). With its 6,000 MW installed power generation capacity, GERD will increase Ethiopian hydroelectric power generation. With GERD, the future hydropower production capacity will be more than four times the current Ethiopian available energy. The cumulative Eastern Nile energy generation will double. In the long term, once the GERD reservoir is filled, it will have positive impacts on downstream reservoir operation by releasing more regulated and uniform flow. There will be regulated inflows to HAD and Sudanese reservoirs due to the operation of GERD. Inflows to downstream reservoirs will increase from November to June (dry months) and decrease from July to October (wet months). The flow to these reservoirs will be more uniform as compared to the current scenario.

GERD construction will reduce HAD energy due to water level reduction in the operation simulation period; but at the same time, GERD will generate around 15,330 GWh year^{-1} which considerably increase the present production capacity of the whole Nile Basin.

The construction of new reservoirs in the Blue Nile results in two competing effects with respect to evaporation. The first effect is increased evaporation resulting from the proposed reservoirs while the other is reduced evaporation from HAD as a result of decreased inflows to the reservoir and evaporation rate difference. Egyptian irrigation and Sudan water demands of 55.5 BCM year^{-1} and 18.5 BCM year^{-1}, respectively, are always satisfied during the simulated period,

The reservoir levels have less fluctuation due to a better control of water release as a consequence of upstream flow regulation. Flood control in the Blue Nile will be better. The routing capacity (flood storage capacity) of the Nile River will be increased with the implementation of GERD. Such a routing capacity will also improve the flood control downstream of HAD.

There will be reduction of the risk due to hydrological variability with sequences of dry and wet years. Indeed, at the present time, excessive water may be spilled during a wet period at downstream reservoirs because existing reservoirs are already filled and, on the other hand, water demand failure can occur during a dry period. With GERD, the total storage capacity along the Nile River will significantly increase in the long term. Basin water management will be easier to optimize with higher storage capacity and upstream regulation capacities.

At least, it will offer the following benefits:

1. The possibility to optimize the water resources management at HAD.
2. The agricultural schedule may be reconsidered to optimize and improve the agricultural production.

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Chapter 28
Transboundary Rivers and the Nile

Wossenu Abtew and Assefa M. Melesse

Abstract The courses of the world's rivers in most cases are created by geological and natural factors regardless of political boundaries. Human activities such as dams and diversions have interfered with natural courses of rivers for the benefit of upstream and downstream settlers. As population and human knowledge of water resources exploitation increased, military, diplomatic, and legal actions have marked the history of many transboundary rivers in the form of occupations, treaties, and lawsuits. Some international conflicts include Nicaragua and Costa Rica on the San Juan River; USA and Canada on the Skagit River; USA and Mexico on the Colorado, Tijuana and Rio Grande rivers; Guinea and Mali on River Niger; and China, Cambodia, and Vietnam on the Mekong River. There are no uniform international water agreements on transboundary rivers as each river has unique and complex relations to interests within nations and between nations. As water becomes scarce, conflict on water will increase and controlling water will be part of a survival strategy. There is no water issue that does not include land. New political and military developments will grow out of the need to control the watershed and secure water. The Nile probably stands first with 11 nations and over 443 million people claiming it as theirs. The Nile countries are Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. Fragmentation of countries such as Ethiopia and Eritrea, Sudan and South Sudan, and rising autonomous regions within countries increases the number of claimants to the same water, thereby increasing the difficulty of getting into a water agreement.

Keywords Transboundary rivers · International rivers · Transboundary basins · Nile River · Nile countries · Water conflicts

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Table 28.1 Number of international basins and percentage of area in basin in 1999. (Extracted from Wolf et al. 1999)

Continent	No. of transboundary basins (% of area in international basin)
Africa	60 (62 %)
Asia	53 (39 %)
Europe	71 (54 %)
North America	39 (35 %)
South America	38 (60 %)
Total	261

28.1 Introduction

According to Wolf et al. (1999), as of 1999, there were 261 international river basins, covering 45.3 % of the land surface of the earth. One hundred forty-five nations have territories within international basins and 33 nations have more than 95 % of their territory within international basins. Since 1999, many countries in the former Soviet Union, Eastern Europe, and other parts of the world have emerged as independent nations creating more international river boundaries. Examples include the Amu Darya River basin in Central Asia. After the end of the Soviet Union in 1991, five new independent states emerged in Central Asia: Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and Turkmenistan. The river basins within the five independent states then became transboundary basins and each country began to follow its own priorities. Similarly, the Nile River basin in Africa has two new member states, Eritrea (1991) and South Sudan (2011). Twenty of the 25 largest rivers are transboundary, accounting for almost 50 % of the total flow of the world's rivers. Table 28.1 shows the number of countries within transboundary river basins in each continent and percent area in basin (Wolf et al 1999).

Eighteen basins are shared by more than five nations. International watersheds including numerous aquifers cover half of the globe land surface (Hamner and Wolf 1998). Forty percent of the world's population is in these basins (Young 1997). Big rivers of the world travel long distances with opportunity of crossing nations and several regions within nations. The longest river is the Nile traveling 6,650 km from East Africa to the Mediterranean Sea with watershed within 11 nations.

Nations sharing hydrological boundaries of surface and groundwater resources differ on sharing the water resources, and in some instances, this leads to conflicts. Differences in their socioeconomic development, capacity to manage water resources, infrastructure, political orientation, and institutional as well as legal contexts contribute to challenges for collaboration, coordinate development, and jointly manage the common transboundary water resources. Transboundary rivers and basins are usually associated with issues of equitable water use and conflicts associated with water rights and abstractions. Although sharing the same water resources at times when water availability is dwindling due to increase in demand, shrinking of recharge areas, land degradation, and nature-induced phenomenon as climate change is a challenge, countries have been trying to settle their differences on transboundary water rights. The rising human population and the water demand have been a major contributor to increasing tensions in transboundary basins. History has shown that dialogues and practical measures to ensure countries sharing transboundary river have a fair share of the water resources is the best and sustainable approach to settle transboundary water conflicts. There are countries that have also used linkage created by the transboundary rivers as an opportunity to collaborate and work together for the betterment of all with mutual economic development and cultural exchange and bondage. Table 28.2 depicts major transboundary rivers of the world and their attributes.

Justification for the competition for water rights comes through historical, riparian, legal, and authoritative justifications. Powerful upstream nations influence the terms of water share. Water resources in the Middle East are part of military and political goals (Gleick 1993). The Harmon Rule of 1895, stated by Judson Harmon, Attorney General of the USA is an example. Concerning the Rio Grande River use by the USA and Mexico, he gave opinion to the effect that a nation can fully exploit waters in its territory without regard to other riparian nations. Most of the big rivers of the world whether transboundary or not originate from stronger nations, economically and militarily.

The United Nations (UN) has attempted to develop laws or norms of international rivers shared water uses. According to Salman (2007), who has presented legal analysis on the Helsinki Rules, UN Water Courses Convention and the Berlin Rule concluded that there is no universal rule regulating shared water resources. At the same time, he acknowledged the efforts made by the International Law Association, by Institute of International Law, and the International Law Commission of the UN. Principles and rules formulated by these professional legal associations are not binding as they are not agreements and treaties ratified by nations. The earliest UN attempt was in 1959 (November 21) with resolution 1401(XIV) when the assembly dealt with the problem and possibility of codifying non-navigational uses of transboundary or international rivers. However, 3 months earlier (August 8, 1959), Sudan and Egypt signed an agreement on sharing the Nile water excluding the Nile source countries.

The Helsinki Rule formulated in 1966 by the International Law Association was based on equitably shared use of the drainage basin of one nation with riparian nations. In 1970, the UN general assembly assigned the International Law Commission to develop draft codes for non-navigational uses of international rivers. In 1994, the commission presented a draft to the general assembly, and it was adopted on May 21, 1994 (Resolution 51/229). Very good account of agreements and treaties concerning transboundary major rivers of the world and the Nile River in particular is given by Degefu (2003). The role of political economy of riparian states on success of having water-sharing agreements is presented by Song and Whittington (2004). They concluded that “Western civilization” nations are more likely to have international river treaties than countries in other civilizations. Fischhendler (2003) studied why climate uncertainties as droughts are not included in water treaties and concluded that sovereignty, water stress, optimism, and power asymmetry influence the agreement process. A detailed presentation of all international agencies involved in the area of transboundary river and their efforts is documented by Dixon (ATLIS, online-journal, http://atlismta.org/online-journals/human-security/global-water-sensitivity-of-transboundary-rivers/, Accessed 17 December 2012). Transboundary freshwater

Table 28.2 Major transboundary rivers of the world and their attributes

River	Countries/states	Upstream/ headwater	Major contributor	Average annual flow (billion m^3)	Issue
Colorado	Wyoming, Colorado, Utah, Nevada, Arizona, New Mexico, California, Mexico	Wyoming, Colorado	Colorado (86 %)	17.14	Equitable use, salinity in Mexico, California is major user
Columbia	Washington, Oregon, Idaho, Montana, Wyoming, Nevada, Utah, Canada	British Columbia, Canada	USA (85 %)	96.8	Highly engineered
Rhine	Switzerland, Italy, Austria, Liechtenstein, Germany, France, Luxemburg, Belgium, the Netherlands	Switzerland	Switzerland	63.1	Pollution
Nile	Burundi, DRC, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, Uganda	Ethiopia and Equatorial lakes	Ethiopia (80 %)	85.4	Equitable use, low flow, sediment, new demands
Senegal	Guinea, Mali, Mauritania, Senegal	Guinea		21.5	Water quality, sediment
Niger	Guinea, Côte d'Ivoire, Mali, Burkina Faso, Algeria, Benin, Niger, Chad, Cameroon, Nigeria	Guinea	Guinea	40	Seepage, evaporation losses, delta loss
Euphrates	Turkey, Syria, Iraq, Iran, Saudi Arabia	Turkey	Turkey	30.48	Equitable use, Turkey's dominance, upstream projects, vague agreements
Tigris	Turkey, Syria, Iraq, Iran, Saudi Arabia	Turkey	Turkey	50.9	
Mekong	Myanmar, Cambodia, Thailand, Laos, Vietnam, China	Himalayan Mountain ranges of Tibet	China	475	Increase in water demand, water quality
Ganges	China, India, Nepal, Bhutan, Bangladesh	India (Himalaya)	India (80 %)	365.8	Allocation between India and Bangladesh
Amazon	Brazil, Peru, Ecuador, Bolivia, Colombia, Venezuela, Guyana	Andes Mountain, southern Peru	Peru, Bolivia, Columbia	6,963.1	Sediment, flooding, deforestation, life of indigenous people

disputes database with 145 treaties is documented by Hamner and Wolf (1998). Thirty nine percent of the treaties are on hydropower and 37 % are on water consumption. Water treaties and conflicts are also documented by Wolf (1998).

28.2 Watersheds and Tributaries

A claim to waters of transboundary rivers is indirectly a claim to the watershed of the rivers and tributaries and, in many cases, territories of other sovereign states. The type of watershed or drainage basin that sustains transboundary rivers has importance when water is scarce. Without the watershed, there is no river. The realization of the need to directly or indirectly control the source of the Nile was documented as early as the 1800s and was part of the scramble for Africa. A very good detail of historical accounts of Africa's colonization and the Nile is given by Degefu (2003). Transboundary basins in Africa are depicted in Fig. 28.1 covering most of the continent. Rills, gullies, streams, rivers, and lakes feed into transboundary rivers as the Nile River. Snow-covered watersheds are different from rain runoff generating settled and populated watersheds. Any step taken at the watershed level will affect the quantity and quality of transboundary rivers. Watershed operations include soil conservation, afforestation, deforestation, infiltration/recharge, irrigation, ponding, dams, diversions, industrial development, urbanization, water supplies, etc. Figure 28.2a, b depicts a water harvesting pond, a survival effort of runoff collection in a dry area in the Nile basin and India, respectively. As Hasan and Elshamy (2011) remarked, the Atbara does not spring from a lake but totally relies on many small tributaries.

Autonomous regions within nations claim shares of international rivers, such as the case of the Colorado River in the USA; the USA, Mexico, and the seven Colorado River basin US states (Deluca 2010). Based on a 1944 water agreement between the USA and Mexico, Mexico receives 1.8 billion m^3 out of an average annual Colorado River flow of 20.2 billion m^3(McDonnell et al. 1995). The effect of severe droughts on river flow was not addressed during the 1922 water agreement of the seven states of the USA. Drought impact on water shortage was accommodated in 1944 by reducing Mexico's share as much as the reduction in consumptive water use in the US. Tribal water rights are 1.1 billion m^3. The seven states in the USA are in general divided into upper basin and lower basin with allocation of 9.25 billion m^3 for each based on a 1948 water compact. The upper basin states are Wyoming, Colorado, Utah, New Mexico, and some parts of northern Arizona. The lower basin states are Arizona, Nevada, and California. The tribe allocation has not been put to full consumptive use as current demand is low. When that happens, the impact on downstream flow is expected to be as much as a drought. Alabama, Florida, and Georgia in the USA have legal battle on the waters of the Apalachicola–Chattahoochee–Flint River system. Upstream, Georgian cities and farmers depend on water from the river system. Florida needs enough water downstream for its coastal environment and sea food industry. Amazon Indian tribes are resisting the Belo Monte dam on the Xingu River in Brazil to protect their land (Reuters, June 4, 2013). Water conflicts within a nation are as important as internation conflicts. Fifty nations in five continents are heading towards water conflict unless agreements on water sharing are

Transboundary Freshwater Dispute Database
Oregon State University 2009

Fig. 28.1 Transboundary basins of Africa

reached (Zeydan 2006). Fragmentation of nations will further increase the number of claimants and makes it harder to reach water agreements. The Senegal River in West Africa experiences the impact of two dams and a 3 % population growth in Senegal, Mali, and Mauritania. Climate change with increasing droughts and water pollution due to decrease in flashing out the river with floods has created undesirable changes. The Organization for the Development of The Senegal River was formed by the three riparian countries and Guinea, where the river originates. But Guinea withdrew from the organization later. The convention on March 11, 1972, declared that the Senegal River and its tributaries are "international watercourse" guarantying freedom of navigation and the equal treatment of users (UN 2009). The Senegal River basin represents both cooperation and competition. The Manantali dam in Mali is cooperatively managed by Maili, Mauritania, and Senegal for multipurpose including hydropower generation.

Fig. 28.2 **a** Water harvesting pond in the Nile basin with inflow and outflow structures. **b** Runoff collection pond in India with overflow weir

The Itaipu dam on the Parana River is built by Brazil and Paraguay and they share hydropower. Uruguay completely lies in the La Plata basin that is shared by Brazil, Bolivia, Paraguay, and Argentina. It is one of the most developed basins with 31 dams and 57 cities, having more than 100,000 populations. It is under stress from changing climate, population growth, land use change, urbanization, agriculture, and industry (OAS 2005). Ethiopia has 12 basins of which 9 are transboundary with three in the Nile basin (Arsano and Tamrat 2005).

The least considered question of transboundary rivers is the issue of excess water that flood downstream entities, and flood control obligations or no obligation of upstream entities. With increasing population and economic developments, land use changes, such as deforestation, urbanization, water control operations, and drainage system alterations, change the runoff pattern and volume. From 1985 to 2005, there were 175 flooding of transboundary rivers resulting in 37,000 lives lost, 210 million people affected, and over US$ 97 billion financial losses (Baker 2009). The flood magnitude scale of transboundary rivers was higher. Only 13 of 145 transboundary water treaties, 9 %, focus on flood control (Hamner and Wolf 1998).

Water quality of transboundary rivers is not always included in water agreements. A detailed study of water quality and transboundary river agreements throughout the world is given by Giordano (2003). The study shows most water treaties do not include water quality clauses. Out of 227 water agreements, only 27 % have reference to water quality and none of them included all the countries in the basin. An example of water quality issues being a concern for the riparian nations is the lower Mekong basin. Municipal and industrial wastewater releases from upstream have shown water quality degradation in the form of eutrophication, low dissolved oxygen, toxicity, and ecological changes (Hart et al. 2001). Lack of sufficient water quality data was cited as impediment to study the problem. For rivers shared by India and Pakistan, untreated sewage and salinity are water quality concerns (Alam and Yasar 2011).

28.3 The Nile River Basin

The Nile basin has the most number of riparian countries with a total of over 3 million km^2 drainage area (Fig. 28.3a, b). Seventy-three percent of the drainage basin is in the Sudan and Egypt with very little contribution of runoff. Ethiopia, with 12 % of the drainage basin, generates 86 % of the river year-round flow. The remaining 14 % comes from the White Nile. About half of the water generated by the equatorial lakes and watershed is lost in the Sudd marshes before the White Nile joins the Blue Nile at Khartoum. Detailed work on the hydrology of the Nile is presented by Sutcliffe and Park (1999). Varying flow numbers for tributaries of the Nile have been reported. Usually, period of records is not included. This may be one of the causes for the differences. Table 28.3 depicts mean flows of the Nile tributaries with the period of records extracted from Sutcliffe and Park (1999). The climate of the Nile reflects the latitude range (4° S–32° N) and the altitude range from sea level to over 3,000 m. The basin extends from Mediterranean climate at the mouth of the Nile to tropical climate at the sources of the Blue and White Nile. In between is a large area with

Fig. 28.3 **a** The Nile Basin (Source: USDA). **b** Equatorial Lake, source of the White Nile. (Source: USDA)

Fig. 28.3 (continued)

desert and semidesert climate changing into Savannah in South Sudan. Rainfall is influenced by the Intertropical Convergence Zone with moisture sources both from the Atlantic and from the Indian Ocean (Mohamad et al. 2005). Rainfall varies from 2,000 mm in the southwest region of the Blue Nile basin to almost no rain in the Sudanese and Egyptian desert. Detailed temporal and spatial rainfall variation over the Blue Nile basin is given in Abtew et al. (2009). The White Nile source region is wet with the Rwenzori Mountains with rainfall of over 3,000 mm and Lake Victoria region up to 1,600 mm.

The Nile basin countries, Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda, have a combined population of 443 million in 2012. The demand on the Nile is growing from population growth, climate change, and increase in per capita water demand. In 25 years, the population of the 11 Nile countries is projected to be 726 million

Table 28.3 The Nile flows. (Modified from Sutcliffe and Park 1999)

Watershed	Flow (km^3)
Blue Nile at Aswan	84.1
Atbara at Atbara	11.1
Blue Nile at Khartoum	48.3
White Nile at Khartoum	26.0
Sudd at Malakal	16.1
Sobat at Malakal	9.9

(Table 28.4). Stresses on the river are increasing from all the people that dwell in the basin. Tanzania's plan to pipe water from Lake Victoria, Ethiopian dams on the Nile, Uganda's hydropower dams, and Egypt's expansion of the use of the Nile as the New Nile valley (Toshka Canal), and the Sinai Irrigation Project are relatively recent developments in water demand. With a 1,000 m^3 per capita per year water demand, in 25 years, 726 billion m^3 is needed annually from all sources.

The colonial period agreements or treaties on the Nile water use were based on colonial or neocolonial interests and their legalities are questioned by upstream countries (Okoth-Owiro 2004). The 1902 frontier treaty between Ethiopia and the UK was a boundary treaty on the Sudan side in which Britain plugged a condition limiting the use of the Blue Nile, Lake Tana, and Sobat River. The treaty was written in English and Amharic with the two sides having different understanding. The 1929 agreement between Britain and Egypt favored Egypt solely for political and military interests of Britain. The 1959 division of the Nile water by Egypt and the Sudan does not include the Nile source countries, where most were colonies of Britain and Belgium. There are various colonial era protocols at different times that obligated Nile source countries that were under colonial powers. Most of the countries have

Table 28.4 Current and projected populations of Nile countries

Country	Population		Growth rate[a] (%)
	2012[a]	2037 projection	
Eritrea	6,068,495	9,736,900	2.418
South Sudan	8,260,490[b]	13,753,716	2.66[c]
Burundi	10,557,259	18,749,692	3.104
Rwanda	11,689,696	19,729,284	2.751
Uganda	33,640,833	62,235,541	3.4
Sudan	34,206,710	50,283,864	1.88
Kenya	43,013,341	69,294,492	2.444
Tanzania	46,912,768	80,338,115	2.85
Democratic Republic of Congo	73,599,190	121,052,268	2.579
Egypt	83,688,184	123,900,356	1.922
Ethiopia	91,195,675	157,312,539	2.9
Total	442,832,641	726,386,768	

[a] Source: 2012 CIA World Factbook

[b] Source: South Sudan Government (2008 census)

[c] estimate

Table 28.5 Treaties, agreement, and notes on the Nile River. (Most items extracted and modified from Degefu 2003)

Type of document	Date	Parties	Objective
Protocol	April 15, 1891	UK and Italy	Colonial partition
Treaty	May 15, 1902	UK and Ethiopia	Boundary with the Sudan
Treaty	May 09, 1906	UK and Leopold II	Secure Congo's flows to the Nile
Exchange of notes	December 1925	UK and Italy	Secure Blue Nile, Atbara, and Sobat
Business agreement	November 03, 1927	Ethiopia and U.S. company	Dam at Lake Tana
Exchange of notes	May 07, 1929	Egypt and Sudan	Division of Nile waters
Assurance	April 16, 1938	UK to Italy	Support Italy colonization of Ethiopia in exchange for securing the Nile
Agreement	November 08, 1959	Egypt and Sudan	Division of Nile waters
Agreement	1991	Ethiopia and Sudan	The ability to use Nile waters
Framework of cooperation	July 01, 1993	Ethiopia and Egypt	General cooperation
Nile Basin initiative	February 1999	Nile countries	Equitable utilization of the Nile
Cooperative framework	May 14, 2010	Five later six Nile countries	Equitable utilization of the Nile

invalidated the treaties, protocols, and notes upon gaining independence. The colonial setup of the Nile issue has resulted in a problem with no easy solution. The absence of water agreement which includes and satisfies all the riparian countries has led to unilateral efforts to use as much water as possible. Ungauged tributaries in populated areas may go dry first as survival will be the doctrine for sharing water. Details of past treaties and agreements on Nile water are given by Degefu (2003) and other legal scholars, with extracts shown in Table 28.5. Parties cite opposing legal doctrines to secure their interests. With the current rate of population growth and unfavorable climate change, the doctrine of survival may be the justification for water conflicts.

The Nile Basin Initiative (NBI) is a forum to create cooperative and mutually beneficial agreement between Nile Basin countries to equitably develop and use the Nile Basin resources and was launched in February 1999. The signatories are Nile Basin countries except Eritrea, which has opted for observer status. Eritrea's contribution to the Nile watershed is minimal. South Sudan was not a nation at the time. So far, achievements of this initiative supported mainly by the World Bank are listed as follows (http://siteresources.worldbank.org/EXTWAT/Resources/4602122-1213366294492/5106220-1234469721549/33.1_River_Basin_Management.pdf, Accessed 22 December 2012):

Fig. 28.4 Initial stage of water abstraction in a transboundary river basin

a. A forum to advance cooperation
b. A network for professionals
c. A foundation for river management
d. A means for investment for water development
e. A mechanism for capacity building
f. Building trust between Nile interest nations

Since the NBI was formed, upstream nations have asserted their rights for water, when at the same time, their needs have grown. The initiative has strengthened the rights of upstream nations for water use and brings to the surface the region's population growth, poverty, water demand, and potential conflicts. On May 14, 2010, five of the Nile upstream countries (Ethiopia, Kenya, Rwanda, Tanzania, and Uganda) signed an agreement on the Nile Basin Cooperative Framework. Burundi later signed in September 2010. The agreement has 44 articles where the principle of equitable water use by all riparian countries and no harm to others is the central principle. From upstream countries, the Democratic Republic of Congo and the downstream countries of Egypt and Sudan did not sign the agreement. The Nile Basin Commission is formed as a means to execute the agreement with its headquarter in Entebbe, Uganda.

28.4 Conclusion

Population growth, increase in water demand, and climate change are creating competition for water. Transboundary rivers, each with its particularity, are or will be a source of water conflict between riparian countries, autonomous entities within countries, and powers that initiate interbasin water transfer. The trend is food shortage and scramble for water in the watershed, which will result in reduced flows of rivers. Fragmentation of countries and the rise of autonomous regions within countries add to the number of claimants of transboundary rivers making water agreements more challenging. Figure 28.4 depicts initial stage of water abstraction in a transboundary river basin where subsistence farmers attempt to irrigate their fields. When modern machinery is used for water abstraction, the impact on river flow will be felt. Water agreements acceptable by all riparian states that include optimal water management and water conservation can delay conflicts on water and may provide time for new advancements in water resources development or water demand control.

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Chapter 29
International Water Law Principles and Frameworks: Perspectives from the Nile River Basin

Ryan Stoa

Abstract With the current body of international water law limited to customary principles and nascent treaty instruments, the potential for major transboundary water resources conflict is high. Nowhere is this more apparent than in the Nile River Basin. At about 6,825 km long, the Nile is the longest river in the world, sustaining the livelihoods of more than 180 million people in 11 riparian countries. And yet, the Nile River continues to flow without a binding cooperative management treaty or agreement. While the Nile Basin Cooperative Framework Agreement (CFA) may soon come into force, it lacks the support and participation of two of the largest players in the region, downstream Egypt and Sudan. Meanwhile, basin countries' interpretations of customary international water law highlight the inherent and predictable difficulties of reconciling the principles of equitable use and no significant harm. Considering the Nile River Basin's critical importance to the economic development of basin states, the absence of a binding cooperative management agreement places the Nile River Basin at risk of conflict and continued mismanagement. This chapter analyzes the legal status of Nile River Basin water allocations through the lens of contemporary international water law, a developing body of law struggling to resolve transboundary disputes such as those found in the Nile River Basin.

Keywords Equitable use · No significant harm · Customary principles · International water law · Nile River Basin Cooperative Framework Agreement

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29.1 Introduction

On June 3, 2013, Egyptian politicians—unaware that their statements were being broadcast on live TV—called for military action to be taken against Ethiopia. Ethiopia had begun diverting water for the Grand Ethiopian Renaissance Dam being built on the Blue Nile (one of two main tributaries of the Nile River), a move the politicians called a "declaration of war." Among various proposals, the politicians recommended sending special forces to destroy the dam, arming rebel groups opposing the Ethiopian government, and flying fighter jets over Ethiopian airspace as an intimidation tactic (Maher 2013). A week later, the then President of Egypt, Mohammed Morsi, made a televised speech to assert that all options were open to ensure that Egypt's water security remains intact. If Egypt's Nile River water allocation "diminishes by one drop, then our blood is the alternative," he declared (British Broadcasting Corporation 2013). In response, the Ethiopian parliament unanimously ratified the Nile Basin Cooperative Framework Agreement (CFA), with the Ethiopian Prime Minister, Hailemariam Desalegn, vowing that nothing would stop the dam's construction (Agreement on the Nile River Basin Cooperative Framework 2010; National Public Radio 2013). The dispute has raised an alarm in the international community, with both the United Nations (UN) and the African Union urging a peaceful resolution to the conflict.

The exchange between Egypt and Ethiopia is the most recent iteration of a centuries-long legal struggle over the Nile River Basin's water resources, an enduring regional conflict made increasingly complex by the ongoing political change in Egypt. Considering the critical importance of water resources to basin states in the face of widespread poverty and escalating conflict, the question naturally arises—how did we get here? Clearly, the developing body of international water law—including customary principles and nascent treaty instruments—has failed to prevent conflict in the Nile River Basin. This chapter analyzes the Nile River Basin in this context, providing a regional perspective of international water law's strengths and shortcomings. The chapter begins with an overview of international water law in its present form, examining the complex relationship between the principles of equitable use and no significant harm. A historical analysis of transboundary water resources management of the Nile River Basin is then presented to place evolving legal issues in a regional context. The chapter concludes with an assessment of international water law's contribution to Nile River Basin negotiations and prospects for cooperation in the region.

29.2 International Water Law: A Brief Primer

As with many natural resources and environmental issues, rulemaking on an international scale began in the latter half of the twentieth century. Previously, water resources were considered abundant, and allocation schemes were rudimentary and scarcely enforced. In 1966, however, the International Law Association (ILA) convened in Helsinki, Finland, to create the Helsinki Rules on the Uses of Waters of International Rivers (International Law Association 1966). The goal of the rules was to codify customary legal norms and principles, in addition to setting in motion further development of international water law. Given the preliminary nature of the endeavor, the Helsinki Rules were appropriately modest in their ambitions, establishing the groundwork for future action and establishing principles of water law that reflected prevailing notions of water resources management.

The most significant principle—that of equitable and reasonable utilization of water resources, or "equitable use"—was prevalent in many national legal settings and by itself did not present controversy. The principle of equitable use states that "each basin State is entitled, within its territory, to a reasonable and equitable share in the beneficial uses of the waters of an international drainage basin." In other words, states may use water resources as long as their use is reasonable and beneficial. Equitable use has since become a central pillar supporting the international water law regime by stipulating that a basin state has a right to the beneficial uses of the water resource. Not surprisingly, the equitable use principle is commonly invoked by upstream states that seek to make beneficial use of a watercourse. Even so, many downstream states recognize the need for states to make beneficial use of water resources within certain limits. Although the Helsinki Rules did not clearly define those limits, they represented an important first step in the development of international water law.

Thirty years later, the international community attempted to further solidify and codify international water laws and principles in the form of a binding treaty instrument. The 1997 UN Convention on the Law of Non-Navigational Uses of International Watercourses (United Nations 1997a) contains 37 Articles laying down basic norms of international water law. The cornerstone of the Convention, however, is Article 5, Equitable and Reasonable Utilization and Participation. Echoing the Helsinki Rules, Article 5 lays down the equitable use principle and affirms the concept of equitable participation to encourage states to resolve issues of equitable use jointly and cooperatively. However, the Watercourses Convention departs from the Helsinki Rules in one important respect: Article 7's obligation not to cause significant harm.

Standing in contrast to equitable use, the principle of "no significant harm" imposes a higher standard on basin states by requiring them to refrain from taking actions that would cause substantial damage to another state's water resources. The no significant harm principle prevents upstream states from using water resources—even if their use is reasonable and beneficial—if downstream states are adversely affected. This can be problematic in cases where, for example, an upstream state decides to make reasonable use of a transboundary river for sanitation purposes, to the detriment of a downstream state whose prior appropriations are diminished. Accordingly, the no significant harm principle is favored by the downstream states.

Presented in tandem, the relationship between the principles of equitable use and no significant harm is unclear without a declarative interpretation of how the two should or can coexist. Nonetheless, the text was adopted by an overwhelming number of states, with 106 votes in favor to only 3 votes against (United Nations 1997b).

This initial triumph is juxtaposed by the fact that without sufficient ratifications, the Convention has yet to enter into force, and therefore remains a non-binding treaty. To date, only 30 states have ratified the convention, with 35 needed for entry into force.

As a result, the International Law Association reconvened in 2004 to synthesize customary international water law in light of the Watercourses Convention and the development of international environmental laws since the adoption of the 1966 Helsinki Rules. The 2004 Berlin Rules on Water Resources contributed several layers to the development of international water law (International Law Association 2004). First, the rules extended the applicability of international water laws to waters that were purely national. The right of public participation, the obligation to use best efforts to achieve both conjunctive and integrated management of waters, and duties to achieve sustainability and the minimization of environmental harm are principles either new or modified vis-à-vis the Helsinki Rules and the Watercourses Convention, both of which restrict their scope to purely international watercourses.

Importantly, the Berlin Rules maintained the equitable use—no significant harm dichotomy, but acknowledged the apparent tension between the two principles by incorporating one into the other: "basin States shall in their respective territories manage the waters of an international drainage basin in an equitable and reasonable manner having due regard for the obligation not to cause significant harm to other basin States." Reconciling the two principles requires a case-by-case balancing test: While "vital human needs" are given priority, no other use is per se more preferable than another. In the absence of a sovereign body to oversee transboundary water resource conflicts, states are left to cooperate in good faith.

Since 2004, other international legal instruments have exerted some influence on the reasonable use–no significant harm debate. Lacking a binding treaty instrument governing all types of groundwater, the UN's International Law Commission produced the Draft Articles on the Law of Transboundary Aquifers in 2008 (United Nations 2008). The Draft Articles elucidate some relatively uncontroversial and forward-thinking principles governing transboundary aquifers, while reinforcing the dual principles of equitable use and no significant harm. Where the Draft Articles depart from previous understandings of international water law is in Article 3. Article 3 provides that each aquifer state has sovereignty over the portion of a transboundary aquifer or aquifer system located within its territory, in accordance with international law. The Special Rapporteur to the International Law Commission (ILC), Chusei Yamada, indicated that the inclusion of this principle (which does not appear in the Helsinki Rules, Watercourses Convention, or Berlin Rules) was a necessary concession to aquifer states that hold the view that aquifers are analogous to mineral resources and are governed by the principle of territorial sovereignty (Yamada 2011). The UN's Sixth Legal Committee convened in 2011 to determine if the Draft Articles were ripe for a binding convention. The Committee declined to move forward, calling instead for further study and exploration of the topic (United Nations 2010–2011). Nonetheless, the Draft Articles represent a recent and significant attempt to move forward with development of international water law.

Regional treaties and legal instruments can also provide insight into prevailing notions of international law. The United Nations Economic Commission for Europe's (UNECE's) (1992) Convention on the Protection and Use of Transboundary Watercourses and International Lakes, for example, is in force and ratified by 36 countries and the European Union. In 2003, the Convention was amended to allow ratification and participation from states outside the UNECE region, thus expanding the potential scope of the Convention. The UNECE Convention's legal foundation rests on the equitable use and no significant harm principles (as well as the principle of state cooperation) in a manner comparable to the 1997 Watercourses Convention, the Berlin Rules, and the Draft Articles on the Law of Transboundary Aquifers. Since the UNECE Convention has entered into force, however, it is binding on party states and significantly persuasive in the region. It remains to be seen how much broader its jurisdiction will become with the 2003 amendment.

After half a century of development, it is difficult to ascertain with any certainty how international law has resolved the inherent tensions between upstream and downstream states. While the most accurate conclusion likely holds that the principles of equitable use and no significant harm are complementary and operate in conjunction, in cases where the principles cannot be reconciled some observers conclude that equitable use has primacy over no significant harm. A primary argument to support this claim is that the International Court of Justice (ICJ) relied on the Watercourses Convention's equitable use principle to render its decision in the *Gabčíkovo–Nagymaros* case (Gabčíkovo–Nagymaros 1997), while scarcely mentioning the no significant harm principle. While instructive, the ICJ has yet to affirm the decision as reflective of a uniform priority between the two principles, and, of course, an ICJ decision is only binding on the states party to the case. Furthermore, the ruling makes it unlikely that a state invoking the no significant harm principle would agree to allow the ICJ jurisdiction over a factually similar dispute.

The sovereignty principle contained in the Draft Articles on the Law of Transboundary Aquifers also signals a move away from viewing water as a shared resource. On the spectrum of transboundary natural resources management principles, territorial sovereignty is even less restrictive on state action than equitable use, presumably indicating that international sentiment has shifted away from the more restrictive no significant harm principle. However, the fact remains that neither the Draft Articles on the Law of Transboundary Aquifers nor the Watercourses Convention has entered into force. At some point, stagnation in the treaty formation process becomes an outright rejection of the ideas contained therein. It is too early to make that claim here, but the apparent lack of progress does not provide confidence that basic principles are being accepted—or practiced—by nation states, and does not provide clarity with respect to the equitable use—no significant harm relationship. This is especially true if the relationship itself is a primary reason for the standstill.

Perhaps the strongest argument in support of the primacy of the equitable use principle is the notion that equitable or reasonable use doctrines are applied in—or supported by—an overwhelming number of bilateral and multilateral agreements, judicial bodies, and national policies. A 1994 report of the ILC concluded that: "A survey of all available evidence of general practice of States, accepted as law, in respect of the non-navigational uses of international watercourses... reveals that there is overwhelming support for the doctrine of equitable utilization as a general rule of law for the determination of the rights and obligations of States in this field" (International Law Commission 1994). In fact, other international environmental agreements have repeatedly asserted the right of states to reasonably exploit natural resources within their own territory. Given the climate of international environmental negotiations, it is unlikely that the states will welcome a shift away from territorial sovereignty.

Nonetheless, it is not clear how the foundational principles of international water law interact, especially in cases where an equitable use may cause significant harm to a downstream state. On some level, this ambiguity is intentional—each watercourse has its own individual characteristics, so international laws and principles must necessarily be broad and flexible. It seems likely that where a set of reasonable and equitable uses cannot be satisfied by the water resources of a watercourse, the necessary recourse is to balance the competing uses by weighing the relevant factors and circumstances involved. Many of the legal instruments described above provide a list of factors to consider, and, ideally, basin states will invoke the principle of state cooperation to amicably negotiate a binding agreement to resolve the matter. However, in the absence of a sovereign body with jurisdiction over conflicting states, the murky dynamic between the principles of equitable use and no significant harm will allow states in conflict to invoke whichever principle of international water law best suits their needs. As explained in the next section, that is exactly the path chosen by states in the Nile River Basin.

29.3 The Nile River Basin's Complicated Transboundary Management History

The Nile River Basin is a classic example of the upstream vs. downstream, equitable use vs. no significant harm dilemma. Egypt and Sudan—downstream states and historically regional hegemons over the basin—have long been in conflict with the upstream community of states in the basin, with much at stake. In all, 11 countries fall within the Nile River Basin, with a total population of 350 million. Many of these countries have considerable development challenges and rely on the social, economic, and environmental benefits of the Nile River's water resources—70 % of the basin's population relies on rain-fed agriculture for their livelihoods. As a result, there has been a reduction in soil fertility and dry season flows, while droughts and floods put vulnerable populations at further risk of food insecurity. As a result, the basin is viewed as one of the most degraded in the world, due to rapid population growth, poverty, natural disasters, political instability, and poor watershed management (Melesse et al. 2011). In this context, a regional interstate agreement or compact becomes a critical tool to addressing basin-wide water allocations. The following section provides an analysis of the Nile River Basin's complicated transboundary management history.

On a basic level, water conflicts in the Nile River Basin can be attributed to two simultaneous realities: (1) upstream states provide virtually all of the total flow of the basin's waters, and (2) downstream Egypt and Sudan have historically claimed the entire flow for their use. While tensions over the Nile's resources go back centuries, contemporary disputes have, at their root, the framework legal imprints of British colonialism. The thrust of most early agreements aimed to maximize downstream flows by preventing upstream states from disturbing the uninterrupted flow of water resources to Egypt without the prior consent of downstream Egypt, Sudan, and/or the British government. The 1902 treaty between Ethiopia and the UK, relative to the frontiers between the Anglo-Egyptian Sudan, Ethiopia, and Eritrea, for example, precludes the construction of any project that would alter downstream flows without the prior consent of the British and Sudanese governments (Treaty between Ethiopia and the United Kingdom, Relative to the Frontiers between the Anglo-Egyptian Sudan, Ethiopia, and Eritrea 1902). Similarly, the Nile Waters Agreement between Egypt and Britain (representing Kenya, Uganda, Tanganyika, and Sudan) (1929) categorically prohibits any engineering works which could jeopardize the interests of Egypt either by reducing water flows, water levels, or flow schedules. Both treaties invoke literal interpretations of the no significant harm principle.

Upstream states have rejected the legal validity of these agreements by claiming that because the agreements were imposed by British rule, upstream states were not party to the agreements and, therefore, not bound by them. Ethiopia rejects the 1902 treaty, for example, because it was not ratified by any of its government bodies, while Kenya, Uganda, and Tanganyika/Tanzania invoked the Nyerere Doctrine—giving the states 2 years to renegotiate colonial-era treaties before they become invalid—to reject the 1929 agreement (Salman 2013). Egypt's claims of enduring validity of the agreements rests on the principle of state succession, which transfers the rights and obligations of a predecessor state to a successor state. Those claims may have been weakened by the Vienna Convention on Succession of States in respect of Treaties (1978), which establishes that newly independent post-colonial states do not inherit the treaty obligations of their colonial predecessors. However, while Egypt is a party to the Convention, Ethiopia is the only upstream treaty member, precluding other states from enjoying its legal provisions. Meanwhile, when Ethiopia signed the 1902 treaty between Ethiopia and the UK, it was an independent state under the rule of Emperor Menelik II. Both agreements remain points of contention today.

Tensions reached a peak in 1959, when Egypt and Sudan created the bilateral agreement between the United Arab Republic and the Republic of Sudan for the Full Utilization of the Nile Waters, dividing the entire flow of the Nile River Basin to themselves (United Arab Republic and Sudan Agreement for the Full Utilization of the Nile Waters 1959). The 1959 agreement is understandably rejected by all other riparian states, who assert the principle of equitable use to claim that the agreement is an infringement on their rights under international law (in addition to the fact that they are not parties to the treaty).

Up to this point, the international agreements governing water resources of the Nile River Basin heavily favored downstream Egypt and Sudan by asserting the principle of no significant harm to the exclusion of upstream riparian states' potential right to an equitable use of the basin's waters. Accordingly, the agreements lacked consensus and legitimacy, and there was little cooperation between the upstream and downstream riparian states on matters of transboundary water resources management. Changes in the environment, support from intergovernmental institutions, and increased assertiveness from upstream states led to a slight, but significant, shift towards a cooperative management framework in the latter half of the twentieth century.

Initially, however, many of these initiatives were limited to bilateral agreements, technical knowledge exchange, and/or subbasin-level cooperatives (Mekonnen 2010). The most illustrative example is the Hydro-meteorological Survey of the Equatorial Lakes project, or Hydromet. Hydromet was created in response to unexpected rainfall and natural disasters in the Nile River Basin. While it provided a mechanism for transboundary cooperation, the project was limited to technical experts and knowledge exchange. Other attempts at cooperation included the Undugu initiative, an Egyptian-led communication forum, and the Technical Cooperation Committee for the Promotion of the Development and Environmental Protection of the Nile (TECCONILE), an initially technical and scientific body which gradually promoted legal and institutional reform.

While the regional or technical initiatives had their limitations, they were instrumental in laying the foundation for the Nile Basin Initiative (NBI). The NBI—officially established in 1999—is a framework partnership intended to formally convene the Nile River basin riparian states to engage in dialogue and work towards a permanent and binding management framework. With the enduring participation of ten riparian states (Eritrea is an observer) the NBI represented a significant shift towards cooperative management of the Nile River Basin. To this day, the NBI provides the basin with a robust intergovernmental organization with ongoing programs and administrative institutions.

The guiding philosophy of the NBI is stated in the Shared Vision: "to achieve sustainable socio-economic development through the equitable utilization of, and benefits from, the common Nile Basin water resources." (Shared vision program n.d.) The Shared Vision features prominently throughout the NBI's official documents, programs, and publications, and serves as the tagline of the NBI's official website. The significance of the shared vision should not be understated: The de facto mission statement of the most inclusive cooperative management framework of the Nile River Basin to date unequivocally embraces the equitable use principle, while the characterization of the basin's water resources as "common" refutes the notion that Egypt and Sudan have priority use to the entirety of the basin's flow.

Given the bipolar history of Nile River Basin negotiations, the existence of the NBI should be considered a remarkable achievement. It is broadly inclusive of the basin's riparian states, remains active through ministerial and diplomatic engagements and on-the-ground programming, and receives technical and financial support from a diverse donor base. Ultimately, however, the purpose of the NBI is to create and transition to a binding transboundary management agreement—namely, the Nile Basin CFA—that formalizes the NBI as an institution and clarifies the relationships and water rights of riparian states. By this measure, the NBI's record is decidedly mixed. While negotiations to conclude the CFA were initiated concurrently with the NBI's establishment, 14 years later the CFA is at an impasse—while six upstream states have signed the agreement, it has not entered into force and lacks the support of Egypt and Sudan. At the heart of the stalemate are disagreements over legal principles that merely reflect the long-standing disagreements between upstream and downstream riparian states.

On its face, the CFA largely reflects the legal provisions of the Watercourses Convention. Article 4 lays out the provisions of the equitable use principle, as well as a list of factors to be used in determining if a use is equitable and reasonable. Article 5, meanwhile, establishes the principle of no significant harm. However, where the Watercourses Convention is silent with respect to the interplay between the two principles (or, at best, relies on the principle of state cooperation to balance competing uses), the CFA makes an attempt at reconciling equitable use and no significant harm by creating a third legal principle—water security. The CFA defines water security as "the right of all Nile Basin States to reliable access to and use of the Nile River system for health, agriculture, livelihoods, production and environment." However, the application of water security as a legal principle could not be agreed upon. Article 14(b) of the CFA initially required states "not to significantly affect the water security of any other Nile Basin State." Egypt and Sudan, however, required the clause be amended to obligate states "not to adversely affect the water security and current uses and rights of any other Nile Basin State." Essentially, the concept of water security was used as a proxy by upstream states to reinforce the principle of equitable use, and by downstream Egypt and Sudan as affirmation of their preexisting claims to the entire flow of the basin based on the no significant harm principle. Disagreement over the appropriate application of the principle of water security—and by extension, the interplay between the principles of equitable use and no significant harm—has led to an impasse in negotiations.

While the dispute over water security is likely to be the greatest hurdle to full participation, other provisions of the CFA have contributed to the deadlock. Egypt and Sudan have called for robust notification procedures to be incorporated, in line with similar provisions of the Watercourses Convention. Upstream states are concerned that notification requirements will be construed as recognition of colonial-era agreements. Regarding amendment procedures, upstream states prefer a simple majority requirement, while Sudan and Egypt demand veto power. Even the definition of the basin itself is in dispute. Egypt seeks to broaden the definition to include all waters accumulating in the basin area, an interpretation that would render Egypt's water allocation claims from 66 % of the river flow (as established in the 1959 Nile Waters Agreement between Egypt and Sudan) to a more reasonable 3 %. The upstream states have yet to accept this interpretation (Salman 2013).

Despite the deadlock, the CFA has been signed by six countries (Ethiopia, Kenya, Rwanda, Tanzania, Uganda, and Burundi) and ratified by one (Ethiopia). Uganda is expected to become the second state to ratify, while upstream states South Sudan and the Democratic Republic of the Congo are presumed to follow suit on signature and ratification (Heuler 2013). If the CFA receives the requisite six ratifications to enter into force, the creation of the Nile Basin Commission (NBC) will be triggered and succeed the NBI. Without the participation of Egypt and Sudan, however, the CFA and NBC will struggle to resolve disputes over water resources in the basin, a reality the June 2013 conflict between Egypt and Ethiopia reflects.

29.4 The Role of International Water Law: Prospects for Cooperation

With Egypt publicly proclaiming the possibility of war over the Nile River Basin's water resources, and Ethiopia building momentum for entry into force of an agreement untenable to Egypt and Sudan, prospects for cooperation have never seemed more remote. The dispute centers on the ambiguous relationship between the two foundational principles of international water law, a relationship that lacks clarification and guidance for states in seemingly intractable positions. In this section, the experience of the Nile River Basin states is used to examine the utility of the current body of international water law. In turn, prospects for cooperation in the basin are assessed based on current negotiations and legal positions.

As the longest river in the world, and arguably the most geopolitically significant river basin lacking a cooperative management agreement, the Nile River Basin's experience with principles of international water law are a telling barometer of international water law's ability to resolve disputes and foster agreement. While it is understood that one of the primary purposes of international law is to provide a framework for willing states to conclude their own, more fact-specific regional agreements, it cannot be said that the Watercourses Convention or other instruments of international water law have equipped states in conflict with the necessary tools to resolve disputes. On the contrary, the ambiguous relationship between the principles of equitable use and no significant harm allows states to invoke whichever principle best suits their needs. Downstream states like Egypt and Sudan will emphasize the principle of no significant harm to prevent upstream utilization, while upstream states will emphasize the principle of equitable use to legitimize their consumption.

CFA negotiations have demonstrated that even when negotiating in good faith, the lack of clarity in international water law may lead to intractable outcomes. The fact that riparian states of the Nile River Basin felt compelled to create an entirely novel legal concept to resolve the discrepancies between existing legal principles is an indictment of the preexisting legal tools available. The concept of water security quickly became a proxy for incompatible positions, an outcome international water law principles did not prevent. It is prudent for the development of international water law not to overreach. In fact, despite being limited to framework principles that largely reflected customary laws, the Watercourses Convention has yet to receive the requisite support necessary for entry into force. It is questionable whether or not a more robust treaty would be palatable to a critical mass of nation-states. However, if water law principles are intended to be translated into more specific fact-based regional agreements, the fact that they may presently obscure, rather than clarify, basic rights and obligations of basin states does not bode well for the future viability of the Watercourses Convention, Draft Articles on the Law of Transboundary Aquifers, and other treaty instruments.

Similarly, if legal principles serve to provide ammunition for states to take hardline negotiating positions, their value added to international disputes is severely diminished. However, while that may appear to be the case in the Nile River Basin, the influence of historical experience should not be underestimated. Egypt and Sudan's vehement opposition to the principle of equitable use is not simply the product of their status as a downstream state. It is also the consequence of geopolitical supremacy and colonial privileges. Upstream states of the Nile River Basin would be at a significant disadvantage vis-à-vis their downstream neighbors if international water law did not support the idea that a country may make reasonable and equitable utilization of their territories' water resources. Only in the past 10–20 years have upstream states progressively challenged Egypt and Sudan. While economic development, population growth, and environmental uncertainty have contributed to the shift in political dynamics, the continued development and acceptance of customary water laws, such as the equitable use principle, have given upstream states a legitimate legal leg to stand on.

Ultimately, the principle of equitable use is not just a guiding philosophy of international water law, but of international environmental laws governing natural resources in general. States have traditionally supported—and in many cases, vigorously defended—the notion of territorial sovereignty that allows them to utilize natural resources. Contemporary understandings of environmental processes have demonstrated the need for cooperation over transboundary resources and incentivized states to manage resources cooperatively, but the Egyptian-Sudanese reliance on the no significant harm principle to object to any utilization of water resources by upstream riparian states is likely a misconstruction of the principle. Since the principles of equitable use and no significant harm first appeared in the 1997 Watercourses Convention, they have remained together in every subsequent major international legal instrument. It is clear that both principles operate in tandem, and should be interpreted as checks on one another.

Nonetheless, the sheer magnitude of hydro-political discord in the Nile River Basin based on diverging interpretations of international water law should signal to stakeholders that further action is required to clarify the relationship between legal principles. A necessary first step is the entry into force of the Watercourses Convention. While imperfect, the Convention provides states with a basic framework with which to base more fact-based regional agreements. Without a treaty of any kind, states are relying on interpretations of customary international law to legitimize their claims; a binding agreement will provide a more concrete basis with which to cooperate.

Second, continued developments in international water law—and in particular, interpretations of customary principles—should make concrete determinations regarding a state's right to the water resources in its territory. The current reliance on balancing factors is overly dependent on good-faith cooperation between states. A more explicit definition of rights may not resolve disputes between neighbors intent on protecting their short-term interests, but does provide affected states with legal and diplomatic grounds to protect their water resources. A determination that reasonable and equitable utilization of water resources within discernible limits is a state right is in line with contemporary understandings of international water law and provides upstream states with legal grounds to challenge uncooperative downstream neighbors. Similarly, precise limits on uses affecting quantity and quality of water resources assure downstream states that they will receive an equitable share of basin waters. Current legal instruments echo these sentiments but in broad and flexible terms; precise definitions will clarify rights and obligations. In cases where precision diminishes political support for legal instruments, reinforcing the principle of state cooperation is an alternative mechanism to resolving disputes. If the principles of equitable use and no significant harm are to coexist, greater emphasis must be given to the need for states to cooperatively define the relationship.

At present, prospects for cooperation in the Nile River Basin appear slim, with upstream states intent on pushing forward with the CFA as presently constructed, without the support and participation of Egypt and Sudan. If the CFA enters into force without the full participation of basin states, an element of cooperation will be lost, as the CFA's implementing institution—the NBC—will succeed the NBI and assume the NBI's rights and responsibilities. Consequently, the Nile River Basin will lose its primary mechanism for coordination and transboundary management. Many of the NBI's current programs will presumably transition to the NBC, though how this will proceed without the full participation of basin states is unclear. What is clear is that upstream states are asserting their rights under international water law and are no longer hesitant to publicly oppose their downstream counterparts.

Meanwhile, Egypt's reaction to increased pressure from upstream states to assert the principle of equitable use has been invective. After centuries of enjoying nearly complete dominion over the Nile's flow, Egypt and Sudan are facing a new Nile River Basin paradigm. Based on widespread acceptance of the equitable use principle, it is likely the international community will be sympathetic toward the upstream states, many of which are in low levels of human development and receive heightened attention from industrialized nations and the international community. However, Egypt and Sudan are themselves key players in a fragile and evolving Middle East and North Africa region, where major players like the USA and European Union are consummated by explosive issues in the region, and are unlikely to spend their diplomatic capital asserting the rights of upstream riparian states to an equitable utilization of the Nile River Basin.

At the same time, the conflict over water resources has become sufficiently critical to warrant international attention, a development which may present an opportunity for reconciliation. Following the June 2013 exchange between Egypt and Ethiopia, the African Union and UN urged cooperation, with the UN Secretary General, Ban-Ki Moon, personally discussing the matter with the leaders of both states. Former Egyptian Foreign Minister, Mohamed Amr, made an official visit to Ethiopia on June 17, 2013 to resolve the dispute and negotiate a mutually beneficial agreement (Tadese 2013). However, those talks may be irrelevant in light of Egypt's rapidly changing political landscape.

As of writing, Egypt's former President Mohammed Morsi had been removed from office and the Chief Justice of the Supreme Constitutional Court appointed interim president. The move followed widespread protests erupting across Egypt that sparked wholesale changes in Egypt's political leadership. As Egypt tends to an immediate political crisis, talks between Egypt and Ethiopia have been put on hold, with Ethiopia set to increase military spending by 15 % in light of the recent conflict (The Washington Post 2013). Going forward, it is likely that Egypt's interim and elected governments will maintain long-held legal claims to the Nile River Basin's water resources. However, with political transition comes an opportunity for cooperation. Considering the explosive nature of domestic Egyptian politics, maintaining stable relationships with regional and international actors will be a priority of any new government. Increased recognition of upstream states' rights to an equitable use of water resources—by renewing CFA negotiations or accepting the construction of the Grand Renaissance Dam—would be a breakthrough for Nile River Basin relations.

A better understanding of hydrological dynamics may also present an opportunity for cooperation. From an integrated water resources management perspective, the primary water uses of the riparian states involved are not incompatible despite the Nile River's limited flows. The Democratic Republic of the Congo, Rwanda, and Burundi rely on waters of the Kagera River Basin—an upper headwater of the Nile—for small-scale domestic water supply and irrigation. Similarly, Tanzania and Kenya rely on the Nile's water resources to satisfy some domestic water supply needs, while Uganda and Ethiopia are focused on hydropower generation. An integrated water resources management framework can regulate and satisfy these uses with minimal downstream effects on Sudan and Egypt. Sudan partially recognized this possibility when it accepted the conclusion of a ten-member panel tasked with investigating the effects of the dam. The panel's findings included a determination that downstream Egypt and Sudan will not be deleteriously affected, and may even benefit from reductions of siltation and flooding.

The challenge for riparian states of the Nile River Basin is to negotiate a binding legal agreement that effectively defines rights and obligations, while providing a framework for enduring transboundary management and cooperation. The bipolar interpretations of past agreements and international water law principles has led negotiations into the unfamiliar issue of water security, a principle that merely serves as a proxy for states to assert their best interests. Nonetheless, the CFA may be more palatable to Egypt and Sudan than current political dynamics would suggest. The present form of the agreement has omitted the controversial Article 14(b) water security clause, leaving it to the NBC to resolve. In addition, amendment procedures were revised to require unanimity for the most essential articles (including the principles of equitable use, no significant harm, and water security), and a two-thirds majority for all other provisions. Finally, while the CFA does not explicitly protect historical allocations of Nile waters, an enumerated factor to consider when determining equity is an existing use. Considering the significant reliance of Egypt's population on Nile water resources, this factor is likely to be heavily weighted when objectively balanced against other factors.

29.5 Conclusion

Ultimately, the CFA still represents a binding and legal break from Sudanese and Egyptian hegemony over the Nile River Basin. It may take time for Egypt and Sudan to accept this new paradigm, but the rights of upstream riparian states are well supported in international water law, despite certain definitional ambiguities. It would behoove the community of upstream riparians to promote the CFA as a mutual framework cooperative, and limit its use as a political symbol. Meanwhile, the experience of the Nile River Basin should illuminate to scholars and policymakers that the relationship between the foundational principles of international water law—equitable use and no significant harm—is poorly defined and capable of manipulation. While ambiguity may provide flexibility and replicability in some cases, precise articulations of rights and obligations of riparian states will more adequately protect state interests in conflict situations and advance the development of international water law.

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Chapter 30
Supporting the Development of Efficient and Effective River Basin Organizations in Africa: What Steps Can Be Taken to Improve Transboundary Water Cooperation Between the Riparian States of the Nile?

Matthias Morbach, Lars Ribbe and Rui Pedroso

Abstract The riparian countries of the Nile basin have experienced an evolutionary process of water-related cooperation beyond compare. After a long period of bilateral regime building, they finally jointly recognized that the best way to protect, manage, and use the water resources of the Nile is through close cooperation. The Nile Basin Initiative (NBI) reflects this effort because it can be described as an intergovernmental organization that seeks to manage and develop the shared water resources of the Nile basin in an equitable and sustainable manner. The NBI was and is, however, only a transitional arrangement without legal binding status and, therefore, does not completely show the characteristics of a full-fledged River Basin Organization (RBO). In addition, it rather can be questioned if this institution really has the full potential to adequately promote transboundary water cooperation between the riparian states of the Nile.

This study aspires to shed a new light on transboundary water cooperation in the Nile basin. Based on the assumption that current status quo limits the potential and range for cooperation in this region, it aims (1) to identify the major obstacles that can be associated with transboundary water cooperation in this region and (2) to present possible solution approaches to make measures against these problems in order to assist the NBI in its effort to efficiently and effectively improve transboundary water cooperation between the riparian states of the Nile.

The insights, which have been acquired by literature review, show that the environmental, socioeconomic, and political conditions, which are prevalent in the Nile

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River basin (NRB), have created a number of performance obstacles for the NBI. The lack of a legal framework and the various problems emerging in the fields of financing, capacity building, coordination, and public participation further indicate that it has to be very challenging for this institution to manage the transboundary water resources of the Nile in a cooperative and generally accepted way. Nevertheless, the NBI represents the most comprehensive and sustainable transboundary water management plan ever attempted in this region and the possible approaches for improvements presented here show that there are still many paths open to face this problematic situation in an efficient and effective manner.

Keywords Nile basin initiative · Transboundary water cooperation · Nile River basin

30.1 Introduction

A very promising concept for fostering cooperation between states that share a common water resource can be seen in the Nile Basin Initiative (NBI). The NBI is an intergovernmental organization initiated and led by the riparian states of the Nile River that aspires to create international applicable conditions "t*o develop the River Nile in a cooperative manner, share substantial socio-economic benefits and promote regional peace and security*" (NBI 2012a). To realize their common interests, the member states of the NBI, therefore, initiated in 1999 a participatory course of dialogue that resulted in a shared vision *"to achieve sustainable socio-economic development through the equitable utilization of and the benefits from, the common Nile Basin water resources*" (NBI 2011).

Promoting transboundary water cooperation within this region, however, has to be seen as very complex, as the NBI has to establish consensus among differing political- and socioeconomic-minded riparian states that are almost all characterized by extreme poverty, food insecurity, environmental degradation, water scarcity, national but also international conflicts, as well as intense population dynamics (for more details, see Sect. 30.4.1). This already challenging situation is accompanied by a series of shortcomings that occur on the organizational level of this institution. In this connection and besides general problems that affect the overall performance of the NBI (e.g., lack of coordination, public participation, etc.), attention must be particularly paid to one aspect: The NBI was and is only a transitional arrangement without legal binding status and, thus, does not completely show the characteristics of a full-fledged River Basin Organization (RBO) (for more details, see Sect. 30.4.2; Belay et al. 2009). Consequently, the NBI solely can be described as an interim institution binding together the NBI member states to move forward into a Nile Cooperative Framework Agreement (CFA), which would "*pave the way to the establishment of a permanent River Nile Basin Organization*" (Mekonnen 2010). Even though the negotiations over the CFA were concluded in April 2010, continuing disagreements among states led to the CFA not being finalized, agreed upon fully, and ratified yet (Mekonnen 2010). Despite the remarkable progress attained by the NBI in the various fields of transboundary water resources management, the NBI's ambitious goals for establishing regional cooperation and mutually beneficial relationships among all Nile basin countries, therefore, have to be questioned. Thus, new ways for improving transboundary water cooperation between the riparian states of the Nile need to be developed in order to face the very challenging situation of turning the NBI's shared vision into reality.

This chapter aspires to contribute to the growing literature that concentrates on the cooperative management of transboundary water resources in the Nile River basin (NRB). Based on the assumption that current status quo limits the potential and range for cooperation in this region, this part aims to identify the major obstacles that can be associated with transboundary water cooperation in the NRB. Moreover, possible solutions to take measures against these problems will be outlined in order to assist the NBI in its effort to efficiently and effectively improve transboundary water cooperation between the riparian states of the Nile. Here, it is important to note that large parts of this chapter have been taken from the author's master thesis: "Design Determinants for a Nile River Basin Organization (NRBO)," a thesis, which was realized in cooperation with the Institute for Technology and Resources Management in the Tropics and Subtropics (ITT), Cologne, Germany (for more details, see Morbach 2012).

30.2 Background Information

The Nile basin possesses diverse geophysical characteristics along its path to the Mediterranean Sea (Fig. 30.1). It is the longest river worldwide with a length of 6,650 km and a catchment area of about 3,260,000 km^2(Kirby et al. 2010). In terms of freshwater quantity, however, the Nile is only considered as a middle-range basin because it only holds 2 % of the water mass of the Amazon and not more than 20 % of the Mekong (Menniken 2008). For this reason, the Nile River can be distinguished from other great rivers of the world due to the fact that around 50 % of its course flows through regions with no effective rainfall. In addition, most of the waters of the Nile originate from an area that encompasses not more than 20 % of the total basin area. The remaining parts of the basin are located in arid or semiarid regions where water supply is very limited and where evaporation and seepage losses are very high (Karyabwite 2000). Despite the dry climate and the low level of precipitation, mainly in the downstream parts of the NRB, the limited water availability is underscored by the fact that no tributary joins the river on the last 3,000 km of its journey. Resulting from this "water scarcity" it is, therefore, understandable that a study, which set population into correlation with the available runoff of five world regions (China, South Asia, Southeast Asia, West Africa, and the Nile region), came to the conclusion that *"the Nile region is by far the most water scarce"* (Varis 2000 quoted by Menniken 2008).

Along its length and breadth, the Nile basin can be divided into several geographical zones with characteristic features of elevation, topography, and land cover. The north–south orientation of the Nile basin, which extends over 36 degrees of latitude, further causes extreme climate variability between the extremes of the basin. That is why its climate range varies between aridity in the north and tropical conditions in the south (Nicol 2003). In this context, the Nile basin in Sudan and Egypt is rainless during the northern winter, whereas the Ethiopian Highlands, as well as the southern parts of the basin, experience heavy rainfall during the northern summer (Karyabwite 2000). Furthermore, most parts of the basin fall under the influence of the northeast trade winds, which cause a prevailing aridity between October and May. As a result, the precipitation regime of the Nile basin can be characterized as irregular, which varies widely from season to season, from year to year, and from region to region. Starting from the south, the streams of the Nile River flow towards north and expand over 11 countries: Burundi, DR Congo, Kenya, Rwanda, Tanzania, Uganda, Eritrea, Ethiopia, South Sudan, Sudan, and Egypt (Fig. 30.1).

Two major tributaries form the Nile: the *White Nile* and the *Blue Nile*. Although it has several sources, the White Nile originates from the Luvironza River in south-central Burundi and flows into the Kagera River, which in turn runs into Lake Victoria, the world's second largest freshwater lake. From the outlet of Lake Victoria, at an elevation of 1,150 m in Jinja/Uganda, the Nile water then travels downwards through the Great Lakes region into southern Sudan, where the Sobat joins it (Menniken 2008). Afterwards, the river continues to flow northwards and traverses a massive natural swamp system (around 38,000 km^2) called the Sudd (Yasir 2005). At this point, the White Nile is dramatically slowed down and due to evaporation it significantly loses up to 60 % of its original flow. This situation has to been seen as the main reason why the White Nile only contributes less than 30 % to the Nile waters as measured at the Aswan High Dam in southern Egypt.

The bulk of the Nile's waters comes from the Blue Nile, which has it springs in the Ethiopian Highlands at 1,800 m above mean sea level. From the upland plateau of the Ethiopian Highlands, the river flows down towards Sudan and displays huge hydropower potential in that region. This situation can be related to the fact that the Blue Nile drops to 500 m in elevation on its first 1,500 km (Menniken 2008). The flow of the Blue Nile is determined through the seasonality of rainfall over its origin, the Ethiopian Highlands, and significantly fluctuates between 10 million m^3 in April and 500 million m^3 in August. Despite the seasonal variation of flow volumes, the Blue Nile is by far the biggest water supplier to the river system of the Nile. In addition, with its average annual flow of 48.6 km^3, the Blue Nile contributes almost 60 % to the long-term river flow of the Nile (Nicol 2003).

North of Khartoum in Sudan, the two major tributaries merge together and continue to flow northwards. Below the Blue Nile and White Nile confluence, the Atbara River is the last tributary that joins the river system of the Nile. From this point on, the Nile flows through Lake Nasser, one of the largest man-made lakes in the world, and continues its way as a single river through a desert-like area for almost 3,000 km (Menniken 2008). Afterwards, just north of Cairo in Egypt, the Nile finally splits up into two major distributaries, the Damietta and the Rosetta, before it runs into the

Fig. 30.1 The Nile River basin. (Source: World Bank 2000, edited by author)

Table 30.1 The Nile basin repartition and water resource availability. (Source: Karyabwite 2000, edited by author)

Country	Country area in (km^2)	Area within the Nile basin (km^2)	Percentage of the total Nile basin area	Internal renewable water (km^3/year)	Actual renewable water resources (km^3/year)	Dependency ratio in percentage
Burundi	27,835	13,260	0.4	3.6	3.6	0.0
DR Congo	2,345,410	22,143	0.7	935.0	1019.0	8.2
Egypt	1,001,450	326,751	10.5	1.7	58.3	96.9
Eritrea	121,320	24,921	0.8	2.8	8.8	68.2
Ethiopia	1,127,127	365,117	11.7	110.0	110.0	0.0
Kenya	582,650	46,229	1.5	20.2	30.2	33.1
Rwanda	26,340	19,876	0.7	6.3	6.3	0.0
Sudan	2,505,810	1,978,506	63.6	35.0	88.5	77.3
Tanzania	945,090	84,200	2.7	80.0	89.0	10.1
Uganda	236,040	231,366	7.4	39.2	66.0	40.9
Total	8,919,072	3,112,369	100.0	–	–	–

Mediterranean Sea. South of the Atbara–Main Nile confluence, the long-term river flow of the Nile, measured at Aswan, is estimated to be around 85 km^3 (Droogers and Immerzeel 2009).

Holding the confluence of the White and Blue Nile, "former" Sudan (South Sudan and Sudan) has by far the largest portion of the total Nile basin area (63.6 %), followed by Ethiopia (11.7 %), Egypt (10.5 %), and Uganda (7.4 %), leaving less than 7 % for the remaining six riparian countries (Karyabwite 2000). In this context, Table 30.1 illustrates the Nile basin repartition, as well as the dependence on water from upstream catchments to downstream states, and shows how much water the riparian countries of the Nile receive externally against internal renewable water resources. As a consequence of the extreme dependence on external flows, it is not surprising that since the beginning of the twentieth century especially Egypt but also Sudan have executed several supply-side structures in order to capture and regulate the Nile River's flows (e.g., Aswan High Dam, Roseires Dam, Sennar Dam, etc.). Nevertheless, all Nile basin riparian countries have in common the fact that over 85 % of the total water amount available is used in the agricultural sector. Hence, water for irrigation has been and still is the major concern for them, followed by hydropower development and ecosystem maintenance as well as utilizing water for domestic and industrial purposes (Nicol 2003).

The potential and range in utilizing the water resources of the Nile significantly differ from country to country. For these reasons, the following section briefly describes the importance of the Nile for the respective riparian country.

Egypt heavily depends on water that originates outside its borders. About 95 % of the Nile water that flows through Egypt comes from regions further upstream. In this relation, about 97 % of the water, which is used in Egypt, is taken from the Nile. The very arid conditions, which are prevalent in most parts of the country, further makes it necessary that around 98 % of the total cropland of Egypt be irrigated. It is, thus, not surprising that the vast majority of the Nile waters (ca. 86 %) are used for agricultural purposes. Nevertheless, much more than any other riparian country, Egypt also uses the waters of the Nile for hydropower generation and for domestic and industrial purposes (Menniken 2008). As a logical consequence of the above-mentioned aspects, Egypt is by far the nation that is most dependent upon the Nile. Therefore, it has always claimed rights on the waters of the Nile and above the other riparian nations. In this context, it should be considered that despite the political and social unrest, which resulted from the pro-democracy efforts of the Arab Spring, Egypt, as the economically and militarily most powerful nation of this region, was and still is capable of imposing its interests.

Hosting the confluences of the Blue and the White Nile gives Sudan in geophysical terms an outstanding status. Even so, it is somewhat less dependent upon the Nile, due to its rainfed agricultural areas within its borders (Waterbury 2002). However, because of its very poor political performance and its low level of socioeconomic development, both of which can be partially related to the country's internal conflicts (e.g., Darfur 2003–2010), Sudan's momentarily main interest is to attain food security followed by a modest expansion of hydropower. In relation to its dependence on agriculture, it should be further pointed out that Sudan's most reliable agricultural production areas are located in the Nile basin (Menniken 2008).

Although endowed with rich natural and fossil resources, South Sudan remains comparatively very underdeveloped primarily resulting from the struggle for independence. Therefore, South Sudan currently mainly depends on rainfed agriculture, as it receives sufficient rain in most parts of the country (Guvele 2003). At present, the country is not dependent upon the Nile, but it would like to be. This relates to the announced plans to build a hydropower dam at Wau, a city that is located next to a tributary (Jur River) of the White Nile (Ferrie 2011).

For Ethiopia, the most important interest is to attain food security. Because of that, the country sees the Nile as a crucial resource for irrigated agriculture. Moreover, due to the vast potential of hydropower in the Blue Nile basin, it is becoming increasingly interesting for the country to generate electricity through the use of dams (Menniken 2008). So far, the exploitation has been unfairly denied by the prevailing regime in the basin. The regime, which has been established by Egypt and Sudan, is a result of the fear that any additional Ethiopian water-use projects will alter the flow of the Nile and, therefore, cause significant impacts on the nations' water availability. Nevertheless, a potential alliance between Sudan and Ethiopia in a joint effort to develop and utilize the waters of the Blue Nile has been described by Waterbury as "*Egypt's worst nightmare*" (Waterbury 2002).

Eritrea's interest in the Nile is limited to the management of two seasonal streams (Gash and Setit River), both of which flow into Sudan. Furthermore, there has been a periodic understanding between the two countries on how to use these flows. Just like in the other basin riparian countries, the main interest is to use the water of the Nile for agricultural production in order to supply the population with sufficient food.

In company with Egypt, Sudan, and Ethiopia, Uganda can be regarded as the fourth major stakeholder in the Nile basin. Uganda is primarily interested in the generation of hydropower because it mostly does not need surface irrigation or additional surface water for its agricultural cultivation practices (Waterbury 2002). Here, it is necessary to mention that for a long time Egypt has kept Uganda from the implementation of new hydropower development projects. This can be explained by Egypt's aversion to share its technical expertise on hydropower development projects. As explained before, this situation is caused by the fear of Egypt that any upstream hydropower or water supply structures would probably alter the flow of the Nile further downstream (Menniken 2008). Anyhow, the Owen Falls Dam, which was constructed to generate power and regulate the flow from Lake Victoria, is operated in direct cooperation with Egypt. In relation to the operation of the dam, Uganda is bound to Egypt by a treaty (Owen Falls Agreement) (Waterbury 2002).

Besides water for irrigated agriculture, the remaining Nile riparian countries individually do not have any major stake in issues of water use. Anyhow, they play a significant role in the development of the common pool resource around Lake Victoria and are indispensable partners in the Nile basin cooperation process. Kenya and Tanzania, both of which can be characterized as very dry countries with frequently occurring droughts, rely on the resources of Lake Victoria. In addition, they use the Nile water for agriculture and fishery as well as for tourism, especially in the western zones of their countries. Burundi and Rwanda, in contrast, have high and regular rainfall so that their interests on the Nile are confined mainly on hydropower generation. Together with Kenya, Tanzania, and partly Burundi, they have a certain transboundary hydropower potential. Congo has not paid much attention to the Nile so far, but it has shown some interest in shipping and fishing rights next to Lake Albert (Waterbury 2002; Menniken 2008).

30.3 Water Cooperation in the NRB

The following section of this chapter briefly offers insights into the evolution of transboundary water cooperation in this region and provides relevant information about the development, structure, functions, and programs of the NBI.

30.3.1 Evolution of Transboundary Water Cooperation

The first half of the twentieth century can be characterized as an era of hegemonial-steered basin-wide collaboration in the interest of the British Empire, which first conceptualized the Nile basin as a political and hydro-political planning unit (Menniken 2008). Under the British–Egyptian condominium, a shortage of cotton on the world market brought pressure on Egypt and Sudan to cultivate this summer crop. The consequent need for summer water and flood control, therefore, induced an intense phase of water development along the Nile basin with disputes between supporters of Egyptian and Sudanese interests concerning whether the focus for development should be located further upstream or downstream. Two measures, both of which occurred in 1920, underline the hydro-political attitude of Britain: the Nile Projects Commission and the Century Storage System. The Nile Projects Commission, which was formed through representatives from India, Britain, and the USA, was a response to Britain's awareness that any regional Nile basin development plans had to be regulated with a formal agreement on water allocation. In this relation, the Commission estimated that the water needs of Egypt would be 58 billion cubic meters per year. For comparison, the river's average annual flow was estimated to be 84 billion cubic meters. Despite the fact that the Nile flow fluctuates significantly, they also recommended that Sudan would be able to meet its irrigation requirements alone from the Blue Nile. However, the findings of the Commission were never brought into action. During the same year, Britain also published the Century Storage Scheme, so far the most extensive concept for water development along the Nile. The plan included designs for a water storage facility next to the Ugandan–Sudanese border, a dam at Sennar, which was located south of Khartoum, and a dam on the White Nile in order to store summer floodwater for Egypt. During that time, the scheme was far too ambitious to be implemented because of political, technical, and natural reasons. Egypt was also worried that these major storage systems would be located outside of the Egyptian area of influence (Wolf and Newton 2007).

When the riparian countries of the Nile basin consecutively became independent from colonial powers, riparian disputes on water allocation, especially between Egypt and Sudan, became more contentious. After the formal declaration of independence of Egypt (1922), a new commission made suggestions that were based on the 1920 Nile Projects Commission's estimates and finally resulted in the 1929 Egyptian–Sudanese Nile Waters Agreement. This agreement, which fixed quantities of water to be allocated to each country, was signed on 7 May 1929 between Egypt and Britain, with Britain acting on behalf of Sudan and other East African colonies. Based on the Nile's mean annual discharge of 84 billion cubic meters, of which 32 billion cubic meters were lost through evaporation and seepage, the agreement included that 4 billion cubic meters were annually allocated to Sudan, a relatively small amount due to the fact that the entire time flow from January to July (dry season), and a total amount of 48 billion cubic meters per year was reserved to Egypt (Kameri-Mbote 2005). A key clause of the agreement reads as follows:

> Save with the previous agreement of the Egyptian Government, no irrigation or power works or measures are to be constructed or taken (. . .), which would, in such a manner as to entail prejudice to the interests of Egypt, either reduce the quantity of water arriving in Egypt, or modify the date of its arrival, or lower its level (Nile 1929).

This obviously imbalanced distribution reflects the power equation at that time, the British–Egyptian hegemony, and shows in essence that the agreement prohibited upstream countries from undertaking any kind of major water works without the consultation of Egypt. Consequently, it was binding on all Nile basin countries, which had been under British administration at that time. For being inequitable, the agreement that indeed placed priority on Egypt's water needs was later challenged by upstream states and has been repudiated by Tanzania, Uganda, Kenya, and Sudan after gaining their independence. Another bilateral agreement, which also reflected the British long-term interest in securing water for Egypt, was the Owen Falls Agreement of 1953. In this connection, Egypt and Britain, with Britain acting on behalf of Uganda, agreed to construct the Owen Falls Dam in order to generate electricity for Uganda and control the outlet of Lake Victoria. However, irrigation in Egypt and Sudan remained the priority area of Britain's hydro-politics. That is why the flow regulations of this dam had to be approved by an Egyptian technical committee in order to control Ugandan water utilization from negatively impacting Egypt's interests (Wolf and Newton 2007). As a result, Uganda was allowed to "*take action at Owen Falls which it may consider desirable provided that the action does not entail any prejudice to the interests of Egypt in accordance with the Nile Water Agreement of 1929*" (Nile 1949). Due to the aspects mentioned above, it is worth noting that in relation to its water needs Egypt has benefited from the English occupation. Although Egypt was already the strongest Nile basin's riparian country at that time, it would have never been able to assert such demands on the other riparians without the assistance of Great Britain (Menniken 2008). The situation changed after World War II because many of the British colonial territories attained their political independence. The uncertainty, which came along with the political changes at that time, made it necessary for Egypt to establish new bi- and multilateral agreements, especially with the military regime of Sudan that gained power in 1958 (Okoth 2009). Besides the new political climate in this region, this new strategy of Egypt was also caused by the need to obtain funding (mainly from the World Bank) to construct the Aswan High Dam. This dam, with a project storage capacity of 156 BCM/yr, was another attempt of Egypt to solidify its hydro-political hegemony in the Nile basin and to secure its future water demands. After the Egyptian revolution in 1952, the construction of the Aswan High Dam, therefore, became one of the key objectives of the Egyptian government. In order to receive funding from international donors, Egypt was consequently adopting a more conciliatory tone to its neighbor. The result was the adoption of the 1959 Egyptian–Sudanese Agreement for the full utilization of the Nile waters (1959 Nile Water Treaty). This mutual agreement, which in the widest sense comprised water allocation and harm mitigation, had the following key provisions:

- The average annual flow of the Nile was estimated to be 84 billion m^3, whereas evaporation and seepage losses were considered to be 10 BCM/yr, leaving 74 BCM/yr to be divided.
- The related acquired rights were described to be 48 BCM/yr for Egypt and 4 BCM/yr for Sudan. The remaining benefits of approximately 22 BCM/yr were allocated by a ratio of 7.5 for Egypt (7.5 BCM/yr) and 14.5 for Sudan (14.5 BCM/yr). In addition, the total allocations equaled 55.5 BCM/yr for Egypt and 18.5 BCM/yr for Sudan.
- Establishment of a Permanent Joint Technical Committee in order to resolve disputes and jointly review claims of other riparian states.

- Any increases in average yield further would be divided equally, whereas any significant decreases would be taken up and addressed by the Joint Technical Committee.
- In order to prevent a drop in Egypt's water level, all countries located further south must receive a permission from Egypt to utilize the waters of the Nile for irrigation or hydroelectric projects.
- Egypt and Sudan concluded that any claims would be faced by one unified Egyptian–Sudanese position (Wolf and Newton 2007).

In relation to these provisions, it is necessary to mention that ever since the signing of the 1959 Nile Water Treaty, the two parties have held on to the allocation conditions until the present. Therefore, the treaty can be rated as the first important bilateral hydro-political agreement between Egypt and Sudan. Furthermore, no riparian country, except Ethiopia, has ever exercised a legal claim to the conditions on how the water is allocated in this treaty. Anyhow, the condition that any country south of Egypt must get Egypt's approval has frequently caused tensions between Egypt and other countries (Kameri-Mbote 2005). Ever since the signing of the 1959 Agreement, a series of cooperative but rather ineffective activities to manage the river have been taking place between the riparian countries of the Nile. The situation changed with the implementation of HYDROMET (Hydro-meteorological Survey of the Equatorial Lakes), a project that was supported from 1967 to 1992 by the United Nations Development Programme (UNDP) and the World Meteorological Organisation (WMO). The project was launched to collect hydro-meteorological information within the basin in order to explain the unpredicted increase in precipitation, which caused a dramatic rise in the water level in Lake Victoria and the other equatorial lakes. Despite the competitive political environment that was caused by the Cold War, all Nile basin states participated from the beginning, except Ethiopia and Congo, which joined as observers in 1971 and 1977. In addition, catchment surveys and models of rainfall and runoff patterns were carried out between 1967 and 1981. To outline the importance of HYDROMET, it has to be noticed that the project can be seen as an early approach to manage transboundary resources in an equal manner, because for the first time all gathered information were shared among the participating riparian states (Menniken 2008).

Not only the end of the Cold War but also the growing awareness within the Nile basin that upcoming development efforts would require a more strategic and cross-sectorial thinking led to a new era of negotiations. In 1993, the Nile Council of Ministers (NILECOM) launched the Technical Cooperation Committee for the Promotion of the Development and Environmental Protection of the Nile basin (TECCONILE), an initiative that had been established for the purpose of creating an informal dialogue between the riparian countries. With the support of the Canadian International Development Agency (CIDA), the TECCONILE initiative then resulted in 1995 in the Nile River Basin Action Plan (NRBAP), a basin-wide plan which included integrated water resources planning and management, capacity building, training, regional cooperation, as well as environmental protection and enhancement (Nicol 2003). At the same time, a series of Nile conferences (Nile 2002 series) began in 1993 bringing together not only mainly technical but also legal, political, and institutional information from all Nile basin countries in order "*to provide an informal mechanism for riparian dialogue and the exchange of views between countries, as well as with the international community*" (Ssebuggwawo 2006). Although the successful outcomes of the NRBAP and the Nile conferences were considerably caused by the distance to any decision-making level, they contributed to reduce the mistrust among the Nile riparian countries. For these reasons, they both prepared the ground for enhancing transboundary water cooperation in this region (Menniken 2008).

Resulting from favorable environment that had been created by TECCONILE and the Nile 2002 conference series, CIDA, the UNDP, and the World Bank started to encourage and facilitate the dialogue between the Nile basin riparian countries in 1997. In this connection, in 1998, all riparian countries of the Nile, except for Eritrea, started negotiation with the aim of forming a regional partnership to manage and develop the Nile basin in a better way. As a result of this dialogue, a transitional mechanism for cooperation was established by NILECOM in 1999. This mechanism, which internalizes the understanding that a cooperative approach in the development and management of the Nile waters holds the best opportunities of bringing mutual benefits to this region, is known today as the NBI (Guvele 2003; Wondwosen 2008).

30.3.2 The Nile Basin Initiative

The NBI, which can be characterized as a reemergence of the NRBAP, unified both tracks of Nile diplomacy, the institutional TECCONILE and the informal Nile 2002 conferences, and describes itself as "an *inter-governmental organization dedicated to equitable and sustainable management and development of the shared water resources of the Nile Basin*" (NBI 2012c). The current ten member states of the NBI include Burundi, DR Congo, Egypt, Ethiopia, South Sudan, Kenya, Rwanda, Sudan, Tanzania, and Uganda, as well as Eritrea as observer. Focusing on a process-oriented approach, the NBI firstly started after its opening in 1999 with a participatory course of dialogue among the Nile basin states, which resulted in a shared vision "*to achieve sustainable socio-economic development through the equitable utilization of and the benefit from the common Nile Basin water resources*" (NBI 2012a). In respect of the common vision, the NBI developed a set of policy guidelines that identified the following parameters as overarching objectives of the NBI:

1. To develop the Nile basin water resources in a sustainable and equitable way to ensure prosperity, security, and peace for all its peoples
2. To ensure efficient water management and the optimal use of the resources
3. To ensure cooperation and joint action between the riparian countries, seeking win–win gains
4. To target poverty eradication and promote economic integration
5. To ensure that the program results in a move from planning to action

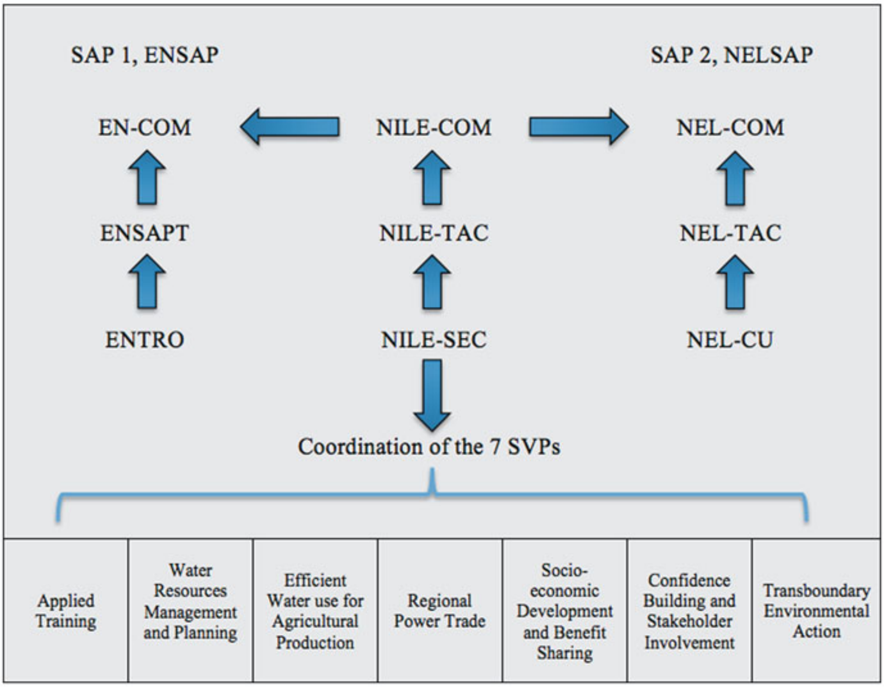

Fig. 30.2 Institutional structure of the Nile Basin Initiative. (Source: Menniken 2008, edited by author)

In relation to the objectives mentioned above, it is necessary to underline that the NBI is a "*transitional arrangement until a permanent legal and institutional framework is in place*" (NBI 2000 quoted by Nicol 2003). Consequently, the initiative "just" can be described as a transitional mechanism to coordinate and encourage cooperative efforts between the riparian states of the Nile. That is why the NBI has undergone an institutional strengthening process (2008–2012), which had the objective to explore and design an appropriate long-term institutional structure (NBI 2011). In practice, however, this should not hide the fact that the NBI is a de facto river basin organization that is only lacking in the legal status of an independent international body. Therefore, it can be expected that the institutional setup of NBI, which is described in Fig. 30.2, is likely to be taken over, once a river basin organization is established (Menniken 2008).

The highest decision-making and governing body of the NBI is the council of ministers, NILECOM, consisting of one minister per riparian country. It is supported by a Technical Advisory Committee (NILETAC), which is responsible to offer technical support and advice to the NILECOM on matters that are related to the management and development of the Nile waters. Therefore, NILETAC comprises two technical senior professionals from each member state. The Nile Basin Initiative Secretariat (Nile-SEC), which is located in Entebbe, Uganda, carries out the administrative, financial, and logistical services of the NBI and supports the activities of the NILECOM and NILETAC. The riparian countries themselves finance the functions of the Nile-SEC through annual dues and further provide funds for all NBI projects (NBI 2012b). The absence of international funding in Nile-SEC, however, should not neglect the fact that since its formation the NBI's operations have been supported by multilateral and bilateral donors. In this connection, NILECOM requested assistance from the World Bank to coordinate donor involvement. Together with the UNDP and the CIDA, they established an International Consortium for Cooperation on the Nile (ICCON) in 2001 where the development partners committed around US$ 130 million to the NBI. Most of the funds were placed into a World Bank-managed Nile Basin Trust Fund (NBTF), a multi-donor trust fund, which has been established in 2003 to finance the preparation and implementation of NBI projects and programs (NBI 2012a). These financed activities, which were aiming to achieve the NBI's shared visions, are reflected in the Strategic Action Plan, a program that is composed of two complementary components: a basin-wide Shared Vision Program (SVP) and the Subsidiary Action Programs (SAPs). In this context, the SVP is focusing in the widest sense on grant-based activities in order to build trust and cooperation in this region, whereas the SAPs are trying to engage the Nile basin countries in concrete activities for sustainable and regional development and economic growth (Guvele 2003).

Shared Vision Program: The SVP, which is designed to create an enabling environment for a basin-wide framework, is acting on a macro-level and was composed of eight programs: applied training, water resources planning and management, efficient water use for agricultural production, regional power trade, socioeconomic development and benefit sharing, confidence building and stakeholder involvement, transboundary environmental action, and shared vision coordination (Table 30.2). According to the World Bank, the SVP is a basin-wide program that "*focuses on building institutions, sharing data and information, providing training and creating avenues for dialogue and region-wide networks needed for joint problem-solving, collaborative development, and developing multi-sector and multi-country programs of investment to develop water resources in a sustainable way*" (NBD 2011). Even if these programs have been established in different riparian states, the SVP is not particularly concentrating on implementing projects for financial investments. It should be rather regarded as an instrument to organize workshops, to gather information, to harmonize the relations between stakeholders, and to build trust and confidence among the riparian states (Menniken 2008). Most of the SVP projects gradually came to an end by December 2009. The only former SVP activities, which were still continuing under the auspices of the NBI's Institutional Strengthening Project (NBI-ISP), were water resources management and planning, as well as regional power trade (NILEIS 2011). The NBI-ISP, which started in 2008 and ended in 2012, was a process to strengthen the NBI's foundation for institutional sustainability, enhanced capacity, and harmonized cooperative management in order to deliver programs and projects more efficiently and effectively (World Bank 2008). During this period, the NBI was also concentrating on analyzing and mainstreaming the outcomes of the SVP, as well as on integrating them into national plans (NBI 2010).

Table 30.2 Summary of the eight SVPs (Shared Vision Program). (Source: UNDP 2011, edited by author)

Applied Training Project: This project concentrated on strengthening the individual- capacity and the institutional capacity of the Nile basin riparian states, especially in relation to integrated water resources management. The project, for instance, offered training courses for practitioners. It further established a forum (Nile Net) in order to promote cooperation between professionals across the Nile region

Water Resources Management and Planning Project: This project had the objective to improve and strengthen the development, management, and protection of the water resources of the Nile with a view to promote socio-economic development in this region. It further sought to improve national water policies not only by the means of good practices and integrated water resources management, etc., but also through a Nile basin decision support system in order to exchange information, support dialogue, and identify investment projects more efficiently

Efficient Water Use for Agricultural Production Project: This project paid attention on developing a forum for all stakeholders concerning the efficient water use in agricultural production. The objectives were to promote regional dialogue, spread best practices, and implement irrigation policies to enhance the national capacity

Regional Power Trade Project: This project aims to facilitate the development of regional power markets with a special focus on technical assistance, as well as on developing infrastructure in order to reduce poverty in the Nile basin by enabling access to reliable low-cost power

Socio-economic Development and Benefits-Sharing Project: This project focused on the establishment of a network across the Nile River basin. It comprised economic planning- and research institutions, public and privates sector technical experts, social, scientists, academics, community groups, and NGOs. The overall goal was to identify alternative development plans and benefit-sharing possibilities

Confidence-Building and Stakeholder Involvement Project: This project aimed to improve public- and stakeholder participation within the NBI, to outline examples, which presented the benefits of regional cooperation, and to offer regional activities for encouraging cross-border cooperation. In this connection, the four main elements of the project were: regional, sub-regional, and national implementation, public information, stakeholder involvement, and confidence building

Transboundary Environmental Action Project: The NBI's largest project concentrated in the widest sense on environmental and water management. It encompassed several fields of activities, such as: promoting basin-wide community action, strengthening regional cooperation, increase the capacity to face transboundary water quality threats, etc. The project consisted of five components: institutional strengthening, community-level conservation, environmental education, water quality monitoring, and wetlands and biodiversity

Shared Vision Coordination Project: This project has been undertaken by NILE-SEC. It was established for the purpose of observing the implementation of the other projects mentioned above. The overall goals were to increase the NBI's capacity to carry out basin-wide programs, as well as to provide effective coordination and supervision

Subsidiary Action Programs The second component of the NBI's Strategic Action Plan, the two SAPs, is related to the implementation of joint development projects and investments on the subbasin level and is focusing on the realization of the fifth objective "move from planning to action." On the one hand, there is the Eastern Nile Subsidiary Action Program (ENSAP), which focuses on the eastern Nile region and comprises Egypt, Sudan, and Ethiopia. On the other hand, there is the Nile Equatorial Lakes Subsidiary Action Program (NELSAP), which concentrates on the Nile Equatorial Lakes region and encompasses Burundi, DR Congo, Kenya, Rwanda, Tanzania, Uganda, and South Sudan. The reason why these two SAPs are treated in a differential manner can be related to the prevailing geophysical and hydro-political conditions of the basin. This circumstance is also reflected in their program structure. ENSAP, with its office being located in Addis Ababa, Ethiopia, has to face the conflict-prone upstream–downstream constellation between Egypt, Sudan, and Ethiopia and, therefore, pays big attention to integrated water resources management (IWRM), drainage and watershed management, flood management, and irrigation (Menniken 2008). NELSAP, with its office based in Kigali, Rwanda, in contrast, rather aims to facilitate sound economic development and, therefore, focuses on water resource management, investments in power development projects, management of lakes and fisheries, transmission of interconnection and trade, and agricultural development. Nevertheless, like the NBI's main corpus, both programs consist of a minister's meeting (ENCOM and NELCOM), a technical support team (ENSAPT and NELTAC), and a secretariat, or in this case a regional office and a coordination unit (ENTRO and NELCU) (World Bank 2007).

The NBI's Strategic Action Plan and its two complementary components, the SVP and SAPs, show that the riparian countries of the Nile basin have experienced an evolutionary process of transboundary water cooperation beyond compare (Table 30.3). After a period of hegemonial and bilateral regime building, the Nile basin states finally jointly recognized that the best way to manage, use, and protect the water resources of the Nile is through close international cooperation, whereby the interests of upstream and downstream states are taken into account. The NBI reflects this effort because it has developed a strong foundation for the Nile riparian states to engage in concrete activities for sustainable development, IWRM, natural resources conservation, economic growth, and regional integration. The various executed NBI programs and projects further show a joint commitment and obligation of the Nile basin states to put the recommendations of Agenda 21 into practice because they try to address all potential problems that occur at the people–environment and development interfaces of this region. In this context, Belay et al. (2003) concludes "*that the NBI represents the most comprehensive and complex management plan ever attempted for sustainable development of international transboundary rivers*" (Belay et al. 2003).

Nevertheless, as mentioned earlier, the NBI is not immune to challenges, weaknesses, and threats due to the situation that this institution has to establish consensus among differing political- and socioeconomic-minded riparian states that all have to face a wide range of environmental, societal, political, and economical problems. For this reason, the subsequent section of this chapter will devote its attention to the major obstacles to transboundary water cooperation in the Nile basin.

30.4 Obstacles to Transboundary Water Cooperation in the NRB

In order to specify the way in which the NBI could be supported to adequately address the needs and expectations of the Nile riparian states, the most prevailing obstacles that are associated with transboundary water cooperation within this region have to be described first.

Table 30.3 Historical overview of water cooperation in the Nile basin. (Source: Wolf and Newton 2007; NBI 2010, edited by author)

1920	Formation of Nile Projects Commission that offered allocation scheme for Nile basin countries. Findings were not put into practice. Century Storage Scheme had been published, which emphasized small-scale upstream projects
1929	Nile Waters Agreement between Egypt and Sudan
1953	Owen Falls Agreement between Egypt and Uganda
1959	Agreement for the full utilization of the Nile waters that was signed between Egypt and Sudan
1967–1992	Start of HYDROMET, a project for collecting and sharing hydro-meteorological data (supported by UNDP)
1993	Establishment of TECCONILE (Technical Cooperation Committee for the Promotion of the Development and Environmental Protection of the Nile basin)
1993	First of ten Nile 2002 conferences in order to foster dialogue and cooperation between Nile basin countries and the international community (supported by CIDA)
1995	Establishment of NRBAP (Nile River Basin Action Plan) within TECCONILE framework (supported by CIDA)
1997–2000	Nile basin countries started an official forum for legal and institutional dialogue and discussion (supported by UNDP). Representatives (legal and water resource experts) from each country and other experts drafted a Cooperative Framework in 2000
1997	Creation of NILECOM, the Nile Council of Ministers
1998	Formation and first meeting of NILE-TAC, the Nile Technical Advisory Committee
1999	Nile basin riparian countries (excluding Eritrea) establish the Nile Basin Initiative (NBI) in order to develop and manage the Nile in a sustainable way
1999–2009	Implementation of the NBI's Strategic Action Plan, comprising the Shared Vision Program (SVP) and the Subsidiary Action Programs (SAPs)
2008–2012	Implementation of NBI's Institutional Strengthening Project (NBI-ISP) to explore and design an appropriate long-term institutional structure, as well as, for gathering, analyzing, and mainstreaming the products of the gradually completed SVP, as well as integrating SVP activities into national plans

30.4.1 Environmental, Socioeconomic, and Political Conditions

The environmental, socioeconomic, and political conditions, which are prevalent in the Nile basin, can be identified as potential regional threats and challenges that obstruct the Nile basin riparian countries from moving forward towards increased cooperation.

30.4.1.1 Environmental Conditions

The imbalanced spatial and temporal distribution of natural resources within the Nile basin can cause political tensions and conflicts, especially if the water qualities and quantities change with respect to the available supply and demand (see Sect. 30.2).

Table 30.4 Basin-wide common causes and priority environmental threats. (Source: Guvele 2003, edited by author)

Common causes of environmental threats	
Basin-wide causes	Policy, governance, institutional and capacity constraints, insufficient environmental education and awareness, limited access to environmental knowledge and information (including relevant scientific data), unclear tenure and inadequate access to resources for local stakeholders, inadequate management of protected areas, and other environmental hot spots
Priority environmental threats by country	
Burundi	Deforestation, soil erosion, degradation of rivers banks and lakeshores, mining, and wildlife hunting
DR Congo	River and lake pollution, deforestation, soil erosion, and wildlife hunting
Egypt	Water and air pollution, filling of wetlands, desertification, water logging and soil salinity, sanitation, and river bank degradation
Ethiopia	Deforestation, overgrazing, soil erosion, desertification, sanitation, loss of biodiversity (including agro biodiversity) floods, and drought
Kenya	River and lake pollution (point and non-point source), deforestation, desertification, soil erosion, sedimentation, loss of wetlands, eutrophication, and water weeds
Rwanda	Deforestation, soil erosion, degradation of river banks and lake shores, desertification, wildlife hunting, and overgrazing
Sudan (former)	Soil erosion, desertification, pollution of water supplies, wildlife hunting, floods, droughts, sanitation, deforestation, and sedimentation/siltation
Tanzania	Deforestation, soil degradation, desertification, river and lake pollution, poaching, and shortage of portable water
Uganda	Draining of wetlands, deforestation, soil erosion, encroachment into marginal lake shore and riverine ecosystems, and point and nonpoint pollution

Water quantities and qualities can be externally affected by natural (e.g., arid and semiarid climate, droughts) or human-made factors, like unsustainable water withdrawal or population pressure. In addition, decreases in water quantity and quality can have severe impacts on the natural systems of the Nile basin and are able to create a multitude of other negative externalities (Table 30.4). On the national level, these difficulties could be faced through monitoring and data analysis. However, when it comes to transboundary water resources management, these issues will become significantly more complex because cooperation between the riparian states of a river basin is not always achieved as a result of social, economical, political, or technical reasons (Robertson 2004). The aspects mentioned above can be demonstrated with the following example: Egypt and Sudan, both of which can be characterized as very water-scarce countries, have recognized upstream water storage facilities as an issue of national security threat. They, therefore, threatened upstream countries (mainly Ethiopia) with political and economical consequences because they fear that any additional major dam projects will significantly affect the countries' water supply (Menniken 2008). The resulting possible impacts of water allocation, like a lower flow regime or degraded stream water quality, thus, caused these two countries to still insist on the compliance of the colonial-era treaty regime (Nile Basin Water Treaties of 1929 and 1959). This status quo has already interfered several times in the process of improving transboundary water cooperation in this region because it can be seen as one of the major causes why Egypt and Sudan so far did not fully agree upon the CFA (Mekonnen 2010).

Another important problem, which is closely interlinked to this situation, is that both transboundary and national water resources management is often restricted on surface water. In addition, groundwater, green water, virtual water, and other related aspects are often not taken into consideration. This situation limits the scope of co-operation, as well as the number of alternatives, to form successful and cooperative partnerships among the states concerned. Transboundary water resources management further needs to consider administrative borders and not hydrological ones. This also poses a challenge to transboundary water cooperation in Nile basin, because, as a consequence of non-water-related conflicts or agreements, these administrative borders themselves can be subject to change over time (e.g., South Sudan separation). Consequently, this complicates the management of transboundary water resources because countries might develop their own strategies to deal and solve issues of planning, developing, allocating, and protecting their water resources (Robertson 2004).

30.4.1.2 Socioeconomic Conditions

Great ethnic, religious, and cultural heterogeneity that cuts across national as well as basin boundaries with neighboring watersheds characterizes the human geography of the Nile basin and creates not only opportunities but also threats for the socioeconomic conditions of the Nile basin (Nicol 2003). The states that comprise the basin host approximately 300 million people, of which around 150 million people live within the Nile basin itself (NBI 2007). Besides the fact that interpretations about demographic dynamics of the Nile region vary significantly from each other, there is a consensus in the scientific discussion that the population will grow continuously in the near future. However, according to Menniken (2008), a realistic assessment of the basin's population has been made by Varis (2000), who estimates that the population of the Nile basin riparian states is expected to grow to 360 million by 2025 (Menniken 2008). In terms of socioeconomic aspects, the riparian countries of the Nile basin are extremely heterogeneous and significantly differ from each other. Due to its industrializing economy and with average income levels amounting to US$ 1,490 per capita, Egypt has by far the strongest economy. In comparison, for the other countries, which are predominantly agricultural economies, the income levels vary between US$ 100 and US$ 360 per capita (NBI 2007). In addition, for large parts of the region's population, the level of socioeconomic development is extremely low. All of the basin countries, except Kenya and Egypt, are among the 50 poorest countries in the world (Kameri-Mbote 2007). External shocks, like fluctuating world market prices, droughts, and national and international conflicts, led to the situation wherein all countries except Uganda and Egypt have to face food shortages every year. Nevertheless, all of these states put a priority on achieving economic growth in order to avoid or break the spiral of poverty and underdevelopment. Together with a considerable population growth, which mutually correlates with the prevalent poverty in this region, this economic expansion will result in an increase in water demands in the coming decades and, therefore, could cause intense competition as well as non-equitable distribution of natural resources (Menniken 2008).

30.4.1.3 Political Conditions

The socioeconomic problems described above are referable to a series of political shortcomings in this region. In this connection, poor governance, competing political systems, and internal and international conflicts have already created several hazards for transboundary water cooperation in the Nile basin. Furthermore, it should be taken into account that the Nile basin appears to be "*a kaleidoscopic procession of civilizations and cultures [with] an almost infinite range of political systems and types of rule [and] striking differences in political and administrative organisation*" (Tvedt 2004 quoted by Menniken 2008). This means that the Nile basin as a whole can be characterized as highly heterogeneous with a wide range of size, cultural and religious backgrounds, population, political systems, military power, gross domestic product (GDP), and population. Some countries are characterized by a federal administrative structure with subnational states that govern territories formed along ethnical boundaries (e.g., Ethiopia, Tanzania). Other riparian states instead have a centralized administrative structure with subnational provinces or governorates (e.g., Egypt, Kenya). These divergent administrative structures are able to affect decisions for IWRM that might arise on the international, national, and subnational level (NBI 2007). Similar to the geophysical conditions, two different pictures emerge if the western Nile basin is dissociated from the eastern Nile basin. The riparian states of the western Nile basin are very poor, conflict prone, unstable, militarily negligible, and donor dependent. Nevertheless, they also share a common pool resource extending around Victoria and, therefore, have a certain potential for water-related cooperation in this region. The eastern Nile basin, in contrast, hosts socioeconomically and politically disparate countries with one socioeconomic, as well as militarily (Egypt), and one geo-physical (Ethiopia) hegemony. This given situation has the potential to generate divergent interests that might collide. Whether these interests will bring about an act of reconciliation or an escalation of disputes depends on the institutional cooperation mechanisms in place (Menniken 2008). Consequently, establishing a common base for managing and developing the transboundary water resources of the Nile in a cooperative manner can become especially difficult with the different political systems and their associated various interests, prior bilateral agreements, and legal frameworks (the failure to develop a legal framework will be discussed later; see Sect. 30.4.2.1). Combined with a lack of political will and the vulnerability to national and international conflicts, this again can significantly complicate the way to find a common ground for transboundary water cooperation.

30.4.2 Performance Obstacles of the NBI

Negotiating the terms of cooperation is often a very complex and lengthy process that can demand significant human, financial, technical, and legal resources, especially when the already-discussed environmental, socioeconomic, and political problems are continuing to increase. Due to the prevailing conditions within this basin, it has to be pointed out that these resources are often limited or not available. Despite the remarkable achievements attained by NBI, this situation, therefore, has created a number of organizational obstacles for this institution, which makes it very difficult to manage and develop the waters of the Nile in a sustainable and generally accepted way. The organizational conditions, which are considered to significantly interfere in the process to foster transboundary water cooperation in the Nile basin, will be explained in the following section.

30.4.2.1 Legal Framework

The failure to develop a strong and clear legal framework that is agreed upon by all member countries can be seen as one of the most serious obstacles, why the transitional NBI has not been replaced by a full-fledged RBO, yet. This relates to the fact that the states concerned so far could not reach an agreement on how the waters of the Nile are going to be allocated in a mutually accepted manner. Even if the so-called CFA has already been signed by six Nile basin states (Ethiopia, Kenya, Rwanda, Tanzania, Uganda, and Burundi), continuing disagreements among states led to the CFA not being finalized and ratified yet (Mekonnen 2010). In this connection, the CFA has to be regarded as a new treaty intended to rearrange the colonial-era water rights and usage regime on the Nile River (see 1929 and 1959 Nile Water Treaties). That is why Egypt and Sudan, so far, have been vehement opponents to the CFA (mostly to Art. 14) due to the fact that:

> the CFA will undermine Egypt and Sudan's long-standing claims that the Nile has already been apportioned according to a 1959 treaty in which the two nations allocated around 90 % of the river's waters to themselves. It would also contravene Egypt's persistence that it holds a veto right over all upstream hydro projects under a 1929 agreement with Britain (Eckstein 2001).

The problems related to CFA are further strengthened by the situation that the NBI is accused of delaying these very controversial issues. In this relation, Lemma states: "*It* is *not a secret that the unwritten but real strategy of the NBI is to secure the consensus of all the riparian countries on the less controversial issues by postponing the key but difficult issues of the Nile to a future date*" (Lemma 2001). It, therefore, can be assumed that the longer the current situation persists, riparian countries, especially those who are most dependent upon the Nile, might relinquish their role as a NBI member. Furthermore, it would likely increase mistrust and misunderstandings between the riparian states of the Nile (Shema 2009).

Another obstacle that is closely linked to the problems mentioned above is the failure to establish sufficient ratifications of the 1997 UN Watercourses Convention, the only global convention in place (but not yet into force) that governs the utilization, management, and development of shared water resources for non-navigational purposes. In addition, most riparian states of the Nile, which had been present at the adoption for the Convention, abstained during the election process. In this relation, there were seven states of the Nile basin, which took part in this session. Four of them, Ethiopia, Rwanda, Tanzania, and Egypt, desisted from voting for the benefit of the Convention. Burundi voted against and Kenya as well as Sudan voted in favor of it. Uganda, DR Congo, and Eritrea were absent (Abdo 2003). The overall voting results illustrate the problematic situation in gaining a consensus on the principles of the Watercourses Convention. Both upstream and downstream states claimed that there is an imbalance in the Convention's provisions between the rights and obligations of upstream and downstream states (Eckstein 2002). The reaction of the Nile basin states towards the Convention, consequently, can also be related to the different hydro-political attitudes concerning colonial-era water rights and usage regime.

This lack of unity concerning the CFA and the UN Watercourse Convention indicates that it has to be seen as very challenging for the NBI to settle down disputes among the riparian states, which are related to the allocation, management, and use of water resources. The presence of a legal framework, however, is a crucial element for improving transboundary water cooperation and resolving water-related disputes in any basin. The 1997 UN Watercourses Convention, therefore, could be used as a good starting point for the Nile riparian states, in terms of searching for a legal framework that potentially would have the capacity to efficiently face the problems mentioned above.

30.4.2.2 Financing

The lack of economic infrastructure, the low levels of investment, and the socioeconomic and geophysical as well as political heterogeneity are challenging barriers to the economies of the Nile basin. This current status, therefore, can create a number of problems for the NBI to finance its activities. Some of these problems include poor cost recovery, lack of public funds, the uncertain political climate, or the vulnerability to conflicts that might end up in the hesitation of donors to invest in regional projects. Further problems are the lack of mechanisms and instruments to manage funds, the shortage of long-term commitments that would be necessary to develop trust and cooperation between the countries concerned, and the inadequate legal framework, which makes it very difficult to create a favorable investment environment for private and public investors. For the implementation of projects, for instance, the NBI is currently preparing to undertake investments in the order of over US$ 1 billion (NBI 2013). In order to develop and implement these complex projects, it will be necessary to create financing instruments and sources of finance that are beyond the current capacity. This relates to the fact that the size of the envisioned NRB projects will pose significant challenges to the host countries because most of them cannot afford to incur much more debts than those already existing. As a consequence of the inadequate country-specific financing mechanisms to support such NBI projects, most of the Nile basin countries may, therefore, favor national projects that would increase the probability to generate immediate benefits. This attitude may originate from the perception that this is less risky than investing large amounts of money in preparing complex and long-term projects, which often include several countries, different sectors, and ongoing costs. In an economic sense, the projects' realization, thus, will depend upon NBI's ability to raise soft financing, such as grants that make it possible to realize such large-scale projects (e.g., hydropower development projects, increase reservoir capacity, etc.). The international community with its implementing agencies (UNDP, World Bank, etc.), thus, has to play a significant role by providing financial and technical assistance to the Nile basin's riparian countries. This could significantly improve the investment climate and would help to reduce the risks taken by public and private investors, who otherwise would be unwilling to participate in such complex projects (SIWI 2007).

Another problem results from the funding conditions that are defined by the international donors of the NBI, mainly by the World Bank. In this context, the World Bank outlines "*the World Banks Operational Policy 7.50 requires consent from all riparian countries potentially affected by a project on an international river before funding is granted*" (World Bank 1994 quoted by Shema 2009, S. 27). The Nile basin riparian states themselves are, thus, not able to secure funding for projects if no consensus of the entire basin, or at least of the countries concerned, is achieved. Under the current structure of the NBI, this fact can be seen as a great obstacle for financing NBI projects, because countries, like Egypt, are able to effectively veto the development efforts of other countries such as Ethiopia (Shema, 2009).

30.4.2.3 Capacity and Coordination

Another issue, why the NBI's ambitious goals of establishing regional cooperation and mutually beneficial relationships among all riparian countries should be questioned, is its lack of capacity and coordination. In many parts of the Nile basin, there is insufficient capacity in terms of facilities, information, trained manpower, and funding. The NBI's projects in place are, therefore, often inadequate to address IWRM issues effectively. This also relates to the small number of staff which are currently unable to sufficiently respond to the increasing and emerging demands that are placed on the institution such as strategic planning, resource mobilization, etc. (Belay et al. 2003). The uneven distribution of capacity among the Nile basin states further complicates this situation. For example, due to the differing ability to address technical, institutional, and financial aspects, there is a great disparity between Burundi and Egypt to implement information- and data-sharing agreements such as lack of capacity to handle regional databases and share water resource information (Hearns et al. 2010).

This situation is accentuated by a lack of coordination among water professionals, suborganizations, and other regional institutions. In this connection, it should be outlined that the NBI so far did not clearly establish sufficient coordination mechanisms with other regional RBOs, like the Lake Victoria Basin Commission. Furthermore, the lack of coordination among NBI institutions, like ENTRO and NELSAP-CU, also created long-term challenges for the operational integration across the basin because these programs have evolved independently from each other (Belay et al. 2003).

30.4.2.4 Stakeholder and Public Participation

It is generally accepted that public participation and stakeholder involvement, especially in the water management decision-making processes, have become an integral component for making transboundary water projects more successful. That is why this mechanism is regarded as one of the key principles for IWRM, due to the fact that participation helps to build awareness, confidence, and trust among stakeholders and governments, to reduce conflicts, to create ownership, and increase the likelihood that cooperation is carried from the international level down to the local level (Newton 2006). Therefore, there are certain concerns that public participation has lagged far behind in both understanding what the NBI does and about how to influence major development processes. One reason for this problematic situation is the NBI's insufficient structure to engage local stakeholders and to involve interest groups outside the government departments, particularly women, the youth, and the civil society. Due to the fact that most of them are highly dependent on the water resources of the Nile, it has to be seen as very conflicting that their needs so far have not been sufficiently reflected on the international level and in the implementation of actions (Hearns et al. 2010; NBD 2012). The failure to involve civil society in NBI's decision-making processes also has been claimed by the Nile Basin Society (NBS), a nonprofit organization which aims to involve all stakeholders in water resources management. In this context, NBS states that, under the current work of the NBI, important water resources management and irrigation projects are solely decided at the highest governmental levels. They argue that the civil society in general is excluded from these projects. Additionally, the simple existence of the NBS can be used as an indication that the NBI currently does not sufficiently include the public in its decision-making processes (NBS 2009).

30.5 What Steps Can Be Taken?

The performance obstacles that has been described earlier show that it would be very challenging for the NBI to efficiently address the regional threats and challenges, which have been illustrated in the previous section concerning the environmental, socioeconomic, and political conditions of the Nile basin riparian states. The lack of a legal framework and the various problems emerging in the fields of financing, coordination, and public participation further indicate that it would to be very difficult for this institution to mange transboundary water resources in a generally accepted way. Due to the fact that this situation indeed limits the potential and range of cooperation within the NRB, the coming sections attempt to show what can be done to efficiently and effectively address these identified problems.

30.5.1 Legal Framework

The second section of this chapter demonstrated why the NBI member states could not reach an agreement on how the waters of the Nile are going to be allocated in a mutually accepted manner. Resulting from their divergent interests, historic agreements, as well as different but also shared socioeconomic, environmental, and political problems, they are still not able or willing to jointly agree on sound rules and principles to manage and develop the transboundary water resources of the Nile. By holding on to the 1929 and 1959 Nile Water Treaties, especially Egypt and Sudan have so far refused to agree on certain terms of the CFA, as well as to acknowledge the associated redistribution of the Nile waters on an equitable basis. This problematic situation is reflected through the NBI and its transitional character without a legal binding status. Anyhow, a permanent legal and institutional framework is of utmost importance for the activities of any RBO because it serves as a basic requirement for effective IWRM (Hooper 2006; Taylor 2008). Thus, it is crucial for the Nile basin countries to find a consensus on the CFA, as they would not be able to share, manage, and develop the water resources of the Nile in an equitable, sustainable, and cooperative way, when they did not mutually agree on some important legal aspects. Without a sufficient ratification of the CFA, it rather has to be questioned that a well-functioning and fully operational Nile River Basin Organization (NRBO) will be established in the future, as the following assumption of Mekonnen (2010) underlines: "*In the first place, the establishment of a permanent Nile River Basin Commission is by no means a matter of certainty as the CFA has yet to be finalized, agreed upon fully, and ratified*" (Mekonnen 2010). In addition, it will be essential that Egypt and Sudan sign CFA. Otherwise, it can be expected that the remaining riparian states will move ahead without them, and this would significantly reduce the relevance of an NRBO. It is also important that Eritrea will join the negotiation process because all riparian states should work together in order to enable the effective implementation of an integrated water management approach. Given the exclusion of Eritrea, the refusing attitude of Egypt, which still can be characterized as the most powerful and influential riparian country, and the relative smaller strategic influence of the other members, a newly established NRBO would most likely remain a club of the weak with negligible impact in changing the status quo.

But how to compensate the current situation when no binding basin-wide legal agreement is in place? A possible legal springboard, which could efficiently address the associated problems of the Nile basin, could be the 1997 UN Watercourse Convention because it already has been the basis for the adoption of several watercourse agreements. In this context, the 1997 UN Convention "*is a framework convention that aims at ensuring the utilization, development, conservation, management and protection of international watercourses, and promoting optimal and sustainable utilization thereof for present and future generations*" (Salman 2007). Even if not yet into force, the Convention, therefore, could potentially provide the riparian states of the Nile with guiding principles for developing sound rules under which a legal framework might evolve. Nevertheless, as outlined earlier, it needs to be noticed

Table 30.5 Important principles of the UN Watercourse Convention. (Source: UN 1997, edited by author)

Article 5: Equitable and reasonable utilization and participation

1. Watercourse States shall in their respective territories utilize an international watercourse in an equitable and reasonable manner. In particular, an international watercourse shall be used and developed by watercourse States with a view to attaining optimal and sustainable utilization thereof and benefits therefrom, taking into account the interests of the watercourse States concerned, consistent with adequate protection of the watercourse
2. Watercourse States shall participate in the use, development and protection of an international watercourse in an equitable and reasonable manner. Such participation includes both the right to utilize the watercourse and the duty to cooperate in the protection and development thereof, as provided in the present Convention

Article 7: Obligation not to cause significant harm

1. Watercourse States shall, in utilizing an international watercourse in their territories, take all appropriate measures to prevent the causing of significant harm to other watercourse States
2. Where significant harm nevertheless is caused to another watercourse State, the States whose use causes such harm shall, in the absence of agreement to such use, take all appropriate measures, having due regard for the provisions of articles 5 and 6, in consultation with the affected State, to eliminate or mitigate such harm and, where appropriate, to discuss the question of compensation

Article 8: General Obligation to cooperate

1. Watercourse States shall cooperate on the basis of sovereign equality, territorial integrity, mutual benefit and good faith in order to attain optimal utilization and adequate protection of an international watercourse
2. In determining the manner of such cooperation, watercourse States may consider the establishment of joint mechanisms or commissions, as deemed necessary by them, to facilitate cooperation on relevant measures and procedures in the light of experience gained through cooperation in existing joint mechanisms and commissions in various regions

Article 10: Relationship between different kind of uses

1. In the absence of agreement or custom to the contrary, no use of an international watercourse enjoys inherent priority over other uses
2. In the event of a conflict between uses of an international watercourse, it shall be resolved with reference to articles 5 to 7

again that most of the Nile basin countries did not agree upon the Convention because they saw an imbalance between the rights and obligations of upstream and downstream riparian states. The Convention, therefore, should rather be regarded as a very good starting point or an appropriate framework under which they could negotiate in order to reach an agreement (Abdo 2003). In this relation, it is recommended that at least the following general principles of the Convention be considered by the riparian countries of the Nile in order to efficiently face and, in the best case, harmonize their differing and sometimes antagonistic expectations, interests, and claims (Table 30.5). In addition, especially the compliance of Articles 5, 7, 8, and 10 of the Convention could help to improve transboundary water cooperation in this region, as they would encourage the Nile basin states to resolve conflicts over the allocation, use, and management of the transboundary water recourses of the Nile and, therefore, help them in their effort to attain an agreement.

If the riparian states of the Nile basin, however, will use the Convention as a foundation and guideline for their negotiations, it is inevitable that they bring their national agreements and legislation into coherence with the international law. In this relation, not only Vollmer et al. (2009) but also Zaag and Savenije (2000a, b) provide several policy and legal framework requirements that should be taken into account, if riparian states are seeking to harmonize national legislation with international law. Considering their suggestions and applying them to the specific conditions of the NRB, it is, thus, advisable that the Nile basin's states will establish (if they are not already available) or strengthen their national water councils or coordination committees in order to avoid fragmentation and the overlapping of responsibilities. This step would help to not only reduce the lack of understanding regarding international law but also increase the likelihood that from the subnational to the national level, coordination between the different ministries is improved.

Besides that, it is also essential to sufficiently inform the stakeholders and the public about the negotiations and on how the resultant outcomes could potentially affect them. In this field, politicians and other decision makers of the Nile basin are requested to clearly show why decisions are being made and for what purpose. Better methods for awareness building should also be increasingly considered in order to support the politicians in their effort to enhance decision-maker understanding. In doing so, divergent attitudes concerning the legal framework might be reconciled or avoided.

Besides the necessity to fully implement sound rules and principles for effective transboundary water resources management, another aspect also needs to be taken into account: the capability of enforcement. As mentioned earlier, the implementation of water laws have remained weak in this region due to the lack of political will and the technical, financial, and human resource limitations. The responsible national and international authorities, therefore, should be equipped with an adequate mix of enforcement mechanisms (e.g., administrative fines, formal notice of non-compliance, financial penalties, etc.) in order to assure that national, regional, or local actors, who are failing to comply with laws and regulations, are brought back into line. In this connection, national and international partners are called upon to provide adequate assistance (financial, technical assistance, etc.) in order to enhance the overall institutional capacity for designing, adopting, and implementing enforcement measures and dispute-resolution mechanisms.

30.5.2 Institutional Structure, Functions, and Capacity

An appropriate institutional structure at the local, regional, national, and international level is a necessary precondition to achieve the sustainable and integrated management of water resources within a river basin (Hooper 2006). Due to the prevailing conditions of the Nile basin, it becomes clear that the CFA seeks to establish a permanent Nile River Basin Commission (NRBC) (Mekonnen 2010). In this relation, a river basin commission is adequate *"when significant development options are still to be considered in the river basin, conflicting uses [are] significant, information and policies still need further development*" (Vollmer et al. 2009). In addition, it is

Table 30.6 Cooperation promotional functions of RBOs. (Source: UN 2009, edited by author)

Coordination and advisory function, which includes coordination of and assistance to riparian states in their activities to implement the agreement
Executive function, which includes direct activities for a joint body to implement the agreement
Control of implementation and dispute settlement function, which includes monitoring of implementation, reporting on implementation, and settling differences and disputes

important to note that the institutional setup of the NBI (see Fig. 30.2) is likely to be taken over if an NRBC would be established. However, the lack of capacity among NBI institutions so far caused some projects to be identified as being inadequate to address IWRM issues efficiently. The NBI and, in the best case, an NRBC consequently should be equipped with a strong implementation and enforcement capacity to ensure that improved coordination and collaboration with the different ministries is possible. Apart from them, other actors, like local stakeholders, community interest groups, donors, NGOs, etc., also need to be involved, as cooperation just can be sufficiently achieved when the interaction between all levels and parties is ensured. In this relation, UN (2009) highlights three major functions, which a transboundary river basin institution should incorporate in order to efficiently promote cooperation between states that share a common water resource (Table 30.6).

As a consequence, it becomes apparent that the NBI/NRBC should sufficiently consider these functions in its design in order to improve transboundary water cooperation between the riparian states of the Nile. In this context, UN-Water (2008), UN (2009), and Hooper (2006) describe several tasks, which might be used to strengthen these different functions. Here, it is important to note that the following suggestions that are described in Table 30.7 will particularly consider the problems that have been identified previously (see Sect. 30.4).

Due to the conflict-laden upstream–downstream constellation between Egypt, Sudan, and Ethiopia, particularly the control of implementation and dispute settlement function would require special attention. The assessment of dispute situations and needs, for example, could help to promote mutual understanding among the different disputing parties and, therefore, would serve as an instrument to build trust and confidence between them. Associated tools, under which the likelihood of water-related controversies would be probably mitigated and resolved, could be additional research, interpersonal or intergroup communication, special meetings of stakeholder and community committees, impartial third-party advice, mediation, etc. (Hooper 2006). Furthermore, appropriate and flexible rules of procedures, as well as terms of references, need to be clearly defined and shaped in a manner that they can be applied to the specific local, regional, national, and internationals levels of a certain region (UN 2009). Anyhow, all these aspects just can be realized if sufficient institutional and human capacities are in place, which is not always the case in the Nile basin. It has been shown that there is insufficient capacity in terms of facilities, financing, and trained manpower (e.g., small number of staff to handle regional database, a different ability to address technical, institutional, and financial aspects, etc.). Together with a lack of coordination among water professionals, suborganizations, and other regional institutions, these conditions extremely complicate the way to improve

Table 30.7 Cooperation promotional suggestions. (Source: UN 2009; UN-Water 2008; Hooper 2006, edited by author)

Coordination and advisory function:
Coordinate the development of a unified information system under which cross-border information exchange and data sharing would be facilitated
Serve as an information platform and forum to enhance stakeholder consultation, public participation, issue clarification, and enable the basin-wide access to knowledge and tools
With regard to transboundary water issues, provide assistance and advice, as well as draft proposals to improve the national legislation of the Nile riparian states as well as to bring national legislations into coherence with international law
Compose, revise, and approve training programs for the personnel of the Nile riparian states
Coordinate actions to prevent or mitigate floods, water quantity and quality deterioration, water pollution, and other issues, which can have a transboundary impact
Executive function
Negotiate with donors and other financiers to obtain financial and technical support, which is necessary for project implementation and maintenance
Identification and implementation of benefit-sharing schemes and programs to enhance the political will to cooperate and share the associated financial costs
Setting up regimes for water reservoirs, especially for those that can significantly affect downstream countries
Developing joint research, planning, and management programs to build trust and confidence between the riparian states of the Nile
Control of implementation and dispute settlement function:
Adopting dispute settlement procedures from international agreements and apply them to the specific conditions of the Nile basin
Perform self-assessment, monitoring, and reporting on the implementation and settling of differences and disputes
Setting up of stakeholder and community advisory committees to inform all parties concerned about the state of the watercourse
Use of neutral third-party assistance (facilitation, mediation, etc.) to ensure equity and thus building trust between parties
Use of regional and joint fact-finding mechanisms in order to make adequate recommendation that help to resolve disputes

transboundary water cooperation in this region. Not only the riparian countries but also the international community is, therefore, requested to provide sufficient capacities, which guarantee that cross-sectorial and cross-national coordination and cooperation is possible. The NBI, consequently, should be equipped with sufficient human capacities that are characterized by broad competences and interdisciplinary skills. As this is currently lacking, the NBI or the riparian countries concerned, thus, could offer courses, where communications, negotiations, diplomacy, and conflict-resolution skills of the staff are developed and improved. In this connection, it is especially recommended that the capacities of managers, who are operating at the national and local levels of the NRB, should be strengthened. This step would significantly help to raise the awareness of the necessity to share transboundary water resources. It should not, however, be forgotten that at the same time, it would also be very important to increase the capacity to establish and implement policies and laws as well as relevant enforcement mechanisms because they form the base for internal and external funding arrangements (UN-Water 2008).

30.5.3 Exchange of Information and Joint Activities

Information, which is based on well-organized measurement networks and monitoring programs, is a crucial precondition for identifying problems and assessing water-related cooperation possibilities because it forms the ground for policy decisions that occur on the local, national, and international level (Zaag and Savenije 2000a). Another possible option for improving transboundary water cooperation in the NRB would be an increased exchange of information, especially across borders, because it could serve as an important tool to efficiently face the lack of coordination among ministries, suborganizations, and other regional institutions. More than before, the riparian states of the Nile should, therefore, seek to share and exchange all the relevant information and data that relate to transboundary water resources issues. This step would significantly help to avoid potential conflicts that might emerge through defuse or controversy information. In this connection, it is suggested that the following five key elements should be considered by NBI when data and information exchange processes are developed, maintained, and improved. It needs to be mentioned here that these key elements have been derived from a workshop on building and managing transboundary water institutions in Africa:

1. Nile basin countries have to agree on data-sharing procedures.
2. Joint databases need to be accessible to all parties concerned.
3. The technical advisory committees of the NBI and its suborganizations should concentrate on data, which would particularly involve committees of country officials, who are responsible for collecting the relevant information.
4. Implementing and strengthening quality control and quality assurance procedure that can range from sensitive versus nonsensitive data.
5. Starting with the exchange of "easier" information in order to learn to work and cooperate with ministries and other institutions. Afterwards "tougher" issues, like water use and allocation, can be faced.

Besides the key elements presented earlier, Hearns et al. (2010) further outline other important aspects that have the potential to increase the likelihood that the basin-wide exchange of information and data is strengthened (see Table 30.8).

The formulation and implementation of concrete and well-defined joint activities (e.g., joint research, planning, ventures, etc.), which are mutually beneficial to all parties concerned, would also be a possible development option to foster the cooperative management of shared water resources (Zaag and Savenijee 2000a; UN-Water 2008). Because of that, they could serve as appropriate tools, under which the riparian states of the Nile would establish mutual understanding for each other. An increase of joint research across borders, for instance, would enable individuals and institutions to enhance their capacities and knowledge, as well as to understand the various problems and needs that can be related to the water resources of the Nile. This would help to balance and strengthen the capacities of each riparian state (e.g., between Egypt and Burundi) and, therefore, could increase the likelihood that conditions for

Table 30.8 Considerations to improve the exchange of information and data. (Source: Hearns et al. 2010, edited by author)

Type of data, which is going to be exchanged, is important. There have to be clear benefits to share data and information. Otherwise problems might evolve that will hinder cooperation efforts
Data and information serve as a confidence-building tool. Some data may include sensitive or nonsensitive information. In order to build confidence among the parties concerned, it is advisable to share nonsensitive data first. Afterwards, information of national interest or sensitive data might be exchanged more easily as well
Data and information must focus on needs because bilateral infrastructure agreements for hydropower generation, for instance, will require different types of information than multilateral agreements for environmental protection
All sources of data can be useful. Information originating from the local, municipal, or district level may not include empirical data. The information and data, thus, will not end in a scientific publication but it will help to capture the knowledge of people who are living in a certain region. As a consequence, it is important to assess all potential data sources
Financing the collection, analysis, and exchange of data and information has to be considered and integrated into agreements. This relates to the situation that the generation and transfer of data and information often create significant costs → *Costs associated with data and information exchange* should be based on the needs and capacity of the countries to supply them
Data and information serve as a leveraging tool. Capacities of poorer countries have to be developed and improved in order to reduce the bargaining power of richer countries that often have more data and information sources to trade
Data and information serve as an awareness tool. The exchange of data and information helps to build and/or increase awareness at all levels → especially at the highest level, more substantive agreements can be made
Formal versus informal mechanisms for data and information exchange. Data and information, which are already available, can be exchanged without a formal protocol, but rather as part of projects. Moreover, data and information exchange should be regarded as a technical necessity and technical experts should be responsible to determine the types, method of exchange, frequency, quality control, etc. Legal advices are also absolutely necessary in order to guarantee the consistency with international norms, etc.
Exchange those data and information which the countries concerned are willing to exchange. Some riparian states are unwilling to make transboundary water analysis, but are rather open to collaborate in relation to transboundary environmental analysis

improved cooperation are formed. Possible topics for joint research could be: cost–benefit analyses, efficient and sustainable use of land and water resources, regional strategies for mitigation of disasters, harmonizing legal and regulatory systems at different levels, etc. (Hooper 2006). Another cooperation promotional measure would be to increase the number of joint plans and programs within the NRB because they can lead to greater effectiveness than efforts, which have been developed by one country alone. Operation rules for large hydropower development projects, for instance, could be jointly prepared in order to assess the impacts of dams on more than one riparian country. The development of joint ventures between two or more countries also could be regarded as a possible solution for cooperatively managing and developing the water resources of the Nile. This is particularly the case when the interests of the Nile basin riparian states are harmonized and try to achieve a common objective. However, joint ventures, which have been established just by a few countries should not affect or threaten the other riparians of the NRB.

30.5.4 Stakeholder Involvement and Public Participation

The obstacles to transboundary water cooperation in the NRB described that under the auspices of the NBI programs, public participation at the local level has lagged far behind because its structure so far did not sufficiently neither engage local stakeholders nor involve interest groups outside the government departments. Due to the fact that this problematic situation can significantly interfere in the various fields of transboundary water cooperation, the NBI and its member states, therefore, should seek to strengthen those issues, which so far have been neglected in this region. In order to enhance transparency and decision making, to reduce conflicts and risks, to create ownership and facilitate the acceptance and enforcement of decisions, agreements, and policies, they, thus, should seek to:

1. Provide information to the public in order to raise awareness about the Nile basin and the potential goals of the NBI.
2. Create local forums for educating and involving all parties concerned to understand their interests, worries, and needs.
3. Recognize the role of stakeholders through (transboundary) agreements that explicitly concentrate at stakeholder and local community involvement in order to foster their participation from the highest level.
4. Identify and reinforce weaknesses that can be associated with stakeholder involvement and public participation (e.g., conducting an analysis for each project on why and where the stakeholders are probably not engaged in order to determine which project parts need to be strengthened).
5. Enhance awareness-raising activities and education of decision makers and government officials to better understand the role of stakeholders at the local level.
6. Increased use of international stakeholder forums that would inform the NBI secretariat about civil society and local interests.
7. Local stakeholder engagement on regional issues in order to develop local solutions, even across borders (Hearns et al. 2010).

30.5.5 Financing, Benefit, and Cost Sharing

It has been shown that the current and very heterogeneous socioeconomic status of the different Nile basin riparian states have created a number of problems to finance and, thus, address transboundary water issues. Once again, and to mention only a few, some of these problems can be related to the uncertain political climate or to the vulnerability to regional, national, or international conflicts, which might end up in the hesitation of donors to undertake long-term investments in this region. Others challenges arise from the inadequate legal framework, which makes it very difficult to form a favorable investment climate for private and public investors. The shortage of long-term commitments that would be strongly needed to develop trust and collaboration between the concerned countries, as well as the funding conditions of international donors (consent-based project funding), like the World

Bank, can also be listed. Sustainable and adequate financing mechanisms, however, are crucial and the key for efficiently and effectively managing the shared water resources of a river basin. In order to improve transboundary water cooperation, the NBI, therefore, should incorporate a mixture of financing mechanisms, as well as various sources of financial resources. These include national budgets, external bilateral or multilateral donors, private–public partnerships, etc. Due to the fact that the investment requirements will probably exceed the available financial resources of the Nile basin riparian states, the international community with its implementing agencies, thus, has to play an important role in providing financial assistance and support. This could significantly increase the likelihood that the investment climate within this region will be improved, as the risks taken up by public and private investors, who may otherwise be unwilling to provide financial support, will be reduced. By providing financial support, they further have the possibility to determine cooperation as a prerequisite for accessing financial resources, which in turn could serve as an incentive for the riparian states of the Nile to collaborate.

Nevertheless, this should not hide the fact that NBI and its member states also have to develop and install sustainable and innovative financial mechanisms that will help to reduce the dependence upon donor support. These mechanisms, for instance, could be regional revolving funds, payments for ecosystem services, increased inter-riparian financing, cost recovery for water services, or payments of polluters. However, all these financing schemes require not only political support and good governance but also an appropriate institutional structure (UN-Water 2008). In this relation, especially the political will, which has been identified to be lacking in the NRB, has to be encouraged. The NBI, therefore, should clearly identify and demonstrate the benefits of transboundary water resources management in order to create incentives for the riparian states to cooperate. Needless to say, there is no right path or "one-size-fits-all" approach to achieve long-term, sustainable, and reliable cross-border cooperation. However, riparian states are normally rather interested in the economic opportunities and ecosystem services which are linked to the access to water than in water itself. The effective implementation of the concept of benefit sharing that has been developed by Sadoff and Grey (2002), thus, could provide a more flexible framework with a wider range of cooperation possibilities as it offers several incentives and nonconsumptive benefits (Table 30.9). In this relation, they distinguish between four types of cooperative benefits:

1. Cooperation between the riparian states enables a better management of the watershed ecosystem as a whole and, therefore, produces *benefits to the river*.
2. Rivers are economic and physical systems. Cooperative management can yield major *benefits from the river*.
3. Rivers have political relevance, particularly when they are shared between states. Tensions between co-riparian states are prevalent to a greater or lesser extent and those tensions generate costs. Cooperation can reduce these costs and, hence, create *benefits because of the river*.
4. By generating benefits from the river and reducing cost because of the river, cooperation can lead to better economical and political relations between states, which can be described as *benefits beyond the river*.

Table 30.9 Types of cooperative benefits on international rivers. (Source: Sadoff and Grey 2002, edited by author)

Types	Challenges	Chances
(1) Providing benefits to the river	Degradation of water quality, water catchments, wetlands, biodiversity, ecosystems, etc.	Enhanced water quality and river flow characteristics, improved soil conservation, improved overall environmental sustainability and biodiversity, etc.
(2) Producing benefits from the river	Growing water demands, inadequate management, development of water resources, etc.	Enhanced water quality and environmental protection, improved water resources management and development → improved hydropower and agricultural production, flood/drought management, etc.
(3) Decreasing the costs because of the river	Regional disputes and disagreements with political, economical, and social consequences, etc.	Policy shift/changes, away from disputes and tense regional relations towards improved cooperation and development → decreasing conflict potential and risk → improved socioeconomic conditions (e.g., greater energy and food security), etc.
(4) Generating benefits beyond the river	Regional fragmentation and inequality etc.	Integration of regional infrastructure, markets, trade, etc.

Through the identification of alternative development plans and benefit-sharing ideas, the riparian countries of the Nile would consequently have more possibilities of finding mutually agreeable solutions concerning the challenging redistribution of the Nile waters. However, the situation mentioned above can just be achieved if the physical locations of resources are separated from the distribution of benefits. This ideally happens by focusing first on identifying and creating basin-wide benefits, and secondly on distributing them in an equitable and fair way. Thus, mechanisms have to be developed which aim to locate energy, industry, and agriculture at places where the level of productivity is highest and the impacts on the society and the environment is least disruptive. Here, it should be considered that related decisions sometimes include very difficult tradeoffs and choices, especially when the amount of available water is limited (Sadoff et al. 2008). The NBI, therefore, has to intensify its efforts to assist and advice the riparian states of the Nile in identifying their potential benefits and how they can create incentives for cooperation. Downstream states, for instance, could be compensated for the implementation and operation of additional storage facilities made by upstream states. This also might lead to the situation that upstream states are going to share a certain portion of their generated benefits, which in turn could generate possibilities of sharing the costs of these practices (UN-Water 2008). In this context, it is recommended that the riparian countries of the Nile basin should concentrate on their comparative advantages in order to develop and enhance political will, economic interdependencies, mutual understanding, and

Table 30.10 Summary of cooperation promotional measures per category. (Source: Hudson 2009, edited by author)

Legal framework	Clearly determine institutional arrangements Clearly set out enforcement and dispute-resolution mechanisms Include not only water quality and quantity, climate change, but also social values Identify possibilities and clear means to share the various benefits of water, not only water itself Consider provisions and arrangements for joint monitoring, information exchange, and public participation Incorporate mechanisms and instruments, which promote joint economic development
Institutional structure, functions and capacity	Clear mandates for regional and national bodies Strong cross-sectorial coordination at the national level Serious and real political will and financial commitment Involve an appropriate range of stakeholders Clearly set out RBO rules of procedures and terms of reference Well-trained staff who are characterized by broad competencies and multidisciplinary skills. Incorporating and providing (1) coordination and advisory functions, (2) executive functions, and (3) control of implementation and dispute settlement functions
Exchange of information and joint activities	Accurate assessment of information in order to make well-informed decision making and policy formulation Information from different countries have to be comparable → implementation of harmonized, compatible assessment methods and data systems, agreed terminologies, etc. Exchange of information between countries is essential (e.g., infrastructure, agricultural production sites, extreme events, hydropower operations, etc. are essential)
Stakeholder involvement and public participation	Enhance transparency and show why decisions are being made and for what purpose Facilitate the acceptance to enforce decisions and policies Create mechanisms and instruments to harmonize the relations between stakeholders Sufficient financial resources have to be available in order to be effective Perform stakeholder analysis in order to involve all relevant groups
Financing, benefit and cost sharing	Concentrate on the use of water to generate benefits, not solely on the allocation of water Focus on the generation of basin-wide benefits Share the generated benefits in an equitable manner Note that benefit-sharing approaches also often include difficult tradeoffs and choices Payments for benefits and the compensation for costs can be an important element for cooperative arrangements Payments for ecosystem services should be considered Short and long-term financing are crucial for legal frameworks, new institutions, capacity building, and investments Innovative financing mechanisms, like regional revolving funds, payments of ecosystem services, cost recovery for water services, etc., need to be considered Strong political support, good governance, and effective institutions are strongly required

confidence building. Due to its hydropower development potential, Ethiopia, for instance, could focus on the generation of hydroelectricity that could also benefit downstream countries. Egypt, in contrast, could provide technical expertise and financial support to upstream countries, as this is significantly lacking in these areas. Sudan and other countries, which have a high potential in agriculture, can focus on the production of agricultural products, which then can be exported regionally. In order to extend the spectrum of benefits, it is also recommended that the concept of virtual water and the assessment of groundwater resources have to be increasingly taken into account, as these could assist the riparian states of the river basin to explore more transboundary water cooperation possibilities than the traditional focus on surface water (Vollmer et al. 2009; Zaag and Savenije 2000a). This situation, thus, could increase the scope of cooperation as well as the number of alternatives to achieve successful and longstanding cross-border cooperation within the Nile basin.

30.6 Conclusion

This chapter sought to shed a new light on transboundary water cooperation in the Nile basin. Based on the assumption that current status quo limits the potential and range for cooperation in this region, it aimed (1) to identify the major obstacles that can be associated with transboundary water cooperation in the NRB and (2) to present possible solution approaches to take measures against these problems in order to assist the NBI in its effort to efficiently and effectively improve transboundary water cooperation between the riparian states of the Nile.

The examination concerning water cooperation in the Nile basin showed that the riparian countries of this region have experienced an evolutionary process of transboundary water cooperation beyond compare, but still have to face a myriad of complex issues. On the one hand, it has been demonstrated that with the formation of the NBI, the riparian states have heralded a new era in governing and managing the waters of this region, as they jointly recognized that the best way to protect, manage, and develop their water resources is through close cooperation, whereby all interests of upstream and downstream countries could be considered. Resulting from their divergent interests, historic agreements, as well as not only different but also shared environmental, political, and socioeconomic problems, on the other hand, it has been shown why the NBI member states so far could not reach an agreement on how the waters of the Nile are going to be allocated in a mutually accepted manner. This problematic situation is reflected through the NBI and its transitional character without legal binding status. In addition, it was found that this interim institution could not have the full potential to sufficiently promote transboundary water cooperation between the riparian states of the Nile. Following the words of Kofi Annan (2002) "(. . .) *the water problem facing our world need not to be only a cause of tension; they can also be a catalyst for cooperation.* (. . .) *If we work together, a secure and sustainable water future can be ours*", this chapter finally provides a number of major conclusions and recommendations:

- The international community with its implementing agencies should encourage Egypt and Sudan to open talks again on the CFA. The equitable redistribution of the Nile waters is crucial to enable the peaceful, cooperative, and sustainable management of transboundary water resources in this region. In this context, the governments of the Nile basin are requested to bring their national agreements and legislations into coherence with international law to facilitate the development of an effective transboundary water agreement for joint cooperation that is applicable to all levels and would allow the equitable utilization of the Nile waters. However, this rearrangement has to enable downstream countries to influence decision made by upstream countries in order to minimize the risk to be negatively impacted.
- When it is applied to the specific conditions of the Nile basin, the 1997 UN Watercourse Convention has the potential to provide the riparian states of the Nile with guiding principles (e.g., no harm rule, equitable and reasonable utilization), which can serve as a guideline for their negotiations in order to reach an agreement that sufficiently considers the upcoming water demands of all Nile basin riparian states. It, thereby, could resolve conflicts over the use, allocation, and management of the Nile waters and would help the riparian states of the Nile in the effort to find legal framework that is accepted and obeyed by all parties concerned.
- The transformation of the NBI into a NRBC that is resilient over time should be regarded as one of the most important factors in order to improve transboundary water cooperation in this region. Once it is established, an NRBC has to be equipped with adequate decision-making and enforcement powers to sufficiently perform the tasks, which can be related to the coordination and advisory function, the executive function, and the control of implementation and dispute settlement function of RBOs. It should also consider and incorporate those functions, which the riparian states of the Nile expect to be provided by such an institution.
- Even though no trust among the Nile basin riparian states exists, cooperation may flourish with the exchange of information and data across borders or with joint activities. This would help to balance and strengthen the capacities of each riparian state and, therefore, could increase the likelihood that conditions for improved cooperation are formed.
- Conduct stakeholder analysis and develop joint activities for participation, especially at the local levels of the Nile basin to sufficiently engage local stakeholders and interest groups outside the government departments. Their needs and worries further have to be adequately reflected on the international level and in the implementation of actions. In doing so, the NBI could enhance transparency, avoid conflicts and risks, create ownership, and facilitate the acceptance and enforcement of decisions, agreements, and policies.
- In order to enhance political will, mutual understanding, economic interdependencies, and confidence building, the NBI should assist and advice the riparian states of the Nile in identifying and assessing the potential benefits of cooperation. The effective implementation of the concept of benefit sharing, however, makes it necessary that the riparian states of the Nile concentrate on their comparative advantages (e.g., technical expertise vs. hydropower generation or agricultural production, etc.). Here, the concept of virtual water and the identification and

assessment of ground water resources should also be taken into account because they could increase the scope of cooperation.

- To reduce the dependence on donor support and ensure the financial sustainability, adequate financing mechanisms (e.g., regional revolving funds, payments for ecosystem services, cost recovery for water services, etc.) and financial commitments of the Nile basin riparian states are strongly required (e.g., financial support through a separate line in the national budget, etc.).
- Various international organizations and development partners are involved in the International Consortium for Cooperation on the Nile (ICCON) and/or finance various development projects within the Nile region. They have, consequently, the possibility to determine cooperation as a prerequisite for accessing international financial resources, which in turn could serve as an incentive for the riparian states of the Nile to collaborate**.**

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Part VII
Watershed Services and Water Management

Chapter 31
Payment for Watershed Services in the Mara River Basin: Part I: Institutions and Stakeholder Engagement

Mahadev G. Bhat, Michael McClain, Doris Ombara, William Kasanga and George Atisa

Abstract This chapter develops a concise, but comprehensive, plan for designing and developing a payment for watershed services (PWSs) mechanism in the Mara River basin (MRB), Kenya. It will describe the current water situation in the Mara and future trends. It will make the "case" for improved land management practices and more efficient water use in the headwaters of the catchment (Nyangores and Amala sub-catchments), and it will introduce PWS as an effective mechanism to facilitate and support improved water research and management. There is a growing sense of optimism among stakeholders in the Kenyan and Tanzanian sides of MRB. National water resources management legislations in both countries have enabled the formation of water users associations (WUAs). Legislative provisions for introducing PWS have been made. Various government agencies, nongovernmental organizations (NGOs), and academic institutions have been conducting extensive studies to estimate a minimum environmental flow regime for the river. Efforts to educate resource users through WUAs are also being made. There is definitely no consensus among user groups as to who should be the lead agency for implementing intracountry or intercountry payment schemes as of yet. However, if the above-mentioned governmental and nongovernmental efforts continue, the prospect of PWS implementation in MRB in the future is promising.

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31.1 Introduction

Water scarcity and attendant conflicts can arise when upstream resource users withdraw water and/or change various components of a watershed—crop lands, pasture, forests, wetlands, riparian zones, etc.—such that the natural ability of that watershed to provide adequate quality and quantity of water to downstream users is compromised. While natural variations in climatic conditions (e.g., rainfall distribution) are primarily responsible for seasonal fluctuations in downstream water flows and quality, the human-induced alterations to upstream natural systems might increase the degree of such fluctuations.

The Mara River basin (MRB) of Kenya and Tanzania, part of the Lake Victoria basin, provides a case in point, where deforestation in the upper catchment area, overgrazing of pasture, upstream diversion of water for small- and large-scale agriculture and increasing demand for residential water have affected the quality and availability of water for downstream users. The impacts are felt most strongly during times of drought, when river flows can drop to dangerously low levels and water quality deteriorates. The natural health of the Masai Mara–Serengeti ecosystem, located in the lower section of MRB, hinges on the year-round adequate flow of unpolluted water across the national boundary. Commercial farmers, tourism-dependent group ranchers, and hoteliers in Kenya and Tanzania also require a sustainable flow of water for the successful operation of their industries. Reducing seasonal fluctuations in water flow and improving water quality along the entire stretch of the river would require certain upstream user groups to undertake river-friendly land- and water-use practices.

In recent years, water resources management worldwide has started to shift from top-down type of regulatory management toward a governance regime that embraces the role of stakeholders in managing their own resources. This change in focus can also be seen in this region. As water demands exceed supply, Kenya and Tanzania have initiated water sector reforms that stress stakeholder participation in water resources management. These reforms encourage local institutions to manage water resources through suitable user-financed funding mechanisms such that the water resources are put to efficient and equitable uses. Additionally, these reforms begin to view water as an economic good and, thus, promote the idea of proper economic valuation and accounting of water and watershed services.

The recent institutional reforms alone will not guarantee effective conservation and management of water resources unless systems of immediate and direct financial incentives are put in place. Sustainable, basin-scale water management requires cooperation between upstream and downstream users in the MRB, where upstream users apply suitable water and land management practices that preserve watershed services and do not impact downstream users (Smith et al. 2008). However, what incentive do upstream users have to implement and at what costs? Their actions will cost them money and resources, while many of the benefits will be enjoyed by downstream users. Upstream communities in MRB also are primarily subsistence farmers that grow food for family consumption. These communities might implement watershed-friendly best management practices (BMPs) if an outside party pays some of the costs of implementation. At the same time, downstream water users are relatively rich and include large-scale farmers, miners, municipal councils/towns, hospitals, touristic hotels, camps and lodges, and business communities that appropriate significant income from nature-based tourism. A logical suggestion that has surfaced recently is that the downstream users pay for the costs of adoption of BMPs upstream so that there is adequate and constant flow of water in the basin for their benefits as well as incentives to the upstream communities to manage and provide more water and of good quality. Upstream communities in this context become sellers of environmental services while the downstream users become buyers. This financial scheme is popularly known as the payment for environmental services (PESs) or the payment for watershed services (PWSs) in the context of watershed management.

The purpose of this chapter is to provide a roadmap for Mara River basin stakeholders participating in a process to design and develop a market-based system of PWSs. This chapter describes the current water situation in the Mara and future trends. It makes a business "case" for improved land management practices and more efficient water use in the headwaters of the catchment (Nyangores and Amala sub-catchments), and it introduces PES as an effective mechanism to facilitate and support improved watershed services provision. It describes what PWS is, with illustrative examples from other parts of the world. It puts PWS in a Mara context by identifying the potential buyers and sellers of services, describing the legal context (current and imminent), and exploring potential institutional frameworks. Finally, it describes the process of developing a PWS and the roles and responsibilities of the stakeholder participants. It includes a checklist and references to support the process.

31.2 Current Ecological and Economic Environments in the MRB

31.2.1 The status of water resources in the Mara Basin

The Mara River originates in the uplands of Mau Escarpment, situated on the western side of the Great Rift Valley of Kenya. The escarpment was originally forested but is now composed of a remnant forest surrounded by silvicultural plantations above, tea plantations below, and broad areas of small-scale farms. Downstream, the river crosses a zone of large commercial farms and grazing lands before entering the vast savannas of Masai-Mara National Reserve (MMNR) and Serengeti National Park, home of the world's greatest variety of megafauna including zebras, elephants, giraffes, lions, and wildebeests. Downstream of the parks, the river traverses a mixed

Table 31.1 The main geographic and economic characteristics of the Mara River basin

Basin size	$\sim$ 13,750 km^2; 65 % in Kenya and 35 % in Tanzania
Rainfall	1,400 mm/year in the Mau Escarpment to 500–700 mm/year in the dry plains of Northwest Tanzania
Seasonality	Short rains last from October to December and long rains from March to June
Elevation range	3,000 to 1,300 m amsl
River length	$\sim$ 395 km
Source	Mau forest complex, Kenya
Outlet	Lake Victoria near Musoma, Tanzania
Main tributaries	Nyangores River, Amala River, Sand River, Talek River, and Borogonja River
Larger basin	Lake Victoria Basin
Population	660,320; KE: 428,706; TZ: 231,614[a]
Conservation areas	Masai Mara National Reserve (MMNR); Serengeti National Park
Tourism numbers	Increase from 133,000 visitors in 1995 to 240,000 in 2004 in MMNR[b], and from 59,564 visitors in 1990 to 378,218 in 2002 in the Serengeti National Park[c]
Livestock	1,079,270; KE: 559,204; TZ: 520,066[a]

[a] Hoffman (2007)

[b] Republic of Kenya, Central Bureau of Statistics (CBS) (2005)

[c] United Republic of Tanzania, National Bureau of Statistics (NBS) (2002)

landscape of small-scale farms and grazing areas before filling the Mara Swamp, which hosts a vibrant fishery and productive papyrus flats. The lazy flow of the river through the swamp eventually enters Lake Victoria and joins the other headwaters of the Nile River. (See Table 31.1 for the details of physical and economic characteristics of the basin.)

The main-stem river of the Mara provides the only perennial source of water to the dry lower basin, fed by the Nyangores and Amala tributaries emerging from the Mau Escarpment (Fig. 31.1). It is in the upper and middle catchment where land-use practices have had significant negative impacts on water resources in the MRB. The area has lost an estimated 40 % of the forest cover to agriculture in the past 40 years with the greatest losses recorded in the year 2000 (World Wildlife Fund 2005). Farmers in the middle catchment grow crops such as maize, tea, potatoes, and beans that require intensive land preparation by plowing and, therefore, aggravate soil erosion. Farmers in both the upper and middle catchment primarily depend on rainfall to water crops, although irrigation is increasingly being developed and utilized by medium- and large-scale farmers in the middle catchment.

Current threats to water resources in the MRB are multifaceted, but there is general agreement that rapid population growth and associated intensification of small-scale agricultural activities in the headwater catchments of the basin have had a significant impact on the quality and quantity of water flowing in the river. Current farming practices facilitate soil erosion that carries along with it chemical fertilizers from farms. Although the river can still be classified as having fairly good quality and quantity of water, the ongoing developments pose serious environmental challenges. Current farming practices also diminish the rate of rainfall infiltration into soils and,

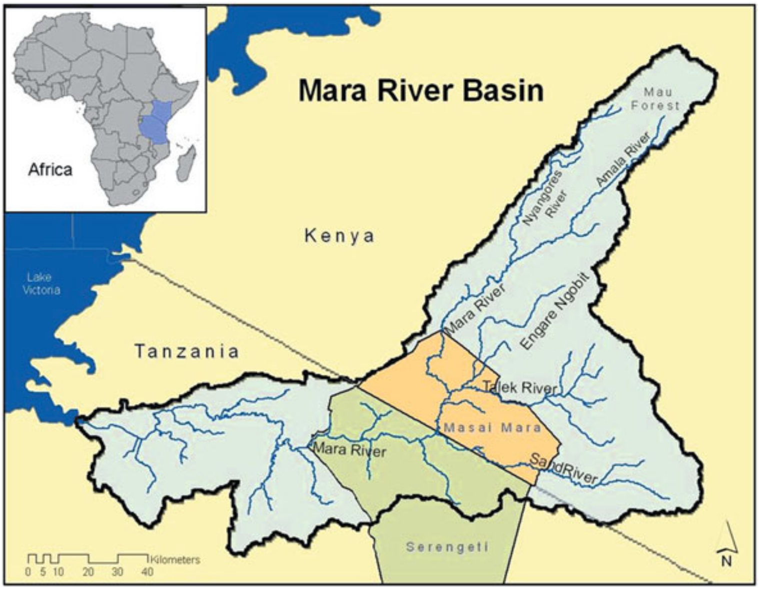

Fig. 31.1 The Mara River basin catchment. (Source: Hoffman 2007)

thus, recharging of underlying groundwater aquifers. This leads to more intensive storm runoff during rainy months and reduced baseflows during dry months. Taking the impacts on water quality and quantity together, there is clear justification to improve agricultural practices.

Conversion of large areas of headwater catchments to agriculture and erosion exacerbated by poor soil conservation practices are believed to explain the increase in sediment load observed in the Mara River over the past years. Modeling studies also suggest that these changes have reduced dry-season baseflows (Mutie 2007). A few decades ago, the Nyangores and Amala catchments were heavily forested, and rainfall there was intercepted by forests and filtered through the soils to recharge aquifers and feed river baseflow throughout the year. Forest soils filter contaminants and reduce soil erosion and sedimentation in rivers (Nkonya et al. 2008). Mau Forest Complex and the middle catchment of the MRB have experienced rapid expansion of agricultural activities and deforestation in the past one and a half decades. In just 14 years, between 1986 and 2000, agricultural land increased by 55 %, forests have reduced by 23 %, and savanna grassland reduced by 24 % (Mati 2005). Runoff from farms in headwater catchments discharges directly into streams. Farmers may be aware that their farming practices cause pollution but applying BMPs to reduce pollution comes with costs that are often beyond their reach. Due to high poverty levels and lack of clear land tenure rights, most farmers are concerned with making the most out of their farms.

In the middle and lower sections of the basin, river water is polluted by discharges of untreated or poorly treated sewage from the hotels and lodges as well as urban centers and runoff of phosphorous and nitrate fertilizers used at the irrigation farms along the basin. Mechanized farming in the lower basin around MMNR has expanded considerably over the years.

31.3 National and International Institutional Reforms for Sustainable Natural Resources Management

Historically, in both Kenya and Tanzania, there had been negligible coordinated efforts on the part of various natural resources agencies—land, water and irrigation, forests, wildlife, agriculture, and environment. Moreover, each agency managed its resources through a centralized decision-making system, paying little attention to local watershed-level issues, cross-resource-system issues, and cross-boundary water issues. However, in the new millennium various national legislations have been reformed or introduced to promote more holistic and decentralized resource management. These legislations emphasize increased stakeholder participation in decision making at catchment, ecosystem, or village levels. They also began to recognize natural resources as economic goods and call for local resource management units to become financially more independent.

31.3.1 Legal Framework

Several legislations in Kenya especially those that govern the use of land resource are clear, and their aim is to dictate which land should be put to which use but are never enforced adequately. The legal approach lacks structures that should involve communities in the management of natural resources. One good example is that the ban on settlement and farming in the Mau Forest Reserve is intact but has not stopped communities from moving and settling there illegally. The Environment Management and Coordination Act (EMCA) provides for the establishment of legal and institutional framework for the management of the environment. The Physical Planning Act (PPA) prepares and ensures that physical development plans are implemented. Any changes in the use of land should be in line with the physical plans developed for that particular local area (GoK 2000).

The existing policy framework in Kenya is broad enough to accommodate PWS schemes. As experienced in other parts of the world, it might be possible that PWS schemes can be implemented easily and do not require specific legal framework to be able to function (Food and Agricultural Organization (FAO) 2004). This is because PWS schemes are agreements and alliances between environmental service providers and beneficiaries of the service. A formation of solid committees and the trust between providers of watershed services and beneficiaries and the existence of good intermediary mechanisms are enough structures and are more important than a legal framework. However, recognition of the PWS scheme within an existing legislation will help to facilitate implementation and avoid using rules that sometimes may cause confusion in different committees.

31.3.2 Institutional Framework

Establishing an institutional framework for a PWS scheme would require tangible organizations and rules to promote PWS objectives and build internal rules of arrangement to rule out fraud or noncompliance. The institutions to manage the PWS scheme should be intermediary organizations that remain semiautonomous with linkages to service providers, service beneficiaries, and public and private sectors under an agreed contractual arrangement. The institutional framework in a PWS context provides information and facilitates the channeling of payments and creates an environment for participants in the scheme to negotiate payments and enforcement mechanisms once the payments have been agreed upon.

In order to strengthen local institutions, the Kenya and Tanzania governments have attempted to operationalize the Water Act of 2002 by decentralizing decision making from the central governments to the local levels where water is used. This has led to the establishment of the Water Resources Management Authority (WRMA) in Kenya and Water Basin offices, called Lake Victoria Basin Water Office (LVBWO) in Tanzania; these bodies are responsible for water management. WRMA now has offices at local level where communities influence decisions on how water should be managed. There are also plans to establish Water Catchment Area Advisory Committees (WCAACs) in Kenya, and an LVBWO sub-office has been established in Musoma, Tanzania, to oversee the activities of Water Resources User Associations (WRUAs) and WUAs in Kenya and Tanzania, respectively. WUAs have been formed by local communities and are charged with the responsibility of deciding how water is used, apportionment of water rights and decision making through the District Water Boards. Mara River WUA (MRWUA) and Mara Catchment Committee, facilitated by the World Wide Fund (WWF) and established by Ministry of Water and Irrigation in Kenya and Tanzania, respectively, are a mechanism that will serve a more representative and transparent process in water resources management and future allocation and management of water resources.

The Government of Tanzania, on the other hand, through the National Water Policy (NWP) has established and trained District Facilitation Teams (DFTs) whose responsibility is to create community engagement structures in the management of Mara water resources. The DFTs have already taken a lead in mobilizing and empowering civil society at various levels for the conservation of natural resources in the Mara basin and sustainable development for the local people. The National Strategy for Growth and Reduction of Poverty (NSGRP) 2004 of Tanzania which originates from the Poverty Reduction Strategy (PRS) of 2000 recognizes the heavy dependence of local communities on the environment for their livelihoods. The NWP provides for the establishment of institutional structures to ensure participation of stakeholders in water resources management to the lowest level of a water user. Legislation to guide the functions of various institutions at different levels of water resources management is still under review.

The formation of Catchment Advisory Committees, WUAs, and DFTs is a good initiative, but there is still no transparency in land allocation procedures, ineffective or weak enforcement of conservation laws, and unclear land tenure rights. There is a need to have a platform that will bring all stakeholders together to discuss incompatibilities in the current agricultural practices, raise awareness about changes in water quality and quantity, and enforce commitments that will support all beneficial uses of water including ecological sustainability.

31.3.3 Transboundary Resource Management

The primary mandate for management and development decisions within the MRB lies within the East African Community (EAC). In 2004, the EAC Council of Ministers adopted the Protocol for Sustainable Development of Lake Victoria Basin (East African Community 2004), which provided for the establishment of the Lake Victoria Basin Commission (LVBC). The primary functions of the LVBC are to promote, facilitate, and coordinate activities of different actors toward sustainable development and poverty eradication within the basin. They are also charged with implementing the Shared Vision and Strategy Framework for Management and Development of Lake Victoria basin (Lake Victoria Basin Commission 2007). Priority strategies within this framework targeted at the ecosystems, natural resources, and environment are directly in line with the needs for addressing critical issues in the MRB. These strategies include improving land use and natural resources management, promoting integrated water resource/water catchment management, promoting water quality and quantity monitoring, and promoting farming methods that reduce use of agrochemicals (Lake Victoria Basin Commission 2007).

Transboundary management structures are also being developed specifically for the MRB. A Transboundary Water Users Forum has been established to promote dialogue between stakeholders from both countries. National Stakeholder Forums are currently being developed to strengthen institutional capacity for future transboundary negotiations. Efforts are also currently underway to develop a cooperative framework for the management of the MRB, with a Secretariat for the Mara residing either within the LVBC or within the Nile Basin Initiative (NBI) (Nile Equatorial Lakes Subsidiary Action Program 2009). These institutional structures would provide a potential platform to bring together watershed service providers and beneficiaries to establish a legal framework for a PES scheme.

31.4 An Overview of PWSs Mechanism

31.4.1 What is a PWSs Mechanism?

The PWSs is a financial scheme wherein the beneficiaries or users of watershed services, or a government or nongovernment entity on behalf of service users, will pay a fair compensation to those upstream parties who provide such services. Services here are positive watershed attributes being generated by keeping the natural components of the watershed in a certain condition or enhancing their existing potential. For example, the watershed services in the MRB include: (a) efficient infiltration of rainwater, resulting in a more uniform flow of river water throughout the year, (b) watershed protection to prevent erosion and undesirable sediment loads, and (c) protection of riparian buffers to prevent contamination of rivers by agrochemicals, resulting in cleaner water for human and wildlife consumption downstream.

Service providers (or sellers) could be private farmers, households, and/or public and private agencies. They undertake productive activities that generate, as a positive externality, the service for which a payment system will be established. Planting trees and pasture grasses, maintaining riparian buffer zones, avoiding excessive upstream water abstraction, and constructing farm filtration ponds exemplify activities that service providers may undertake in order to deliver more reliable clean water downstream. Service users (or buyers) are economic entities who benefit from the service through increased and/or more uniform water flow (especially during dry seasons), improved water quality, increased production of consumable goods (i.e., food and fiber), and expanded tourism, among other benefits.

Finally, the appropriate negotiated compensation must be paid by service users to service providers. Compensation may be in cash or in kind. Like in any other market, for a watershed PES to succeed, there has to be a mutual agreement between service users and providers with respect to the extent and nature of upstream resource management practices, reasonably expected level of their impacts on downstream services, and the corresponding monetary and/or in-kind compensation for the practices implemented. A PWS scheme, therefore, is a mechanism with which society will be able to capture the economic value of watershed services—a public good—which otherwise will be taken for granted, or not be adequately paid for, and, therefore, become unsustainable in the long term.

There are mainly three institutional mechanisms for PWS schemes:

1. Market-financed PWS: This mechanism is strictly a market-based arrangement that involves direct financial transfers between providers and beneficiaries of watershed services. The legally enforceable contracts may be drawn between individuals and or groups representing the above-mentioned market players.
2. Donor-financed PWS: Many conservation measures are being financed by international organizations but do not commit communities to specific techniques.
3. Government-financed PWS: This has been the most common method of financing watershed enhancement projects. The state or central government of a country

> would finance conservation projects through paying landowners direct subsidy or paying back reasonable amount of funds accrued from water fees among other collection modalities to the service providers. The necessary financial resource is funded through a variety of taxes and fees programs.

This chapter focuses on the market-financed PWS, the first mechanism indicated earlier. Oftentimes, people use PWS and PES interchangeably although PES is a broader concept covering watershed services, carbon sequestration, biodiversity, aesthetics, and recreational services also. Throughout this chapter, we use PWS and PES interchangeably.

31.4.2 Lessons from PES schemes in other parts of the World

When designing and implementing PES schemes many questions automatically arise. For example, who should initiate a PES? Should a government agency take an active role in collecting and transferring payments? Alternatively, should the participating users negotiate a self-enforcing, private, or cooperative contract that is mutually agreeable? What should be the scale of such a scheme: local, regional, national, or international? Should there be an enforcing and monitoring mechanism? How should disputes between service users and providers be resolved? As we address these questions in the context of the MRB, a look at the experiences of existing PES schemes around the world provides useful insights.

By reviewing more than 40 case studies from South America, FAO (2004) presents a comprehensive list of lessons learned from former PES efforts. Water-related PWS schemes have been implemented at various geographic and functional levels, from a localized watershed level to a national level. These schemes emphasize specific environmental services: aquifer recharge, sediment control, and year-round river water flow, among others. These PWS schemes are more cost effective and manageable if implemented at smaller scales and with clearly identifiable hydrological connections and quantifiable benefits. Most schemes do not have legal backing from national legislation, but rather depend on the commitment made by local governments or non-governmental organizations (NGOs). The most common problem that undermines PWS schemes is the lack of clear understanding of the connection between land and water management practices and the desired environmental outcomes. Successful programs have been able to commoditize the watershed services clearly so that the service buyers are able to clearly appreciate what they are getting in return for their payments (FAO 2004).

Rosa et al. (2004) found that without adequate support from the local communities, among both service users and service providers, a PWS scheme will not succeed. Further, resource owners/managers have the ability to provide more than one environmental service, for instance, adequate water flow, sediment control, flood control, biodiversity protection, or carbon sequestration. Based on a watershed study in New York, direct compensation is not necessarily the best way to compensate the service providers (Rosa et al. 2004). Instead, a package of compensations tied to individual environmental services might result in the highest environmental benefits. Bond et al. (2009) compares ten PES schemes in the developing world and identifies some reasons for success and failure. The schemes where the actual payments occurred involved an active user negotiation process, which provided a basis for building trust and lowering administrative costs. Six other cases, where PES failed, lacked clear hydrological and ecological connections and demand from potential buyers.

The above-mentioned studies suggest that in order for a PWS scheme to operate, one must clearly identify and quantify demand for water-related environmental services. A cause–effect relationship must be established to link upstream land and water management practices with watershed benefits/services delivered. It is highly desirable that poverty-reduction goals be incorporated into a PWS scheme. A proper monitoring program must be put in place along with the ability to compare the environmental and socioeconomic performances before and after PWS implementation (FAO 2004).

31.5 A Roadmap to Designing and Implementing PWS Mechanisms in the MRB

In this section, we present a step-by-step roadmap for designing and implementing PWS mechanisms in the MRB. These steps, with appropriate modifications, would be applicable to other watersheds in the Nile River basin as well. An important question that arises is, whose responsibility it is to carry out various subtasks and activities of the proposed PWS implementation process? Given the complex ecological and political landscapes of the basin, no single entity or agency would be able to carry out the whole process. The nature of the PWS design and implementation is highly diverse, in that the various subtasks require a variety of specialized expertise and capabilities, including scientific information, political negotiation, stakeholder education, and regulatory intervention. Appropriate agencies and organizations having these expertise and capabilities must be identified and involved in the process. Most importantly, throughout the design and implementation process, all stakeholders—service providers and users, agencies, and other watershed interest groups—must be integrally involved. In both the countries, initially a designated agency will have to take the lead in bringing these stakeholders to the table and starting the dialogue. The designated agency may be from the basin itself that has the broadest representation of stakeholders or an outside entity that enjoys the highest public trust. In addition to the well-functioning intra-country PWS coordinating agencies, an international agency must be identified to coordinate the transfer service and payment efforts at the transnational level between the two countries.

Some of the scientific and management information necessary for designing the PWS mechanisms in MRB is available through existing research and action-based projects, e.g., WWF's Mara River Basin Management Initiative. This is an initiative that emerged out of an agreement between the EAC and the WWF for Nature-Eastern Africa Regional Program Office (WWF-EARPO), Nairobi, in 2003. Extensive research and stakeholder engagement activities have already been conducted under this initiative. More information may be needed as the project gets off the ground. The following PWS roadmap for MRB is based on various field visits, workshops, informal discussions, formal stakeholder surveys, and a literature review of working examples of PES schemes in other parts of the world. The specific steps indicated in the roadmap draw from a checklist developed by the International Conservation Union for watershed services in general (Smith et al. 2008).

31.5.1 Watershed Services and Management Practices

- Identify watershed services necessary for sustaining downstream ecosystems and economies of the MRB

Using the Millennium Ecosystem Assessment (2005) framework, the watershed services necessary in the basin fall under the following categories:

a. *Provisioning services*: water supply for food and nonfood agricultural crops, and water supply for residential and industrial (electrical, mining, and chemical) uses, throughout the basin.
b. *Regulating services*: reduced flood through flow moderation, control of soil erosion, and water purification.
c. *Cultural services*: recreational and aesthetic services, spiritual and religious values, cultural heritage and knowledge systems, and education.
d. *Supporting services*: habitat and environmental flows in order to protect terrestrial and aquatic wildlife in the Mara Group Ranches, MMNR, Serengeti National Park, and the wetlands in Tanzania.

In MRB, the quantity and quality of the above-mentioned ecosystem services that can be delivered to respective stakeholders directly depend on the degree of natural flow of water throughout the year. Also, quality-related watershed services (e.g., fish habitat) will depend on the amount of sediments and chemicals released into the river.

- Identify land and water management practices in the upstream watershed that can generate the watershed services required downstream

Watershed practices depend on land terrain and land covers. The upper and middle catchment areas of MRB consist of diverse land covers, including forest, agriculture, pasture, floodplains, marshes, and swamps. Landowners and managers have a host of options for implementing practices on these land covers. In order to achieve the desired goal of watershed services and types, an appropriate mix of types, locations, and scale of upstream management practices must be determined. Some important steps in achieving the optimal mix of practices are as follows:

a. Determine the areas of different land-cover types in the upper and middle catchments of the MRB, along with spatial characteristics such as proximity to surface water bodies, land conditions, etc.
b. Determine the extent of private, community-owned, and public lands (i.e., property rights) under different land-cover types.
c. Identify land management practices suitable for each land-cover type and property ownership (i.e., public or private lands). Consider landowners and land managers opinions in choosing appropriate practices. Atisa (2009) considered three different land management practice suitability criteria: technical, economic, and water quality improvements. For example, these criteria include how badly certain land need improvement, whether certain locations and practices have most immediate and direct effect on river water improvement, and proximity to water streams. Local stakeholders might be able to provide insight into the suitability of certain practices under certain land-cover type.
d. Prioritize different land parcels, areas, and locations in each sub-catchment based on the above-mentioned management selection criteria. The idea is that the implementation of selected watershed practices as per the priority list will help enhance the river water flow and quality in the basin toward the desired levels.

31.5.2 Service Providers and Buyers

- Identify upstream service providers

Figure 31.2 identifies the connection between various service providers and service users in MRB. For a successful PWS scheme, it is not enough to identify the broad entities of service providers and users. Several socioeconomic, functional, and spatial characteristics of these entities are important.

The following categories of service providers must be identified, along with their number, scale of operation, and locations:

a. Private landowners with clear land titles: Identify small and larger farmers, and ranchers including group ranches. Note that private land ownership is more common in Kenya than in Tanzania. Private owners also bear considerable influence on public lands through grazing, gathering, and other resource-use activities.
b. Community-based organizations: These are groups of citizens who are registered as associations under a national act with charge and commitment to protect a certain natural resource system on a public land. They do not own the land but have the right to extract products and services from the property. Both Kenya and Tanzania have such laws.
c. Informal settlers: A large population has migrated into the basin from other areas and settled on communal lands such as forests and pastures. Some of them cultivate land, graze animals, and/or collect and gather nontimber products.
d. Forest departments: Manage large tracts of forests in both Kenya and Tanzania. Public lands are much more common in Tanzania. Forest departments would be

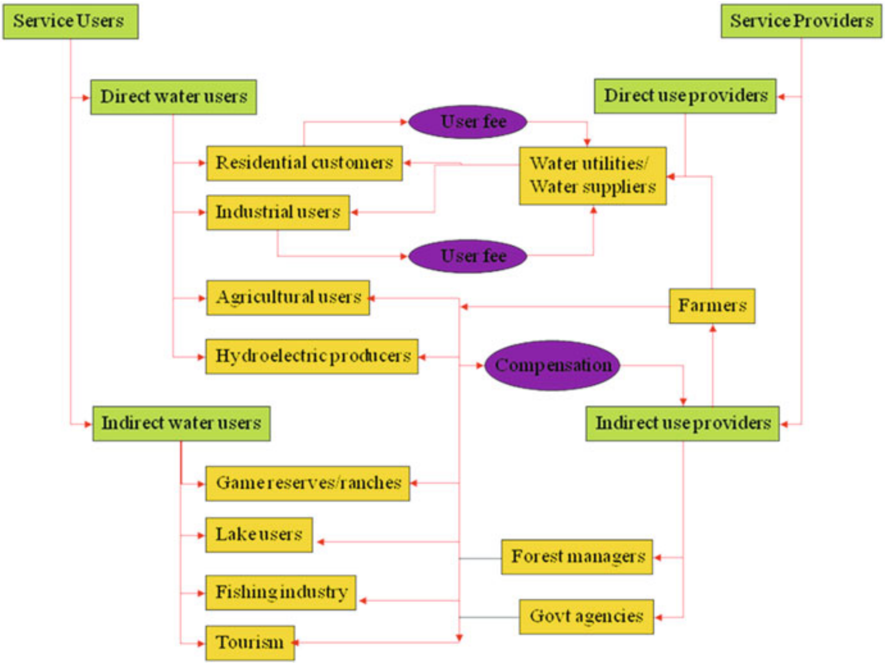

Fig. 31.2 Connection between providers and buyers of watershed services in the Mara River basin (MRB)

responsible for not only managing public forestlands but also providing technical and resource support to private landowners in managing private lands.

e. Government agencies managing protected areas: Kenyan Wildlife Services, Tanzania Wildlife Agency, and district councils managing Masai Mara Game Reserve, Mara Conservancy, and Serengeti National Park.
f. Municipal water and sewer treatment agencies: Managed by district councils or national or local agencies. Often ignored, these entities bear considerable influence over the downstream river water quality.

The property ownership of the land, which needs improvement, is a key factor for the success of payment schemes. Those who receive payments need to have proper control over the land in order to be able to deliver the services expected of them. At the same time, in the MRB there are a number of people with informal rights (e.g., forest settlers) who have considerable impacts on land and river water regime. Therefore, the PES negotiation process must include informal right holders as well.

- Understand the service providers' socioeconomic background, and their perception about the basin's natural resources and attitude toward implementing the BMPs through PWS schemes

It is important to take service providers into confidence. In most cases, service providers of the MRB are large in numbers and are scattered across the watershed. A majority live on land or other natural resource systems for subsistence. Changes in their land- and water-use behavior are expected to cost them money directly or indirectly. They may not embrace all conservation measures eagerly, while they may do some even without cost compensation. Some of the practices may yield immediate economic benefits and, therefore, may only require proper education and training of farmers, which may result in cost-efficient changes in land uses.

Based on a field study conducted during 2006 and 2007 in the MRB, Hashimoto (2008) reports that most sample farmers have noticed water quantity and quality decline in the river over the years. There is an overwhelming support among them for implementing land and water conservation practices on both public lands and private lands. Those who would not implement such practices cite costs of implementation as the main reason for non-implementation, think the government should fund these kinds of programs, and/or feel local resources for such an implementation are not adequate.

Further, because of the large number of service providers involved, not every service provider will be able to take part in the negotiation process. Individuals or organizations that are democratically chosen to represent service providers must be involved in the PWS negotiation process. It should be made clear to service providers that the PWS is not necessarily an entitlement or welfare measure against poverty or low income. The payment is an incentive for designated watershed services, and a prompt delivery of those services through attendant conservation practices is expected as in any market transaction.

Not all service providers will have equal priority in terms of implementing land management practices and, therefore, in receiving payments. The PWS priority must be based on certain ranking criteria that embody highest environmental and economic benefits and equitable benefit sharing. Such priority-based investment strategy will ensure most effective and timely delivery of watershed services.

When landowners implement certain better management practices (e.g., buffer zones, contours, and terraces), they might experience permanent decreases in yields or profits or incur excessive costs over time. Such farmers will have to be compensated for several years. In addition to implementing land management practices on their private lands, some farmers may be willing to volunteer their time and private resources to take part in public conservation projects. Services of such farmers may have to be explored in the basin.

- Identify downstream service users

The buyers of watershed services in MRB are those who live downstream and enjoy the four types of watershed services: provisioning, regulating, cultural, and supporting. The following are the specific service buyers of MRB:

a. Large commercial farmers in Kenya: They need year-round flow of water for agricultural irrigation. Eventually, low water levels in the river during the dry season might limit on how much water they can draw for irrigation.

b. Group ranchers: They indirectly benefit from having enough water in the river as it is critical for the survival of their cattle as well as the migrating wildlife. The survival of their livestock as well as success of any wildlife-based tourism on their ranches depends on a sufficient amount of clean water, a healthy river ecosystem, and an abundant wildlife population.
c. Protected area managers: Both in Tanzania and in Kenya, protection of wildlife biodiversity on the national parks depends on adequate flow of sufficiently clean water in the river.
d. Tour lodges and tourists: Wildlife tourism is a major industry in both the countries. Tourism is also a significant source of revenue for local and national governments. In Kenya, the tourist areas, wildlife habitat, and physical location of the Mara River are overlapping and, therefore, the connection between tourism users and watershed services is direct. On the contrary, in Tanzania, the Mara River traverses through the northeastern side of the Serengeti National Park while the tourists are mostly concentrated in the southern range of the Park. Special effort is, therefore, necessary to make this user group understand the significance of the watershed services provided by the upstream service providers.
e. Gold miners: Two large-scale gold mines and several small-scale mines in Tanzania are significant users of water from the river.
f. Wetland users: These are mostly subsistent fishers living around the Mara Swamp at the mouth of the Mara River in Tanzania. Their ability to pay for ecosystem services is limited.
g. Urban residents: Several small cities and townships are located along the river. The two major townships are Bomet and Mulot in Kenya. The quality of the drinking water from the river continues to be of concern to this group. They will benefit from more reliable quality of water flow in the river.

- Understand the service buyers' socioeconomic background, and their perception about the delivery of watershed services with the aid of PES schemes

The service buyers in MRB are much more organized and are in a better position to collectively bargain for services and payment deals. With the exception of tourism services, other groups are small in their sizes, but wield considerable influence on the negotiation process. Based on the informal discussions we had with several key members of these groups and also a recent study of service buyers (Castillo 2009), we observed the following issues which concern service buyers in the basin:

a. Most of the service buyers (especially large farmers, tour lodges, and park managers) are willing to take part in the PES process.
b. Service buyers expect certain level of assurance for the delivery of services that they are asked to pay for. Government agencies must ensure strict enforcement and monitoring of service provisions.
c. Some buyers prefer a third party, an NGO, or a trust to play the intermediary role between them and the upstream service providers.
d. Buyers, such as tour lodges, feel that they already pay considerable amounts in taxes, fees, and surcharges to various governments. These service buyers feel

local governments like district councils, which collect the park entry fees, must bear the significant share of the PES financial burden.

31.5.3 Sources of Funding and Levels of Payment

- Identify the existing and potential sources of funding to support PWS schemes in MRB

In MRB, funding support from government sources is less likely to come forth due to the budget scarcity and other socioeconomic priorities of the countries. Donor-based finances also are becoming increasingly difficult to come by over the years. That leaves the user-based finance as the most likely candidate for future funding sources for PES schemes in the basin.

There already exist some programs and arrangements in MRB, whereby users of natural resources and amenities are charged for certain resource-based services that they enjoy. Almost none of them are originally intended for paying toward watershed services generated by upstream users. However, it is important to recognize that if the users are already accustomed to paying certain prices, fees, or taxes, they may be more willing to pay an additional fee for the delivery of new or extra watershed services or products. It is always challenging to introduce entirely new service fees.

The PWS managers must first identify the existing sources of revenues that the downstream buyers are generating. The new funding sources for the PWS can be then carved out of such revenue bases. Table 31.2 shows various income-generating activities, the attendant revenue streams, and service fees or taxes the users currently pay in MRB.

The PWS-implementing agency in each country must start exploring their funding source options by carefully answering the following questions, preferably in the order listed:

a. Would the public or private entities that currently collect the above-mentioned taxes or service charges be willing to dedicate a portion of the collection toward PWS schemes?
b. If the answer to this question is no, or the dedicated revenue allocation from the above-mentioned sources is inadequate, ask the questions:
c. Would the above-mentioned users (e.g., large farmers, tour lodges, etc.) be willing to pay *additional* charges or fees exclusively toward dedicated watershed services?
d. Would the tax collection agencies and the private businesses involved in the attendant revenue-generating activities have any objection to raising service charges? It is quite possible that the local agencies or businesses may object to such fee hikes for sociopolitical reasons.
e. If the answers to the preceding two questions are no or uncertain, or the expected revenue collection is not adequate, are there other income sources that may have potential for additional funding?

Table 31.2 Nature-based income sources and current taxes and user fees in the Mara River basin by user groups

Activity/users generating income	Income sources	Fee, tariff, taxes, or rebates paid	Paid to whom?
Water extraction by commercial farmers	Crop sales	Water tariff Income tax	Irrigation department National government
Tourists	Personal income	Park entry fees Sales taxes on services	Park agencies State/local governments
Tour lodges	Hotel service charges on guests	Bed taxes Income taxes	Local governments and National governments
District councils managing National parks	Gate entry fees from tourists	Rebates given to hotels	Tour lodges
Group ranches	Gate entry fees from tourists	Not available	Not available
Gold mining companies	Gold sales	Sales, export, and income taxes	National government
Domestic water users	Personal income	Water tariff	Municipal or private utilities
Industrial water users	Business income	Water tariff	Municipal or private utilities
Lake fishers	Subsistence income	None	Not applicable
Small farmers and pastorals	Agricultural income	None	Not applicable

f. In addition to funds raised through taxes, fees, and charges, are there possibilities for privately negotiated payment schemes? A private user or group of users may be willing to make payment for dedicated conservation efforts. Such negotiation may take place exclusively between private parties without the direct intervention of any government agencies.

The following factors must be considered while targeting these sources:

a. Not all income sources would be appropriate as funding sources.
b. The stakeholders involved in the PWS implementation process have to first decide a suitable combination of different revenue options indicated earlier.
c. Income-generating activities are subject to frequent economic fluctuations in the marketplace and, therefore, may not result in a constant flow of income and, in turn, a constant flow of user-paid tax revenues.
d. Some of the taxes or users fees (e.g., park entry fees, irrigation water tariffs, and income taxes) are enabled through national laws, whereas others (e.g., water utility tariffs and entry fees to group ranches) are determined by local agencies or markets. The PES-implementing agency must involve appropriate legislative members of the local, provincial, and national governments early on in the decision-making process.

- Determine the levels of payment

Determining suitable prices to be paid for watershed services is a challenge in that the services or products the buyers buy in the market are not identical to the actions or decisions that the service providers take in order to provide such products. Per economic theory, the *maximum* price that the buyers would be *willing to pay* for a service is the benefit that they expect to derive from the purchase. On the other hand, the *minimum* price that the service providers would be willing to accept for land management practices is the *opportunity cost* that the owners will incur. Depending on the forces of market demand (reflecting buyers' choice) and supply (reflecting providers' ability and expectations), optimal market prices will occur somewhere in between. However, to put this theory into practice is extremely difficult in the case of watershed services because of the physical separation between buyers and sellers, possible time gap between practices and services, and the physical transformation between practices undertaken and services delivered. At best, one can use the buyers' willingness to pay or the providers' opportunity costs as a reference point and then determine prices through stakeholder negotiation and consultation.

In our opinion, the easier approach to pricing in MRB is the opportunity cost principle. We suggest the steps given in Table 31.3, in order to determine appropriate levels of sellers' compensation and users' prices for MRB watershed services.

With regard to the authority or process that is normally responsible for determining prices, Porras et al. (2008) observes that three types of pricing mechanisms have been used in PWS schemes around the world:

a. Administratively determined payments: The implementing agency would determine the amount of compensation to be paid to service providers and the amount of charges to be recovered from service users. The basis of compensation to service providers could be the opportunity cost principle or simply ad hoc. The rates of charges, service fees, or taxes on the other hand could be decided based on the total amount of revenue required to fund an upstream watershed conservation program in relation to the volume of downstream businesses (e.g., agriculture, tourism, mining, etc.) which benefit from watershed services.
b. Buyer and seller negotiated payments: This method is rare. Since buyers and more so sellers in the MRB are highly scattered, the transaction costs of implementing such privately negotiated payment programs will be high.
c. Negotiation through an intermediary: The rates of compensation and service charges would be determined by an outside agency in consultation with stakeholder representatives. Such an agency may act as an intermediary between the two parties for price determination, actual payment transfers, overall program coordination, and monitoring. The agency may be government appointed entity, outside trust, or an NGO.

Our study in MRB shows that service buyers prefer a nongovernmental entity such as a trust, NGO, or stakeholder-owned cooperative to manage the PES schemes.

Table 31.3 Step-by-step process for determining the cost of payment for watershed services schemes in MRB

Steps	Determine
1. Unit cost of land improvement	Determine per acre opportunity costs for different land management practices on both private and public lands. Certain land management practices recur every year whereas others involve one-time improvements with periodic maintenance or repairs. Have experts and stakeholders review these costs periodically and update the estimates
2. Area of land improvement	Determine areas in different catchments and sub-catchments of the river basin needing different land management practices. Remember to prioritize these areas depending on the selection criteria developed earlier. Not all areas might be possible to develop in a year or two
3. Total costs of improvement	Compute the total costs of compensation to be paid to landowners by multiplying estimates in steps 1 and 2 for each time period
4. Administrative costs of implementation	Determine the total costs of administering the program. This could be anywhere between 3 and 10 % of the actual costs of implementation at the farm level
5. Total costs of program implementation	Add the costs in steps 3 and 4 to arrive at the total program costs. Determine what portion of this must be in cash and what portion in kind. Estimate the annual total costs of implementation for several years at a time
6. Users' fees and taxes	Through stakeholder negotiation, decide how the total annual program costs will be distributed among various users' groups (e.g., large farmers, park managers, group ranches, etc.). One of the bases for an optimal distribution of the program cost burden among users may be their income or revenue generated through water-dependent activities. With the program costs apportioned among users, determine what tax rates, services fees, or charges will make the proposed PWS programs solvent

31.5.4 Institutional Mechanisms Managing PWS Schemes in MRB

- Establish a suitable institutional structure with multiple agencies and stakeholders involved and with their roles clearly defined

One of the immediate decisions that the stakeholders need to make in MRB is who the implementing agency should be. As indicated earlier, funds can be transferred from buyers to sellers either directly or through an intermediary. The intermediary can be a government-appointed agency or a stakeholders-appointed entity. Given the complex geographic and sociopolitical nature of the Mara watershed, a direct buyer-to-seller payment system is unlikely. Any proposed PWS schemes in the region should have an intermediary agency, which is the main implementing agency and has a strong mandate from stakeholders. However, several institutions, including

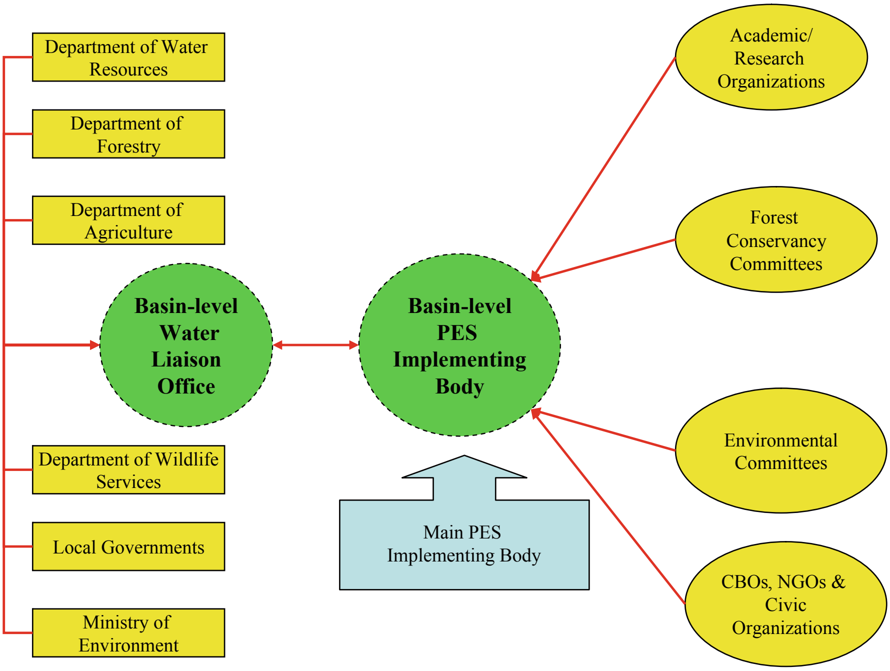

Fig. 31.3 Proposed institutional mechanism and collaboration for implementing payment for watershed service (PWS) schemes in Mara River basin (MRB)

government agencies, must be creatively involved in the process. Figure 31.3 shows a proposed multi-institutional collaboration necessary for each country in the basin.

The main features of this proposed institutional collaboration are as follows:

a. There must be one primary implementing agency at the basin level in both Tanzania and Kenya. Stakeholders in each country must decide if this should be the WUA, an outside trust, or a government agency. This agency should have the necessary legal power to solicit information, technical cooperation, and legal and enforcement assistance from government institutions as well as citizen groups.
b. The various government departments shown in Fig. 31.3 have critical roles to play. Their involvement can be facilitated by a basin-level water liaison office that represents all national- and district-level government agencies in the basin. Especially water resources, agriculture, wildlife, forestry, and environmental agencies must provide necessary technical, information, and regulatory assistance in implementing the schemes. For instance, the forest department would supply seeds, seedlings, and technical skills for reforestation programs. Similarly, the agricultural department would be involved in providing extension education to farmers on soil and water conservation practices. Water resource management agency must involve itself in monitoring the impacts of land-use changes on the river water quality. The district governments will play a major role in the

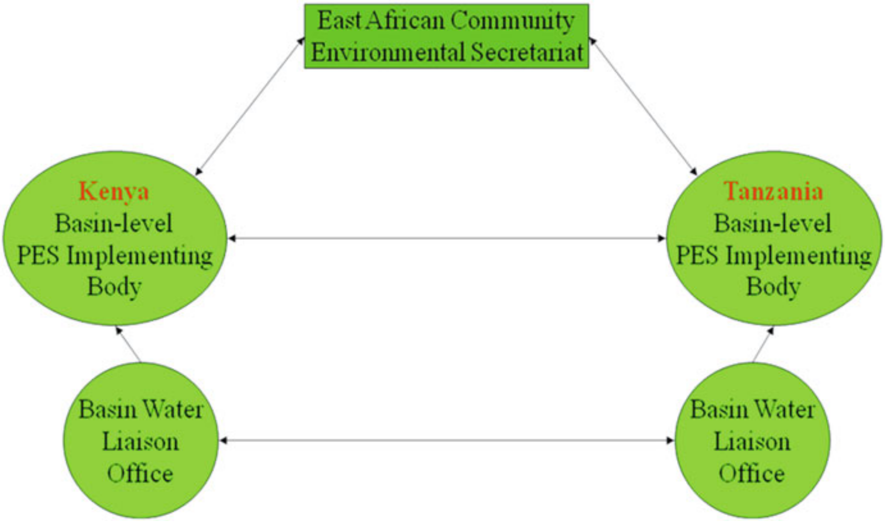

Fig. 31.4 Proposed institutional arrangement for implementing transboundary payment for watershed service (PWS) schemes in Mara River basin (MRB)

enforcement of the PWS schemes throughout the basin. The roles of each agency and its potential contributions to the PWS must be periodically reviewed and reinforced.

c. The implementing agency must involve the services of different local organizations, some of which have been constituted under forestry, environment, and water resources legislations (e.g., forest committee, environmental committees, etc.). Civic organizations, community-based organizations, and social and environmental NGOs can be key allies in implementing PES schemes as well. Particularly the network of such organizations will be a great asset for carrying out effective educational programs, or for forming local watchdogs against noncompliance of the agreement or misuse of funds. Research and academic institutions can lend their technical expertise in designing management plans and decision tools for monitoring and enforcement.
d. The implementing agency should make sure to have proper mechanism for providing stakeholder input. The assistance of a designated advisory committee or the various advisory committees existing under current national legislation (e.g., basin-level advisory committees in Tanzania) may be obtained. The implementing agencies of the two countries also should be responsible for making negotiation at the transboundary level and must convey back to their national constituents for suitable actions and decisions within their respective national boundary (see Fig. 31.4).

- Develop specific terms of payment structures

This is the final step that needs to be taken before the actual implementation of the PWS schemes. The PWS implementing body, in consultation with both buyers' and sellers' representatives, must develop a set of rules governing the nature and terms of payment. The following considerations must be factored into forming such rules:

a. Nature of payment: One must decide whether the payment is in cash, kind, or both. Most probably, certain cash incentives are expected to buy necessary inputs by landowners themselves or as compensation for lost revenues, which might occur as a result of change in land management practices. This should not preclude the option of payment in kind. The PWS implementing agency should consider procuring certain resources (e.g., seedlings, equipment, and chemicals) in large quantities and distribute them to participating service providers.
b. Timing and frequency of payment: Depending on the nature of land and water management practices, the timing and frequency of payment must be decided. Certain practices such as bench terracing and buffer strips may require a large initial payment. A one-time fixed payment may be suitable in such cases. On the contrary, practices such as limited- or no-till productions may require continuous annual payments for certain number of years.
c. Amount of payment: The amount of cash payment is generally a fixed rate per hectare each time a payment is due. As discussed earlier, the rate of payment must be decided based on the opportunity costs of each practice. Such costs could vary from location to location and practice to practice.
d. Indirect financial motivation schemes: PWS implementing agency must also help service providers secure indirect financial assistances. Commercial banks may be encouraged to lend soft loans to farmers toward dedicated conservation activities using future PWS payments as collateral. Another innovative scheme would be in-kind support for supplemental income activities on farmers' land in lieu of certain water and land conservation activities. For instance, farmers may be given free beehives in exchange for their commitment to maintaining or conserving forests.

- Develop specific terms of performance monitoring and penalty and sanctions

A monitoring program is necessary to ensure that the service providers continue to apply water and land conservation practices and the downstream river water quality and quantity are met. Therefore, this program must cover the implementation of upstream land and water management practices and the achievement of desired downstream watershed services flow.

Four important monitoring issues must be addressed:

- Who will be monitoring the performance?
- How often is the monitoring done?
- What criteria will be used for performance measure?
- In the event of noncompliance of PWS terms of agreement, what sanctions must be applied?

In the upstream basin, the monitoring responsibility depends on the ownership of the land that is being targeted for land improvement. If it is a private land, a stakeholder's watchdog group can be formed. Such a watchdog group could involve local government and nongovernmental representatives. The stakeholder watchdog group can bring social peer pressure on individuals who are out of compliance with practice implementation requirement. Alternatively, one of the government departments, e.g., forests, irrigation, agriculture, or environmental, can be entrusted with monitoring and enforcement, with suitable compensation for enforcement costs.

Measuring performance in the downstream watershed may require more technical expertise. The PWS implementing agency may seek help from the proposed basin-level government liaison office (see Fig. 31.4) or any of the environment, water resources, and wildlife departments for measuring watershed services performance.

How often the performance must be measured depends on the nature of the projects undertaken upstream and the type of downstream watershed services intended. If the local watchdogs are involved in monitoring best land management practices, more frequent site inspections are possible at low costs. If the inspections are to be carried out by a basin- or district-level authority, random site visits may be considered with less frequency. Relating to watershed services, environmental flow requirements need monitoring during the low-flow season. Water quality performance might require more frequent year-long monitoring. The costs of monitoring will be a key determinant of how often and how detailed the performance measurement can be made.

The performance monitoring criteria again depend on the services and practices. If the project involves reforestation activities, periodic casual observation of tree density and health will be sufficient. Similarly, changes in the cropping and tillage practices can be casually observed once or twice a year. However, monitoring of downstream watershed services is more technically involved. Water flow and quality measurement should be done by experts with proper instruments.

Clear terms of sanctions and penalty must be established and be made known to service providers at the time they sign the contract for implementing BMPs. Sanctions and penalty structure should be stringent yet flexible enough to accommodate poverty considerations. The type of penalty varies from withholding of future payments and social sanctions to more stringent legal actions. The implementing agency must decide the nature of penalty in consultation with stakeholders.

31.6 Conclusion

The MRB appears especially well suited to the development of one or more PWS schemes. There are clear upstream–downstream dependencies: Water originates predominantly from the upper reaches of the basin, while the greatest concentration of financial resources (e.g., from environment-related tourism) lies in the mid and lower basin. The national water, forest, and environmental laws in Kenya and Tanzania have recently been revised or are being revised to recognize the need for paying for water and watershed services, and recent legislation has created legal mechanisms to formalize PWS in watersheds. Recent legislations also have enabled the formation of local and regional resource users associations, government and semi-government advisory and expert committees, and public–private partnerships. These grassroots institutions can be useful players in implementing PWS. Because of their familiarity with local issues and problems, they can play a critical role in a basin-wide initiative through promotion of BMPs, training, knowledge dissemination, monitoring, and monetary transfers. Involving grassroot organizations will also help promote resource users' trust in the proposed PES system.

At the same time, the MRB presents significant challenges for PWS implementation. That the basin is transnational raises a host of cultural, social, political, economic, and institutional issues. There are vast differences in land and water uses, property rights, economic pressures, and ecological needs between the two countries. For example, Kenya has a more defined legislative framework, but it also has a complex mix of users with different legal and traditional rights over river and riparian zones. Each country brings unique ecological and economic dynamics to the river basin. Watersheds of Kenya have a strong influence on how much water flows to and across the national border, supporting the migratory wildlife (e.g., wildebeest) that generates significant tourism dollars in Kenya and Tanzania. Inadequate water flow in the mainstream Mara River during the northward migration of wildebeest would be detrimental to their population and, in turn, the tourism industries on both sides of the boundary. Thus, a significant portion of the benefits derived as a result of river-friendly activities in Kenya accrues to Tanzania without much cost to the latter. The Serengeti National Park Authority and the tourism businesses are the direct beneficiaries.

In order for the cross-border PWS to take place smoothly in the MRB, an international agreement and a coordinating agency are critical. The EAC, which is a five-country regional economic block, may be very well poised to oversee the implementation of such an agreement. However, the EAC will need a strong enforcing agency in each country to enforce and monitor PWS-related monetary transactions and watershed service provisions (e.g., farm-level implementation of best watershed management practices).

The two countries could stand to benefit from an international cooperation involving a PWS mechanism. However, such a benefit is seemingly hard to realize until and unless the river users, not just the government agencies and scientists, come to:

- Understand the cross-border, reciprocal ecological–economic connections, resulting in user actions in subbasins ranging from northernmost catchments of Kenya (e.g., forest dwellers and agencies avoiding deforestation) to the southern tip of the Serengeti National Park in Tanzania (e.g., tourists and park managers willing to send appropriate compensation payments to Kenya).
- Institute mutually agreeable international mechanisms that help ensure more uniform cross-border water flow and wildlife migration, as well as compensation payments

- Align national water resource management laws with international agreements and vice versa.
- Maintain constant international dialogue at government, academic, and user levels to make adaptive changes to PES as required by changing natural, economic, and political environments of the two countries.

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Chapter 32
Payment for Watershed Services in the Mara River Basin: Part II: An Analysis of Stakeholders' Perceptions and Willingness to Implement Conservation Practices

Koji Hashimoto, Mahadev G. Bhat, Michael McClain, Doris Ombara and William Kasanga

Abstract Understanding the landowners' willingness and attitude toward best management practices is a key step toward implementing payment for watershed services (PWS) schemes. This chapter presents the results of a field research that was conducted in the Mara River basin (MRB) focusing on the demographic, economic, and environmental factors that might influence farmers' willingness to implement water conservation practices. The influencing factors were assessed by applying descriptive statistics and a logit regression model. The data were collected via a household survey of more than 700 farming families in the basin. The results indicated high levels of farmers' willingness to implement water conservation practices except for cutting down on water extraction. Cost compensation would be necessary to promote implementation of such practice. The farm size consistently had a positive effect on conservation practice implementation. We recommend that the PWS managers in the MRB target larger farmers first in implementing the schemes and fully compensate small farmers for the same. In general, farmers in Tanzania had a slightly higher degree of willingness to implement water conservation practices on public lands. This higher level of participation could be directly attributed to the nature of agriculture,

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water uses, and public landownership. Animal husbandry is a more prominent activity in Tanzania, and, therefore, its farmers appear to depend on rivers and streams for their animals more frequently than other countries.This usage motivates them to participate in public land conservation measures, an encouraging motive that the PWS agencies may want to consider while planning.

Keywords Water conservation practices · Payment for watershed services · Willingness to participate · Mara River basin

32.1 Introduction

For a successful design and implementation of a payment for watershed services (PWS) scheme, the service providers have to be willing to commit to the activities that generate watershed services, and the service buyers have to be willing to pay the compensation to the upstream service providers in return. In the Mara River basin (MRB), the key potential service providers are farmers and forest managers. The potential service buyers include tourism lodges, park managers, large-scale farmers, group ranchers, mining companies, fishing industries, and municipal water users.

Studying the nature of participation of all stakeholders is beyond the scope of this study. This chapter is focused on the farmers. Since the majority of the inhabitants' employment and the land uses in the MRB is agriculture, their practices have a significant influence on the flow of water in the Mara River. As agricultural expansion without environmentally sustainable practices and intensification is one of the threats in the basin, farmers could exacerbate the water resource degradation. For PWS, farmers have a role as service providers to implement water and land conservation practices that will improve the water flow of the river. This chapter presents the results of a study conducted in the MRB of Kenya and Tanzania, on farmers' perception and attitude toward implementing practices that enhance watershed services. The main goal of the study was to understand the level of interest in adopting best management practices as part of a basin-scale PWS scheme. It is of policy relevance to know what demographic, economic, and social factors affect their adoption decision. Such a study will help us identify implementation or participation barriers that may warrant management intervention.

Our research primarily focused on understanding the farming and demographic characteristics of small farmers and pastorals in the basin, who might be the potential recipients of payment for environmental services. Further, we analyzed their willingness to implement water conservation practices and identified factors that influence their willingness to implement water conservation practices. Based on these results, we also attempted to draw policy recommendations for increased implementation of water conservation practices.

32.2 Past Research on Willingness to Implement Conservation Practices

There have been many adoption studies which analyze the diffusion of newly introduced technologies or practices. The adoption studies have caught the attention of social scientists. Researchers in different fields have studied the adoption–diffusion of innovations. Adoption studies came out as an important research theme in rural sociology in the 1940s and 1950s (Ruttan 1996). Marra et al. (2003) described itas, "Sociologists have traditionally conceptualized the adoption decision process by examining distinguishing characteristics of adopters and nonadopters and opinion leaders, farmers' perceptions of the attributes of the innovations, rates of adoption and diffusion, and the channels of communication during the various stages of the adoption decision process" (Marra et al. 2003). The technology adoption studies by economists started expanding in the 1970s and their diversion from the approach of sociologists included the emphasis on profitability and investment risks. In addition, geographers have approached the adoption–diffusion process emphasizing spatial differences, and anthologists have emphasized compatibility with the norms of society. Traditionally, new or improved production inputs for conventional technologies such as the Green Revolution have been a focus of the adoption studies. However, adoption studies of the agroforestry and other natural resource managements have also expanded since the 1990s (Mercer 2004).

Many of the adoption studies have used regression analysis in order to identify the factors which influence farmers' decisions on adopting new practices. The independent variables used in many adoption studies include factors such as age, education, perception of environmental problems, family size (household labor availability), gender of household head, adoption history, farm income, off-farm income, size of farm and number of livestock, membership in community associations, land tenure, location of the farm and residence, and training in the new practices. Perception of attributes of technology and practices such as costs and profitability from the adoptions also were found to affect the adoption decisions (Bayard et al. 2007).

Utility functions are used in many studies to explain the farmers' decision about the adoption. In a study of farm-level soil and water conservation techniques, Sidibe (2005) noticed that farmers' response to new techniques is consistent with utility maximization and that they would adopt new techniques only when the utility obtained from them exceeds the utility from current ones. Another study (Zbinden and Lee 2005) about adopting conservation practices within PWS projects opined that the farmers would participate in such projects only when the utility of doing so was higher than the utility from nonparticipation.

As a general tendency, factors such as income, wealth, education, perceptions of environmental degradation, and household labor tend to have a positive effect on the willingness to invest in the conservation practices (Zbinden and Lee 2005; Sidibe 2005). However, some researchers found contradictions to the above results and reported that the nature of practices and other conditions of the study area were more critical to farmers' adoption decisions. For example, Marenya and Barrett (2007) found that the value of livestock had a significantly positive relationship with one resource management practice while it had a negative relationship with three other resource management practices.

Marenya and Barrett (2007) conducted a household-level analysis of the determinants of adoption of four different integrated natural resources managements by smallholder farmers in western Kenya. These practices included uses of stover lines, livestock manure, inorganic chemical fertilizers, and agroforestry. The study stated that these practices had been employed by farmers in western Kenya for a long time. The independent variables in the model used in this study include farm size, education, age of household head, number of adults, value of owned livestock, gender of household head, nonfarm income, previous experience of adoption, and presence of maize–bean enterprise on plots. The study concluded that indicators of household wealth, which was measured by labor (number of adults), land, livestock, and nonfarm income, positively influenced the adoption decisions, implying that poor farmers were less able to implement the conservation practices. The variables of education, farm size, number of adults, and nonfarm income significantly (at least at $P < 0.10$) and positively affected the adoption of all the practices. The adoption of agroforestry, a practice also analyzed in my research, was positively and significantly affected by the independent variable of education, number of adults, value of livestock, gender (male), nonfarm income (at $P < 0.01$), farm size (at $P < 0.05$), and maize–bean intercrop (at $P < 0.10$).

Marenya and Barrett (2007) also found a negative relationship between the variable of age and adoptions of some of the practices. The possible reasons were (1) as the decision maker gets older, his/her planning horizons shrink and so the incentives for them to invest in the future productivity decreases, (2) since the young people have limited experience, their learning and adjustment costs involved in adopting a new practice are lower, and (3) the relatively and stronger younger farmers can implement the conservation practices that require more physical effort.

Zbinden and Lee (2005) studied farmers' and forest/landowners' willingness to participate in forest conservation programs under payment for environmental service (PES) programs. The respondents were asked if they would participate in three kinds of programs: (1) a reforestation program by assigning a certain part of his/her land to tree planting; (2) forest protection that included a contract in which the forest owner transferred his/her forest use rights to the government for the contract period; and (3) sustainable forest management that emphasized the selective harvest of timber. They concluded that farmers with large farm size were able to forgo a portion of their lands for reforestation, without the loss of household food security or income in the short term.

After the 1980s, the researchers had started analyzing the participatory approach, which "empower farmers to choose the technologies they wanted to test and then to design and implement the research themselves" (Franzel et al. 2001). In Africa, farming systems were often more complex, more subsistence-oriented, and more variable. Therefore, there was a need to integrate the priorities and circumstance of the farmers to the researches.

32.3 Study Methodology and Conceptual Model

32.3.1 Assessing Farmers' Implementation of Conservation Practices

Farmers' decision to adopt a production practice can be modeled using a simple utility-theoretic choice framework. The underlying assumption of the model is that a farmer desires to maximize the expected utility he/she derives from adopting or not adopting a technology. Following Zbinden and Lee (2005), the decision by an individual farmer to adopt the technology i ($Y_i = 1$) or not ($Y_i = 0$) can be formulated as below:

$$\text{Implementation: } Y_i = 1 \text{ if } U_i^0 \leq U_i^1 \tag{32.1a}$$

$$\text{Non-implementation: } Y_i = 0 \text{ if } U_i^0 > U_i^1 \tag{32.1b}$$

That is, the farmer will adopt the water conservation practices if the utility obtained from its implementation (U_i^1) exceeds that of non-implementation (U_i^0).

The utility that the ith farmer obtains is formally described as:

$$U_i = B_0 + B_1 X_{i1} + B_2 X_{i2} + \cdots + B_n X_{in} \tag{32.2}$$

where X_{i1}, $X_{i2}, \ldots, X_{in}$ are n independent variables representing demographic and farm environment characteristics, and B_0, $B_1, \ldots, B_n$ are the model parameters.

Using the utility function described above, the probability that a farmer might implement a water conservation practice, i.e., P_i (YES), can be modeled using the following logistic equation (Zbinden and Lee 2005):

$$P_i(\text{YES}) = \frac{e^{Ui}}{1 + e^{Ui}} \tag{32.3}$$

The probability variable is measured as a binary variable with a value of 1 if a farmer's response is "YES" and of value 0 if the response is "NO."Since P_i is the probability that a farmer implements a practice, the probability that the same farmer does not implement the same practice can be written as (1-P_i). The odds of adoption then can be defined as the ratio of the probability of adoption to the probability of non-adoption. That is

$$\frac{P_i}{1 - P_i} = \frac{e^{U_i}/(1 + e^{U_i})}{1 - [e^{U_i}/(1 + e^{U_i})]} = e^{U_i} \tag{32.4}$$

By taking the natural log of both sides of (32.4), the estimating equation for an individual farmer's implementation can be written as the following:

$$\ln [P_i/(1 - P_i)] = U_i = B_0 + B_1 X_{i1} + B_2 X_{i2} + \cdots + B_n X_{in} \tag{32.5}$$

Table 32.1 Independent variables for assessing the farmers' willingness to implement conservation practices

Independent variable	Definition of the variable	Expected effect on adoption	
		Logistic model	Tobit model
Household size	Number of adults and children in the household	Negative	Positive
Gender	Gender of the respondent: 0 = female, 1 = male	Positive	Positive
Age	Age of the respondent	Negative	Negative
Membership in community organization	0 = the respondent is not a member of any community organization, 1 = the respondent is a member	Positive	Positive
Off-farm income	0 = the respondent doesn't have any off-farm income, 1 = the respondent has off-farm income	Positive	Positive
Land size	Land area of the household's farming operation, under crops and pasture in hectares	Positive	Positive
Distance to the river	The distance to the river or tributaries closest to the respondent's village or township, in kilometer	Negative	Negative
Perception about access to the resource	1 = the respondent perceives that access to and availability of resources in public lands have gone down over the years, 0 = the respondent does not have such a perception	Positive	Positive
Public land uses	The number of public land uses the respondent has, out of 10 types of uses in the questionnaire	Negative	Positive

The independent variables used for the logistic binary regression model (Eq. 32.5) are listed in Table 32.1. The variables of household income and livestock are common variables to be used in the adoption studies, but they are excluded from the models of this research in order to avoid the multicolinearity problem with some independent variables.

32.3.2 Survey Design, Data Collection, and Sampling

In order to assess the farmers' willingness to implement the conservation practices, a household survey of 500 farmers in Kenya and 326 Tanzanian farmers was conducted. The respondents were selected as randomly as possible from among the 360 villages throughout the MRB project area. For the Tanzanian farmers, the number of the respondents from each district area is as follows: 120 respondents from Serengeti District, 116 respondents from Musoma Rural District, and 90 respondents from

Tarime District. For the Kenyan farmers, the names of the districts were not available. A group of volunteers working for the World Wildlife Fund (WWF) in Kenya and Tanzania assisted in conducting the household survey.

During the survey, the respondents were asked if they would be willing to adopt seven types of water and land conservation practices. Before the respondents decided if they would implement or not, it had been explained to them how their implementation of the practices would become important to the Mara basin. They were informed that the water flows in the Mara River and its tributaries had drastically reduced overtime and the health of the river was critical for the survival of wildlife, ecosystems, and human communities living further down the river. Additionally, they were told they could play an important role in enhancing the water flows in the river, and in turn, improving the overall environmental and human welfare in the MRB.

The conservation practices in this research were selected based on the discussion among key stakeholders groups of the MRB. This discussion took place at a workshop, which was held in collaboration with WWFMRB directors, in the town of Narok in January, 2006. In the workshop, they discussed what each group of stakeholder could do to achieve the sustainable resource management in the basin. The participants representing the farmers discussed what efforts would be needed for the sustainable conservation of the MRB, and identified important practices. It has been important to integrate the participation of local stakeholders in designing the research in adoption studies (Franzel et al. 2001). This research valued the importance of their perspective and decided to test the potential adoption of these practices.

The following are the conservation practices included in the questionnaire:

Practice A: Plant and nurture trees and shrubs on your private property, without cutting them for a reasonably long time
Practice B: Plant and nurture trees and shrubs on public lands in your area, as part of a community-managed project
Practice C: Cut down on extracting water from river and/or streams for various purposes
Practice D: Maintain buffers along water bodies
Practice E: Remove existing water structures that result in water obstruction
Practice F: Stop using or considerably reduce the use of forest trees for charcoals, timber, and nontimber products
Practice G: Reduce considerably grazing cattle and other livestock on public lands

Each respondent was asked if he/she would adopt each practice. In addition to the choices of a “yes/no” answer to the implementation of these practices, the respondents were given a choice to answer “not sure.” In a follow-up question, when the respondents answered “no” to implementation of practices, they were asked to indicate the reasons for being unwilling. The respondents were also asked questions regarding their demographic characteristics, farming and livestock production activities, public land uses, and perceptions about the natural resource issues.

32.4 Study Results

32.4.1 Sample Characteristics: Demographics and Agricultural Activities

The demographic characteristics of the sample farmers in the MRB were analyzed. The mean age of the Kenyan respondents was 31.11 years, while the mean age of the Tanzanian respondents was 44.06 years. The average size of the family was 6.62 in Kenya, about half of whom were adults (3.56) and the rest (3.06)were children. Similarly, the size of the sample family in Tanzania was 9.41 with 4.09 adults and 5.31 children.

In Kenya, the numbers of sample men and women were even. However, in Tanzania, 79.2 % of the respondents were men and 20.8 % of respondents were women. For family annual income, Kenyan farmers were asked to choose one from 13 income groups which described their annual family income in Kenyan shilling (KSH). The median income of the Kenyan family fell into the group of KSH 30,000 and TSH 40,000 ($n = 485$). Tanzanian farmers were asked to choose one from 12 income groups in Tanzanian shilling (TSH). The median income of the Tanzanian family fell into the group of TSH 300,000 and TSH 400,000 ($N = 324$). By taking the midpoints of the ranges of the income groups, the mean value of income of Kenyan farmers was KSH 41,784.The same for Tanzanian farmers was TSH 465,972. Further, 39.0 % of Kenyan respondents ($N = 490$) and 24.6 % of Tanzanian respondents ($N = 325$) answered that they were the members of some community organization(s). These percentage numbers are rather on the lower side and may present a challenge for water conservation practices.

Almost all of the sample farmers in both the countries practiced some kind of crop production. The percent of farmers that practiced different activities in Kenya are: crop production (99.4 %), vegetable/fruits (88.2 %), chicken (86.4 %), dairy cattle (81.0 %), beef cattle (67.5 %), goat (60.7 %), sheep (30.9 %), others (5.6 %), flowers (1.8 %), and fish (0.4 %). The same data for farmers in Tanzanian are as follows: crop production (99.4 %), chicken (91.1 %), goat (73.6 %), beef cattle (66.0 %), sheep (54.9 %), vegetable/fruits (22.4 %), dairy cattle (5.5 %), fish (2.5 %), others (1.8 %), and flowers (1.2 %).

In Kenya, the mean of household land area under crops was 2.26 ha, pasture 2.36 ha, and woody plants and brushes 0.98 ha. In Tanzania, the mean of land area under cropland was 7.88 ha, pasture 11.99 ha, and woody plants and brushes 3.55 ha. There was a considerable difference between Kenya and Tanzania in terms of the number of livestock. For instance, an average Kenyan sample farmer held an average of 3.20 heads of cattle while an average farmer in the Tanzanian side of the MRB had 32.55 heads of cattle.

32.4.2 Use of Public Lands and River Resources

Understanding the use of public lands by farmers is key to assessing whether farmers would be willing to participate in projects that increase watershed services. We

Table 32.2 Use of public lands in Kenya and Tanzania

Types of public land uses	Kenyan farmer			Tanzanian farmer		
	Percentage	Frequency	*N*	Percentage	Frequency	*N*
Livestock grazing	18.59	74	398	70.77	230	325
Fuelwood	13.85	55	397	69.54	226	325
Charcoal	3.78	15	397	53.70	174	324
Timber	4.53	18	397	37.93	121	319
Nontimber forest products	2.53	10	396	36.66	114	311
Bush meat	2.54	10	394	17.55	56	319
Herbal medicines	16.16	64	396	47.20	152	322
Other wildlife products	2.28	9	395	15.36	49	319
Recreation	3.30	13	394	23.29	75	322
Other use	0.51	2	395	3.43	11	321

identified ten kinds of public land uses and asked if farmers derived any of those uses (see Table 32.2). Respondents answered "yes" or "no" to each of the uses. In Kenya, the top three reasons that the sample farmers used the public land were livestock grazing (18.59 %), herbal medicine (16.16 %), and fuelwood (13.85 %). The top three uses of public lands in Tanzania were livestock grazing (70.77 %), fuelwood (69.54 %), and charcoal (53.70 %). It was evident that the percentage of farmers using public lands was higher in Tanzania than in Kenya. These results are important in that the public land management agencies may have different challenges in implementing water conservation in public lands.

In order to study the farmers' perception about the natural resources, particularly water issues, the respondents were asked whether they had been observing a general decline in water availability and decline in quality over the years in their area. In Kenya, 96.6 % of the respondents had observed a decline in water availability and quality ($N = 494$). In Tanzania, 99.1 % of the respondents had observed a similar trend ($N = 326$). When asked about the causes of such water quantity/quality decline, 93.4 and 90.1 % of the Kenyan and Tanzanian sample farmers, respectively, indicated drought as the main reason, and 91.3 and 87.3 %, respectively, gave forest loss as the second main reason. Other reasons for water quantity decline were diversion of rivers, excessive water extraction upstream, and population increase. About 82.0 % of the sample farmers in Kenya believed that communities that lived upstream of their closest river or tributaries might be affecting the quantity and quality of the water flow in the river. In Tanzania, 91.0 % of the respondents had the same perception about their upstream water users.

32.4.3 Level of Farmers' Willingness to Implement Conservation Practices

To assess the farmers' willingness to implement the conservation practices, the respondents were asked whether they would be willing to undertake seven types of

Table 32.3 Percentage of sample farmers willing to implement watershed service best management practices (BMPs)

Practices	Kenya		Tanzania	
	N	Percentage	*N*	Percentage
Practice A: tree planting on private land	487	86.4	325	91.4
Practice B: tree planting on public land	485	75.3	325	88.0
Practice C: cut down on extracting water	480	49.0	321	75.7
Practice D: maintain buffers along water	475	88.8	319	87.8
Practice E: remove water extraction	476	80.7	314	86.9
Practice F: stop/reduce the use of forest trees	484	89.3	318	84.3
Practice G: reduce grazing on public lands	483	82.4	317	80.1

Table 32.4 Distribution of farmers' willingness to implement different water conservation practices in Kenya and Tanzania

Number of willing practices	Kenya			Tanzania		
	Frequency	Valid percent	Cumulative percent	Frequency	Valid percent	Cumulative percent
0	2	0.6	0.6	0	0.0	0.0
1	0	0.0	0.0	0	0.0	0.0
2	3	0.9	1.5	1	0.4	0.4
3	4	1.2	2.7	3	1.2	1.6
4	31	9.3	12.0	6	2.4	4.0
5	42	12.6	24.6	8	3.2	7.2
6	110	32.9	57.5	36	14.4	21.6
7	142	42.5	100.0	196	78.4	100.0
Total *N*	344	100.0		250	100.0	

water and land conservation practices. The results indicate that there is a high degree of willingness to implement the conservation practices in both Kenya and Tanzania (Table 32.3).

Except for the Practice C (cutting water extraction rate), the majority of the farmers were willing to implement the study best management practices (BMPs). In Kenya, practices F (reduction in forest use), D (buffer zone next to streams), and A (tree planting on private lands) were the most popular, in terms of the percentage of farmers willing to implement a practice. In Tanzania, practices A (tree planting on private land), B (tree planting on public land), and D (buffer zone next to streams) received the highest acceptance rates.

Table 32.4 presents the distribution of farmers who were willing to implement one or more watershed protection practices. It was evident that almost 42 % of the sample farmers in Kenya were willing to implement all seven practices. More than 75 % of them said they would implement six or more practices. Only less than 1 % of the sample farmers said they would adapt only one or no practice. In Tanzania, even a larger percent of the sample farmers were willing to adapt the suggested practices. About 78 % of the farmers were willing to adapt all seven practices. Like in Kenya, less than 1 % of them said they would implement one or no practice. These results

Table 32.5 Logistic regression of willingness to reduce water extraction

Variable	Kenya		Tanzania	
	Coefficient	t-value	Coefficient	t-value
Family size	– 0.091*	2.772	0.026	0.327
Gender	0.747**	6.530	– 1.041	2.179
Age	– 0.014	1.379	– 0.011	0.518
Off-farm income	– 0.255	0.692	– 0.294	0.464
Membership in community organization	– 0.191	0.367	– 0.186	0.185
Land size	0.103**	6.036	0.088*	2.741
Distance to the river	0.272*	3.660	– 0.021**	3.885
Perception about access to the resource	– 1.305***	17.177	0.587	0.463
Constant	1.164	3.330	2.158**	3.774
N	244		224	
Log-likelihood	291.566		177.28	
Chi-square	41.94		9.996	
Significance	0.000		0.265	

***Significance at 1 % level; **Significance at 5 % level; *Significance at 10 % level

indicate that there was an overwhelming support for implementing BMPs in the study area.

With regard to Practice C, which had the highest rate of nonacceptance, we asked a follow-up question of those who had refused to implement the practice, regarding the reason behind their response. Most of the respondents thought that cutting water would be neither practical nor too expensive. Some of them said they would implement the practice provided they were adequately compensated for.

32.4.4 The Logistic Regression on Reducing the Rate of Water Extraction

The logistic regression analysis was conducted to identify the determinants of the probability that farmers were willing to implement the conservation practices. Since most of the farmers answered they would adopt all practices except cutting down on extracting water (Table 32.3), there was not enough variance in the dependent variables to observe the effect of independent factors. Therefore, we conducted the logistic regression only on the practice of cutting down on extracting water from river/streams (Practice C), which received the least willingness to implement in both countries. The definition of each independent variable used in this analysis is listed in Table 32.1.

In Kenya, the perception that the access to water had become limited was a significant determinant of the likelihood of implementing Practice C (see Table 32.5). The land size had significant impacts on the practice adoption, indicating that larger farmers were more likely willing to lower the water extraction. The reason small farmers were less willing to cut down water extraction was that they probably were already at a low rate of extraction and were not in a position to reduce water consumption any further. The independent variables of the distance of the river or tributary closest to the village, gender, and family size were found to have an influence on the adoption as well. Since the probability of implementing Practice C was negatively and significantly affected by the perception that access to and availability of resources in public lands have reduced over the years, it implied that farmers who perceived this issue had a lower probability of implementing this practice.

For the Tanzanian farmers, the logistic regression did not fit the data well. Only two variables of the model were found to have a statistically significant influence on the willingness to lower water extraction. At the 95 % confidence level, the distance of the river or tributary closest to the village was found to have a significant but negative impact on the likelihood of the practice implementation. That is, the farther off the rivers and streams are from the village, the less likely the households would cut back on water extraction. This result was contrary to what was observed in the case of Kenyan sample farmers. Further, the land size variable revealed a significant level of impact on water extraction reduction.

32.5 Discussion

32.5.1 The Nature of Farming Operation and Motives for Water Conservation

Both in Kenya and in Tanzania, the majority of the farmers practised crop production, along with beef cattle, goat, and chicken. On the other hand, less than 3 % of the farmers had the production activities of fish and flowers. The most noticeable difference in the production activities between Kenyan and Tanzanian farmers was with respect to dairy cattle production. Only 5.5 % of Tanzanian farmers engaged in dairy cattle production while 81.0 % of the Kenyan farmers did so. Another noticeable difference was that while 88.2 % of Kenyan farmers produced vegetable/fruits, only 22.4 % of Tanzanian farmers had such production.

The size of the farming operation, in terms of both the land size and the number of livestock, is bigger in Tanzania than in Kenya. For all land-use types studied, which included crop land, pasture, and woody plants/bushes, the average land areas were higher in Tanzania than in Kenya. Similarly, for all types of livestock, which included beef cattle, dairy cattle, sheep, goat, and chicken, the mean number of heads of livestock the farmers owned was higher in Tanzania than in Kenya.

As both dairy production and vegetable/fruit production normally use more water than other activities, the representative small farmers in Kenya might find it more difficult to cut their current water use than the small farmers in Tanzania. This might be the reason that a lower proportion of farmers in Kenya (50 %) were willing to cut water use than those in Tanzania (75 %).

32.5.2 The Use of Public Land in Kenya and Tanzania

Sample farmers in Kenya did not have many public land uses, while Tanzanian farmers commonly did have such uses. While the majority of Tanzanian farmers used public lands for livestock grazing, fuelwood, and charcoal, no more than 20 % of the sample farmers in Kenya used public lands for any purposes. About 70.2 % of the farmers did not have access to any public land use in Kenya while 80.1 % of farmers had access to, and did use, public lands in Tanzania.

Probably, the difference in the public land use can be attributed to the difference in landownership policies between the two countries. In Kenya, there is clear private landownership which is more properly enforced by the government. Public lands have restrictions in Kenya, and people cannot use it without prior authorization. In Tanzania, all the land belongs to the government. Private individuals are given land for private use by the government. If an individual is given land in Tanzania and he/she fails to develop it, the government can take it back without any compensation. Farmers routinely have unrestricted access to lands under government control.

32.5.3 The Willingness to Implement the Conservation Practices

In both the study countries, all the water conservation practices received high marks on the willingness to implement from the majority of the respondents, with exception of the practice of reducing water extraction in Kenya (yes = 49.0 %). Although the results revealed farmers' high willingness toward the implementation of conservation practices, it is likely that not all of them would be actually capable of implementing them without being compensated for the costs of such action. Therefore, it is important to know from the results what would be the obstacles toward farmers implementing the conservation practices.

The most common reason for the nonimplementation of any of the seven practices was cost. Most of the unwilling farmers said they would take part in the implementation only if they were adequately compensated for the loss of their income. The majority of the unwilling respondents listed this reason for their nonimplementation in the case of planting and nurturing trees and shrubs on their private land, maintaining buffers along water bodies, and removing existing water structures that result in water obstruction. Also, the "lack of resources and/or too much cost" was the common reason farmers were unwilling to plant trees on private or public lands and maintain buffers along water bodies. Therefore, it can be concluded that the PWS could play a major role in incentivizing upstream farmers for adopting water conservation practices.

Of those who were unwilling to implement the practices of "cutting down the water use" and "considerably reducing charcoal, timber and nontimber production," a significant number of the farmers felt that these practices would not work. This could be the result of the fact that these farmers may be already extracting only the necessary amount of water, especially given that they have to walk for a long distance to the river for water collection (the mean distance to river was 1,301.06 m in Kenya and 6,864.64 m in Tanzania). It would not be possible for them to further cut down on extracting water. As regards forest product use, forests are the major source of farmers' energy and timber needs. Again, these farmers may expect a substantial monetary compensation for their behavioral changes.

If the PWS managers want to impose these practices on farmers, the infrastructural support is possibly important. For example, the new water source or water harvesting system such as the rainwater harvesting system can possibly help farmers to reduce their water extraction from the river. Another possible example is the introduction of a gas heating system that would considerably reduce the dependency on forest trees for their lifestyle. Also, providing the farmers with energy-saving stoves might help them reduce the dependency on forest trees. There is an effort to promote the use of this stove in the basin by the community organization, Bomet Improved Stove Organization. According to a communication with a few members of the organization during the field visit, this stove would save about 50 % of the fuelwood by using two dry woods at one time instead of using charcoals.

32.5.4 Factors Influencing the Extraction of Water

In this study, the factors that significantly influenced the farmers' implementation as per the logistic models were land size, family size, gender, distance to river, and access to and availability of natural resources.

For both the countries, land size significantly and positively influenced the farmers' implementation of conservation practices. This result is consistent with that of Marenya and Barrett (2007). The main reason behind this positive and significant effect of land size is that the farmers with larger land area can more easily spare a portion of their land for nonproduction uses such as buffer zones and tree plantings. On the other hand, it would be difficult to do so for farmers with small landholdings because the opportunity costs for them to spare their land for nonproduction uses are higher. The farmers with larger land area should also find it easier to reduce grazing livestock on public lands by sparing a portion of their land for grazing. Another possible implication of the positive effect on this practice was that the land size might be a proxy for the household wealth. The results from Kenyan farmers revealed a strong correlation ($r = 0.75$, $p = 0.008$) between the land size and the household income. The farmer with larger land should be able to grow more cash crops in addition to subsistence farming (Marenya and Barrett 2007). Farmers with more income should be able to purchase water from other water sources such as vendors if they exist in their area.

The fact that the land size affects participation rate also implies that different per-acre compensation rates might be necessary for farmers with varying land sizes. Those with smaller landholdings would need to receive higher rates of compensation per acre than those with larger lands; the former group has lower willingness for, and probably the capability of, implementing the conservation practice. In terms of the cost, it can be concluded that it should be more effective to compensate farmers with larger lands. However, it is also important to note that the effectiveness also depends on the location of the farm: If small farms exist by the river, it should be a priority to compensate them even if the compensation rate per acre is high since the effect of their practices on the river water flow is also high.

In Kenya, family size negatively influenced the implementation of water extraction reduction. This result simply shows that the larger families have larger water consumption needs and, therefore, it would be harder for them to cut down on extracting water. While the larger families may consume more water and forest trees, they also have larger household labor force, which would make it easier for them to implement such practices as planting trees. The result possibly implies that the need for consumption of natural resources outweighed the advantage brought by availability of the household labor.

The male farmers were more likely to implement the practice(s) in Kenya. Marenya and Barrett (2007) observed similar results in West Kenya. They concluded that the African women's lesser access to critical resources undermined their ability to mobilize labor needed to carry out labor-intensive conservation practices. Women have to spend a lot of time on collecting water for their basic family needs and probably use water efficiently. They are unlikely to make further cuts in water uses.

Surprisingly, the distance to the river had the opposite effects in the two study countries on the practices of cutting down on extracting water. In Kenya, the farmers who lived closer to the river had less probability of cutting down on extracting water. In Tanzania, the farmers who lived closer to the river had more probability of implementing such practice. The above difference could be partly due to the differences in landownership and the nature of livelihood. As indicated earlier, the Tanzanian farmers are more dependent on livestock activities and tend to use public lands, streams, and rivers for their animals more often than their counterparts in Kenya. Therefore, the Tanzanian farmers who lived closer to rivers perhaps saw the need for conserving public lands and protecting rivers and streams more readily than the Kenyan farmers.

32.6 Conclusion

The MRB is increasingly facing degradation in water availability, water quality, and other kinds of natural resources. The degradation would adversely impact both the human and natural environments. Faced with these environmental challenges, the stakeholders in the region are considering the introduction of a market-based approach or PWS schemes for financing water conservation and promoting more sustainable resource management. With the ultimate goal of helping the establishment of such PWS systems in the MRB, this study conducted an analysis of farmers in the Kenya and Tanzania sides of the basin. Based on the current activities, stakeholders' perceptions, and other resource use situations, this research analyzed the farmers' willingness to implement water conservation practices. Seven different water conservation practices were the subject of the investigation. A logistic probability model was estimated to identify the factors influencing the stakeholders' participation in the respective programs.

The study results provided evidence for high levels of farmers' willingness to implement the proposed conservation practices in both Kenya and Tanzania. However, it was not certain whether all of the farmers who have such willingness would be capable to do so at the time of actual implementation. From the question about the reasons of unwilling to implement the conservation practices, it was inferred that the farmers would be more cooperative in implementing the practices if appropriate compensation was given to them to cover the costs. The farmers were least willing to implement the practice of cutting down on extracting water from rivers and streams.

The result of the logistic probability model revealed that for Kenyan farmers larger land area, longer distance to the river, smaller family size, female gender, and perception about the lack of access to availability of resources in public lands did influence their willingness to implement water conservation practices. In Tanzania, farmers with larger land and shorter distance to the river had higher willingness to reduce the rate of water extraction from rivers or streams. This research recommends that the PWS managers in the MRB target larger farmers first in implementing the PWS schemes and fully compensate small farmers for the same.

Overall, this research provides a critical piece of management information for an effective implementation of the PWS system in the MRB, i.e., the buy-in of the low-income stakeholders such as small farmers into participation in a market-based approach to funding integrated, transboundary river projects. This is only the first, but important step toward implementing such schemes. As discussed in Chap. 41, before this scheme can become a reality, the managers need to have a clear understanding of: (a) the watershed service levels and timing (i.e., the minimum water flow in the dry season), (b) the appropriate amounts of compensation for upstream water conservation practices, and (c) an institutional mechanism for the actual PWS implementation, including conservation adoption, compensation payment, service fee collection, monitoring of practice adoption, and service delivery.

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Chapter 33
Climate Teleconnections and Water Management

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Abstract Advancements have been made in identifying teleconnection between various climate phenomena and regional hydrometeorology. This knowledge can be systematically applied to predict regional hydrometeorology to gain lead time for resource and risk management decision making. Adaptations for droughts, floods, and cold and warm weather conditions are necessary for optimal food production and, in many cases, for survival. The El Niño Southern Oscillation (ENSO) climatic phenomenon has been linked to seasonal weather of many regions mainly through rainfall and temperature. The development of El Niño or La Niña has usually opposing regional effects. Its effects are manifested in regional droughts and crop yield reduction, loss of livestock feed, water supply shortage or floods and flood damages, insect population and pathogens, wildfires, etc. A new method has been used to track ENSO development using cumulative sea surface temperature (SST) anomaly and cumulative Southern Oscillation Index (SOI) from freely available data. The relationships of ENSO indices and the Blue Nile hydrology have been shown using an index that tracks cumulative SST anomaly. It has been shown that the Upper Blue Nile basin rainfall and flows have teleconnection to ENSO. Dry years are likely to occur during El Niño years at a confidence level of 90 % and La Niña years favor wetter condition. The results of this study can be applied to resource management decision making to mitigate drought or flood impacts with a lead time of at least few months. ENSO tracking and forecasting helps prediction of approaching hydrologic conditions to make early water management decisions. A case study with organizational structure and decision making process is presented where ENSO conditions are tracked weekly and results are applied for water management decision making.

Keywords Climatic teleconnections · Water management · El Niño and La Niña · Sunspot · Nile basin · Hydrometeorological prediction · Climate prediction

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33.1 Introduction

Atmospheric circulation exhibits substantial variability that is reflected in weather patterns and circulation systems that recur with a given frequency. The weather or circulation systems can last few days, few weeks, few months, and several years to several centuries (CPC 2012a). Although the earth–atmosphere–ocean system is large and complex, steady knowledge of understanding and predicting the processes has been progressively growing with the increased ability of monitoring, computing, and modeling. In the last century, significant progress has been made towards an increased understanding of the physical and dynamic atmospheric processes with a deeper appreciation of the association between atmospheric variations of different parts of the globe and regional hydrometeorology. Such associations are known as teleconnections. Modeling these complex systems and predicting weather and climate have achieved significant progress although a great deal more work remains to better understand the various processes and to reduce uncertainties in weather forecasting and climatic predictions for practical applications (Abtew and Trimble 2010).

The ability to forecast regional weather patterns based on short-term climatic patterns is gaining momentum. Changnon and Kunkel (1999) reported that in the previous 20 years, the use of climate data and information in agriculture and water resources has increased remarkably due to the improved access to such information through the personal computer. The trend has continued. In an era where water shortage and water source variability have an impact on food production, power production, drought, and flood control, all available hydrometeorological predictive resources have to be utilized in water management and related operations in decision making. Few months of lead time for forecasting calamities during droughts can provide opportunity to take steps to mitigate losses. Early forecast of wet conditions and flood potential provides tremendous opportunity in reservoir management and flood mitigation. The initial step is identifying the climatic phenomena that are related to a region's hydrometeorology. The following step is to continuously monitor the climatic phenomenon and to develop the capability to forecast. Setting up the organizational structure and skills to use the knowledge for application in resource management is the critical and final part. In the Nile River and its tributaries, there are dams and water-use operations that can also benefit from climate forecasting. Rain-fed subsistence farming and small-scale irrigation operations can benefit from climate forecasting in developing adaptable cropping strategy.

33.2 Climatic Phenomena

The sun's energy drives the climate and weather of the earth. Energy stored in the ocean's shows delayed effects. Temperature gradients cause pressure gradients and density gradients resulting in massive energy and mass circulation around the globe. Variations in the sun's energy and surface activities create variations in ocean temperatures creating short-term and longer term measurable patterns. These patterns in return create measureable climatic phenomena that have been observed for a long time. These climatic phenomena have been found to have associations with weather patterns that affect life on earth as precipitation, evapotranspiration, air temperature, water temperature, and wind speed. Short-term and high-intensity energy and mass transfer from the tropics to higher latitudes that complements oceanic circulations are tropical storms including hurricanes. These systems have physical link to changes in climatic phenomenon where some conditions are favorable for development and intensity and some are not.

Observations of climatic teleconnections and systematic analysis were published in early twentieth century. Bliss (1926) remarks that the observations of climatic teleconnections started when winter in Western Europe was found to be related to the flood stages of the Nile. One of the earliest works done on global climatic relationships is by Walker and Bliss (Walker 1926; Walker and Bliss 1932). The Southern Oscillation (SO), the North Atlantic Oscillation (NAO), and the North Pacific Oscillation (NPO) were cited to be related to weather at different locations on the globe.

Natural climate variability is expressed as temperature and pressure anomaly resulting in variations in air masses and moisture flows and ocean circulation occurring at frequencies from few years, decades to centuries. The Atlantic Multidecadal Oscillation (AMO) is a sea surface temperature (SST) anomaly between the equator and Greenland. Its cycle between warm phase and cool phase explains 10 % of the Mississippi River outflow and 40 % of Lake Okeechobee inflows (Enfield et al. 2001). The Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability that fluctuates between warm phase (positive) and cool phase (negative) cycling on a decadal time frame. The NAO is a high-frequency climatic phenomenon different from AMO characterized by the difference in sea level atmospheric pressure between Iceland and the Azores. In the tropics, the Intertropical Convergence Zone (ITCZ) is a weather-making climatic phenomenon where the northeast and southeast trade winds come together. Its relative position along the equator as a band of clouds, trough, has importance in weathers of many regions including the Nile basin. El Niño Southern Oscillation (ENSO), AMO, and PDO have also been linked to regional climate (Enfield et al. 2001; Zhang and Trimble 1996). Table 33.1 depicts commonly referred climatic phenomena and their respective periodicity.

33.3 El Niño Southern Oscillation

The most well-known climatic phenomenon that affects seasonal weather at many parts of the globe is the ENSO. ENSO is an ocean–atmosphere phenomenon where the cooler equatorial eastern Pacific Ocean warms up once every 2–7 years. The increase in equatorial eastern Pacific SST is attributed to the weakening of the normally persistent easterly trade winds and results in warm water from the western Pacific moving to the east (Fig. 33.1a). An average of + 0.5 °C deviation from average SST for 3 consecutive months indicates an El Niño event (NOAA 2009). When over the

Table 33.1 Periodicity of climatic phenomenon (Most from Obeysekera et al. 2011)

Climatic phenomenon	Periodicity
ENSO	3–7 years
AMO	55–70 years
ITCZ	Location varies along the equator
PDO	20–30 years
NAO/AO	Highly variable/high frequency
Short-term solar eruption	Highly variable/high frequency
11-year solar cycle	9–14 years
90-year solar cycle	80–90 years
200-year solar cycle	190–210

ENSO El Niño Southern Oscillation, *AMO* Atlantic Multidecadal Oscillation, *ITCZ* Intertropical Convergence Zone, *PDO* Pacific Decadal Oscillation, NAO/AO North Atlantic Oscillation

equatorial pacific, easterly trade winds become strong and a condition is created for cold water to upwell to the surface. Patterns of wind and moisture flow over the ocean change creating the La Niña event (Fig. 33.1b). These patterns result in influencing the pattern of the polar and subtropical jet streams resulting in influencing the seasonal weather of many regions. The SO is the variation in air pressure between the western and eastern tropical Pacific. The Southern Oscillation Index (SOI) is a measure of air pressure difference between Tahiti in the east and Darwin, Australia, to the west as compared to the historical average of the differences. Negative differences indicate El Niño conditions as lower pressure in the eastern Pacific is associated with warmer water and weakened easterly trade winds. Positive SOI corresponds to La Niña. Neutral conditions, as the term indicates, are manifested by SSTs of eastern Pacific being neither too warm nor too cold compared to historical average, and the pressure anomaly is small (Fig. 33.1c). Tropical storms which are significant weather patterns that affect lives and property are influenced by ENSO events. El Niño condition with westerly winds generates atmospheric shear that creates less favorable condition for Atlantic tropical storm development and intensity. La Niña conditions favor Atlantic tropical storm development. Table 33.2 depicts ENSO events of El Niño, La Niña, and neutral years from 1877 to 2012 with strong events shown in bold.

33.4 ENSO Monitoring and Prediction

33.4.1 Standard Methods of ENSO Monitoring and Prediction

SST is monitored in the pacific at four regions, 1, 2, 3, and 4 from west of Peru to the western Pacific (5°N–5°S Latitude; 80°W–160°E Longitude). A combined area from regions 3 and 4 (5°N–5°S; 120°W–170°W), Niño 3.4, is commonly used to monitor ENSO (Fig. 33.2). The US National Weather Service, Climate Prediction Center, reports weekly values of SST at Niño 3.4 region and $1 + 2$, 3, and 4 regions. An index, Oceanic Niño Index (ONI), is used to track ENSO development. A total of 3-month moving mean of SST is reported as the last month's index. Values $\geq 0.5\,°\mathrm{C}$ indicate

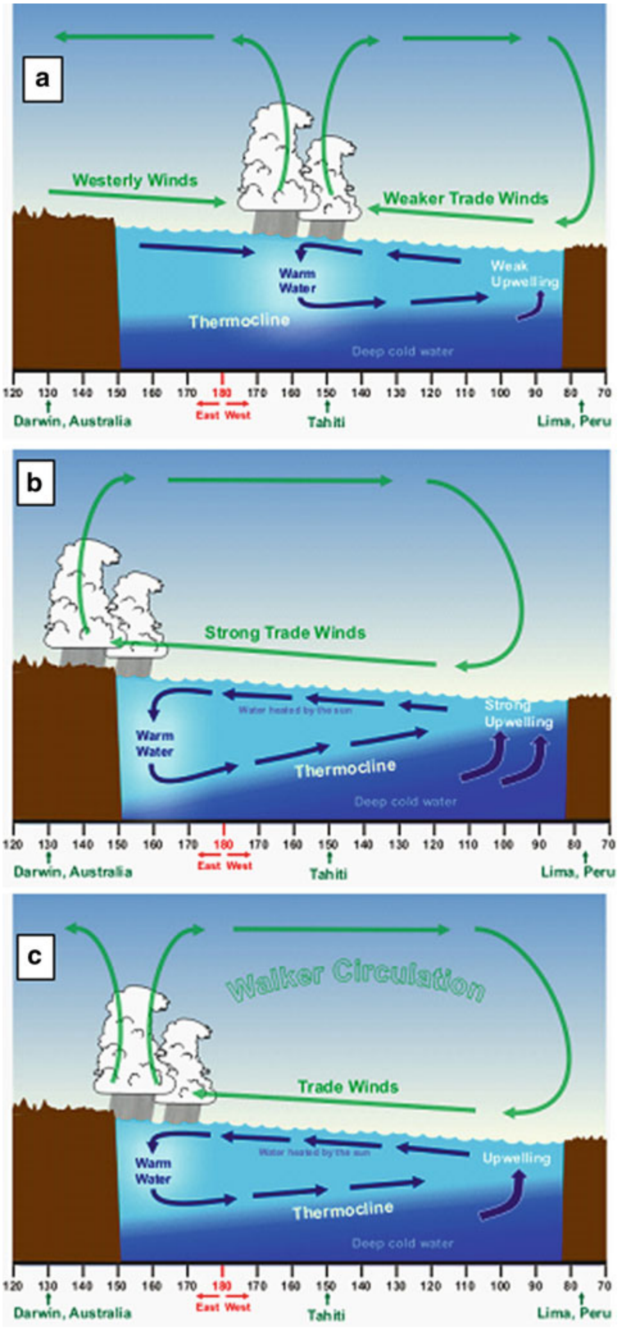


Fig. 33.1 El Niño Southern Oscillation **a** El Niño, **b** La Niña, and **c** Neutral. (Source: US National Weather Service)

Table 33.2 ENSO events (1877–2012)

El Niño Years			La Niña Years			Neutral Years
1877	1923	**1977**	1871	**1916**	**1964**	1881
1878	1925	1979	**1872**	1917	1967	1889
1884	**1926**	1980	**1873**	1921	**1971**	1901
1885	1929	**1982**	**1874**	1922	**1973**	1906
1888	1930	1983	**1875**	1924	**1974**	1927
1891	**1931**	1986	1876	**1933**	**1975**	1928
1895	1932	**1987**	**1879**	1934	1978	1935
1896	1936	1990	1880	1938	1981	1939
1897	1937	**1991**	1882	1942	**1984**	1944
1899	**1940**	**1992**	1883	1943	**1985**	1952
1900	**1941**	**1993**	**1886**	**1945**	**1988**	1959
1902	1948	**1994**	**1887**	1946	**1989**	1960
1903	1951	**1997**	**1890**	1947	1995	1968
1904	**1953**	**2002**	**1892**	1949	1996	1976
1905	**1957**	2003	**1893**	**1950**	**1999**	1998
1912	**1958**	**2004**	1894	**1954**	**2000**	
1913	**1963**	2005	**1898**	**1955**	2001	
1914	**1965**	2006	1907	**1956**	**2007**	
1915	1966	2009	1908	1961	**2008**	
1918	**1969**		**1909**	**1962**	2010	
1919	1970		**1910**		2011	
1920	**1972**		1911			
bold indicates strong event						

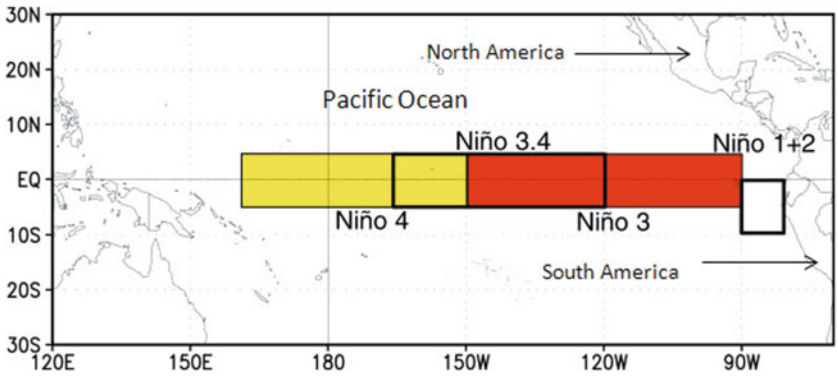


Fig. 33.2 Regions of SST monitoring for El Niño Southern Oscillation

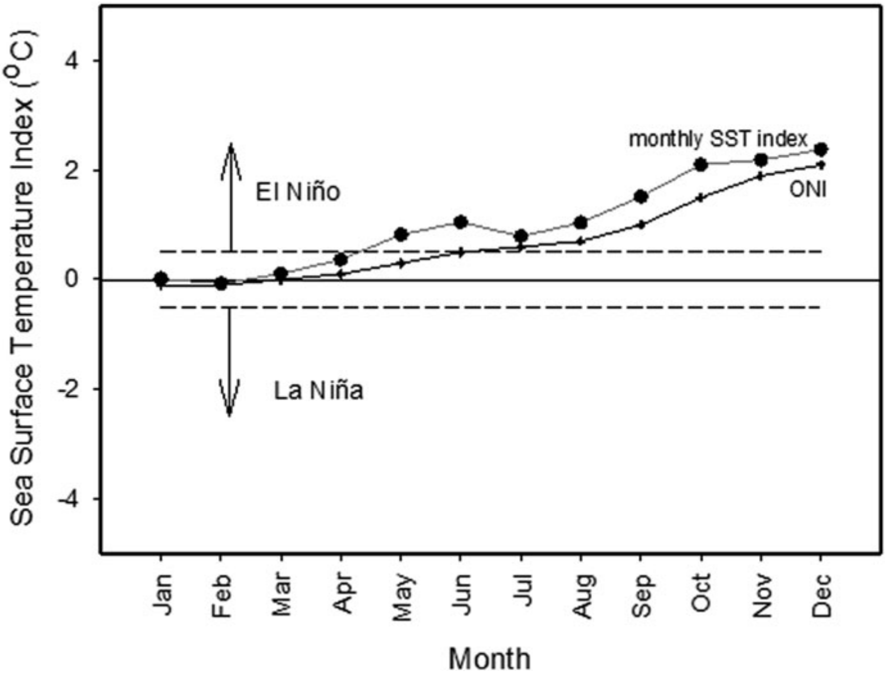


Fig. 33.3 Tracking ENSO development with the monthly SST and Oceanic Nino (ONI) Index

El Niño and ≤ − 0.5°C indicate La Niña conditions (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml, Accessed, 7 November 2012). According to this method, conditions have to be observed five consecutive 3-month moving averages to confirm an occurrence of an ENSO event. Neutral ENSO conditions prevail when SST anomalies are between − 0.5 and + 0.5 °C. Figure 33.3 depicts monthly SST and ONI indices. This monitoring is supported by dynamic and statistical modeling predictions from a large number of climatic models that usually produce widely varying results. The International Research Institute (IRI) for Climate and Society uses 17 dynamic and 8 statistical models and the US Climate Prediction Center generates model predictions on a weekly basis.

33.4.2 The Cumulative SST ENSO Tracking Method

ENSO prediction has more certainty than hydrologic prediction for a region. Identifying ENSO and hydrologic relationships can aid water management decision making by providing a lead time of months to mitigate drought or flood impacts and to optimize water use and agricultural production. A new ENSO tracking index is not affected by short-term fluctuations in SST and air pressure anomalies. The method is shown to be fully dependable in predicting ENSO events before the traditional methods when the wet season starts in subtropics and tropics. ENSO predictions by numerical models produce varied results from model to model. Critical water management decisions are related to storage in the wet season and water supply in the dry season. Seasonal agricultural production decisions benefit from early prediction of ENSO events. Several years of ENSO were successfully tracked with hind casting with this method and compared to traditional methods.

Discrete monthly climatic index as ENSO does not amplify the strength of the event. The cumulative index clearly indicates the comparative strength of a climatic phenomenon, such as SST and SOI. Abtew et al. (2009a) and Abtew and Trimble (2010) presented the use of a new approach, cumulative climatic ENSO index, for tracking and predicting ENSO development. Based on historical records of ENSO events analysis, a cumulative SST index ≥ 5 indicates a strong El Niño and a cumulative SST index ≤ -5 indicates a strong La Niña. A positive SOI corresponds to a negative SST index and La Niña, and a negative SOI corresponds to positive SST index and El Niño. SOI strength indicators are cumulative values of 7 and -7 for La Niña and El Niño, respectively. The ENSO strength classification from cumulative SST and SOI presented here agrees with other consensus classifications (Null 2013). The cumulative ENSO index is tracked from the beginning of the year as shown in Eq. (33.1), with pattern identified by October, will influence the following months' weather.

$$\text{Cumulative Index} = \sum_{1}^{M} I_m \quad \text{For} \quad \text{M} \leq 12 \tag{33.1}$$

where I is SST or SOI index and m is month.

Figure 33.4 and 33.5 depicts application of the method for the 1982 strong El Niño using cumulative SST and SOI indices. As shown in the figures, by June it was clear that this will be a strong El Niño based on the direction and the slope of the cumulative lines (Abtew and Trimble 2010; Abtew et al. 2009a). The limitation of the traditional method of ENSO tracking and predicting is summarized by the following excerpt from the time—"The 1982–83 El Niño, by many measures the strongest thus far this century, was not predicted and not even recognized by scientists during its early stages. In retrospect, its beginnings can be traced back to May 1982, when the easterly (east to west) surface winds that usually extend nearly all the way across the equatorial Pacific from the Galapagos Islands to Indonesia began to weaken. West of the dateline, winds shifted to westerly and a period of stormy weather set in" (http://www.atmos.washington.edu/gcg/RTN/rtnt.html, Accessed 04 November 2012). Application of the method will be shown in a later section in a case study. By June, El Niño can be predicted with certainty with high chance of being a strong event.

33.5 Relationship of Climatic Phenomena and Regional Hydrometeorology

The relationship between the ENSO and regional hydrology has been determined for various regions of the world. In south Florida, dry season (November–May) rainfall and flows are higher than average during El Niño years and lower during La Niña

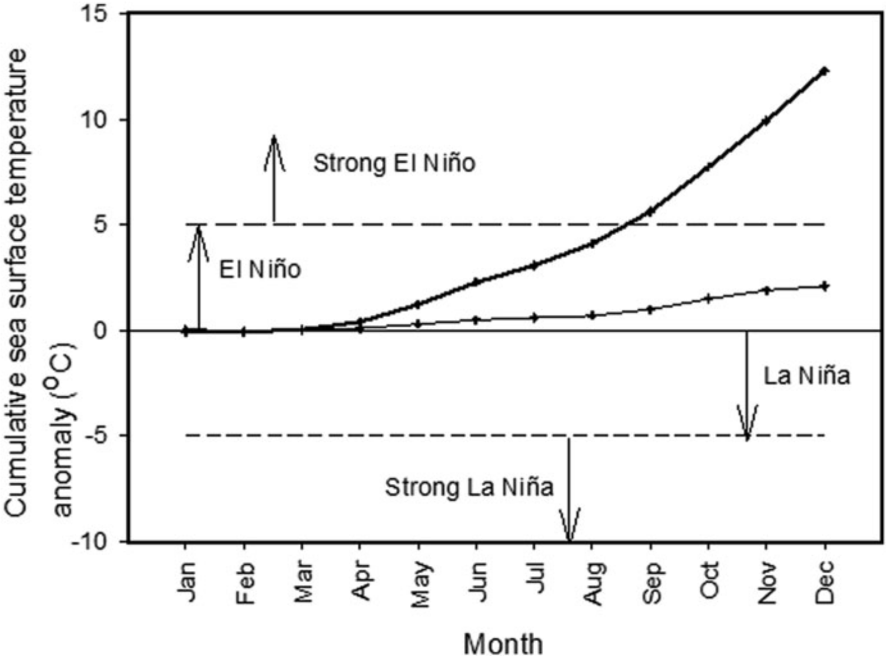


Fig. 33.4 Cumulative SST index for 1982

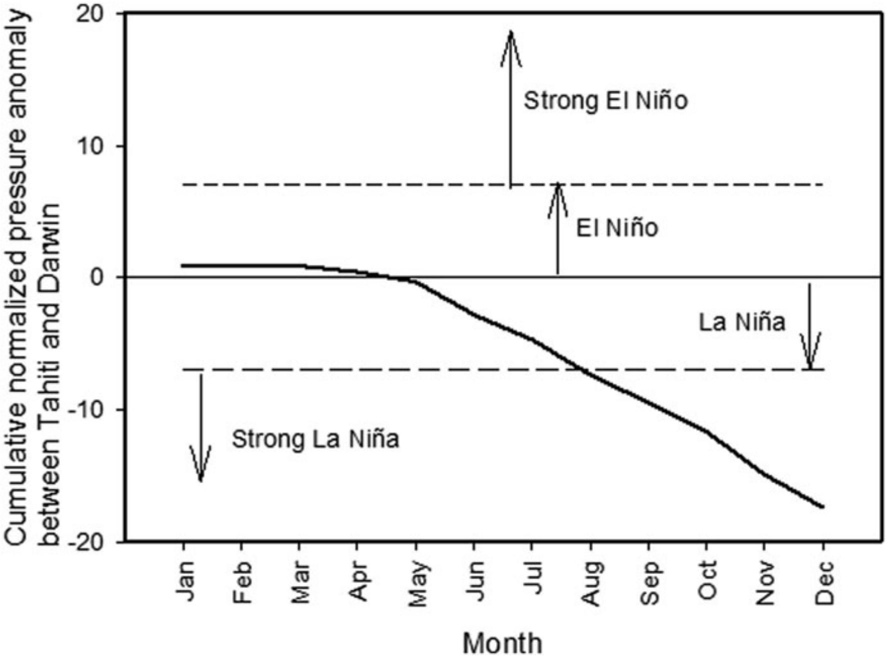


Fig. 33.5 Cumulative SOI index for 1982

years. The relationship is strongest when the ENSO event is strong. The correlation of July, August, September, and October flows of the Blue Nile to Pacific SST and the ability to forecast flow with a lead time are reported (Eldaw et al. 2003). Based on analysis of the relationship of the Nile flow at Aswan (1872–1972) to Pacific SST, it was concluded that 25 % the variability in flow was associated with ENSO (Eltahir 1996). Conway (2000) reported that dry years show a degree of association with low values of SOI (El Niño). Other studies that relate El Nino events to Ethiopian droughts are reviewed in Gissila et al. (2004). Seleshi and Demarée (1995) evaluated monthly rainfall variability in the Ethiopian and Eritrean highlands and its links with the SOI. They used monthly Darwin Sea Level Pressure (DSLP) as a substitute index to SOI. Negative correlation was reported between January DSLP and June rainfall and July DSLP and September rainfall, and positive relations were reported between March DSLP and rainfall. Jury and Enfield (2002) have shown that African rainfall variation is related to ENSO. In a study of decadal periodicities of the Nile River historical discharge (A.D. 622–1470), it was suggested that both ENSO and solar periods were factors related to Nile flows (Putter et al. 1998). A Global Circulation Model (GCM) study of teleconnections between global SST anomalies and rainfall over the Sahel and Southern Africa showed that externally forced SST variability dominates over internal variability in explaining the 1973 drier conditions (Semazzi et al. 1996). Abtew et al. (2009a) showed that the Upper Blue Nile basin rainfall and flows are positively related to La Niña and negatively to El Niño.

33.5.1 Climate Teleconnections and Blue Nile River Basin Hydrology

In the Blue Nile River basin, El Niño years are likely to correspond to dry years and La Niña years to high rainfall and high flow years (Abtew et al. 2009a). The great Ethiopian famine of 1988–1989 corresponds to the 1988 strong El Niño. From 1960 to 2003, seven of the nine highest annual Blue Nile flows correspond to La Niña years (**1964**, **1999**, **1988**, **2000**, 2001, **1975,** and 1962) with strong La Niña years shown in bold. Seven of the driest 9 years occurred during El Niño years (**1994**, 1983, **1972**, **1982**, **1987**, 1990, and 2003) with strong El Niño years shown in bold. There is statistically significant correspondence between cumulative SST and annual Upper Blue Nile basin rainfall anomaly with rainfall deficit occurring during El Niño years and wet years occurring during La Niña years (Fig. 33.6). Similar statistically significant correspondence is shown between the Blue Nile flow at Bahir Dar and cumulative SST (Fig. 33.7). Seleshi and Zanke (2004) reported that June–September rainfall of the Ethiopian highlands is positively correlated to the SOI and negatively correlated to the equatorial eastern pacific SST. Chamberlin (1997), over the concern of past three decades, droughts that created food crisis in Ethiopia and the Sudan, evaluated climate teleconnection to July through September rainfall. It was reported that 79 % of the variance in rainfall was explained by Bombay surface temperature. It was also acknowledged that the Nile basin rainfall is associated with ENSO.

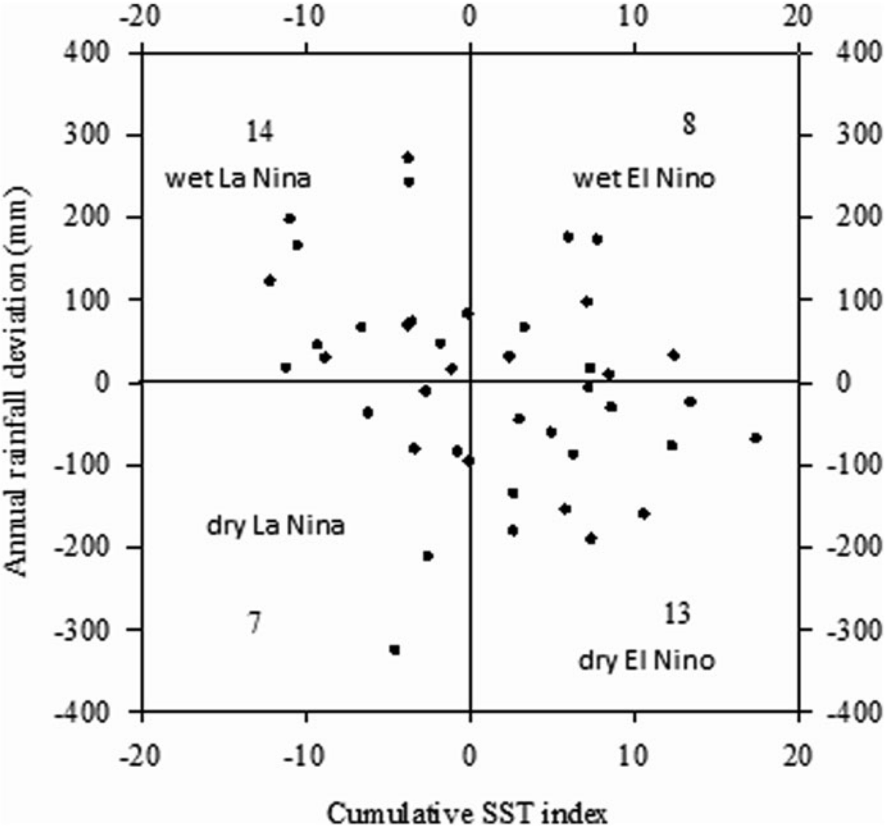


Fig. 33.6 Relation of cumulative SST and Upper Blue Nile basin annual rainfall anomaly. (Modified from Abtew et al. 2009a)

33.6 Applications of Climate Prediction for Resource Management

After many experiences of flooding during strong El Niño and drought, Peru has implemented short-term prediction of ENSO events to adapt agricultural production to changes in rainfall. Based on observation of winds and water temperature in tropical Pacific and output of numerical models, prediction is provided to farmers in November on prospects of the coming rainy season. One of four possible scenarios is predicted: near normal condition, weak El Niño with slightly wetter than normal, strong El Niño with flooding, and La Niña with drought conditions (http://www.atmos.washington.edu/gcg/RTN/rtnt.html, Accessed 04 November 2012). The application of the prediction to crop selection for farming and successful results is cited.

In South Africa, El Niño results in dry and warm weather, while La Niña favors wet and cool conditions. Drought warnings during the major El Niño of 1997/1998

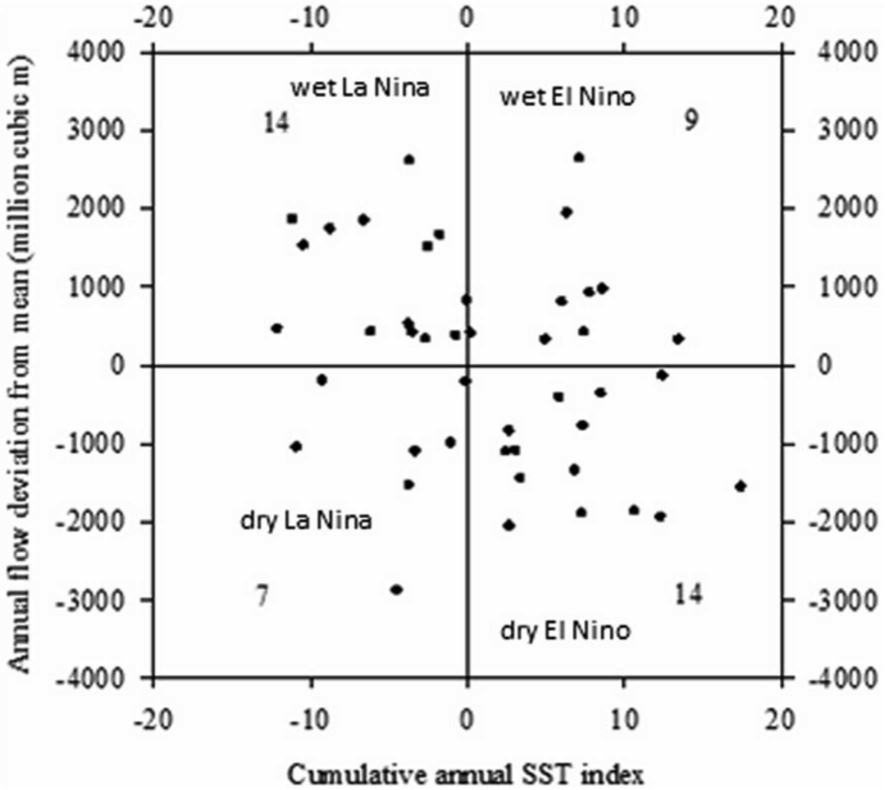


Fig. 33.7 Relation of cumulative SST and annual Upper Blue Nile at Bahir Dar flow anomaly. (Modified from Abtew et al. 2009a)

were shared with farmers, water managers, energy suppliers, construction, education fields, and policy-making sectors by South African climate forecasters (Klopper 1999). Later, surveys showed that forecast users made decisions based on the warning. The use of relationships of simultaneous and lagged SOI with rainfall in Ghana and its potential application to management of rained agriculture are discussed by Adiku and Stone (1995). Knowledge of initial observation of the strength of the 1997/1998 El Niño was used in drawing down dams on the Colorado River to successfully manage the increased runoff (Pulwarty and Melis 2001). Studies have shown that dry conditions during the summer planting season in Zimbabwe correspond to El Niño conditions and greater than 60 % of variance of maize yield is explained by SST anomalies in the equatorial Pacific Ocean (Patt et al. 2005). The study demonstrated the importance of communicating climate forecasts with individual farmers and implications to their livelihood. It also presented a quantitative estimate of subsistence farmers' use of ENSO forecast to adapt their farming practices and to minimize the impact of adverse climatic conditions. In a study of El Niño and La Niña influence on droughts in the Iberian Peninsula, Vincente-Serrano (2005) found a statistically significant relationship between droughts and La Niña events and concluded that such studies can be used for developing drought early warning systems.

Zhang and Trimble (1996) investigated the application of neural networks in climate-based forecasting for water management of Lake Okeechobee in south Florida. The climatic indices used in their work were ENSO events and solar activity. A study of the relationship of solar activity to stream flow of the Parańa River in south eastern South America produced a very high correlation between stream flow and sunspot numbers (Mauas et al. 2008). The study also showed a correlation of stream flow and the Niño1 + 2 index (SST index), and the results could improve flood prediction. A case study in the use of climatic forecast for water management in Arizona is presented for the 1997/1998 El Niño (Pagno et al. 2002). They showed the limited advantage taken by resource managers from the prediction of the 1997/1998 El Niño. Arizona rainfall from June through November is positively correlated with El Niño events, and the study presented ways of improving communication between forecasters and users for better water resources management. Wernstedt and Hersh (2002), in their discussion of climate forecasting challenges for flood planning, pointed out that in the northwest of the USA, ENSO event's correlation to stream flow is affected by the phases of the PDO. Kahya and Dracup (1993) studied US stream flow patterns in relation to ENSO events and concluded that stream flow and ENSO are related in the Gulf of Mexico, northeast, north central, and Pacific Northwest states. El Niño events create wet conditions in the Gulf of Mexico and the north central regions and dry conditions in the northeast and the Pacific Northwest regions. In their study of North American precipitation and temperature patterns associated with ENSO events, Ropelewski and Halpert (1986) reported that the south-eastern US rainfall is associated with ENSO for the period from October of the ENSO year through the following March. Thomas (2007) developed regression equations forecasting Colorado River stream flow using climatic index as variables for application in water resource management.

In addition to the atmospheric, oceanic, and land processes that affect the climate, solar activity also is linked to hydrometeorology variation (Trimble et al. 1997). Solar sunspot activity is measured by the number of sunspots and by the magnitude of geomagnetic activity. Solar sunspot activity has an average cycle of 11 years with a reversal in the sun's magnetic field between cycles. Trimble et al. (1997) have shown that the runoff inflows into Lake Okeechobee of South Florida are associated with solar activity as estimated by the number of sunspots and geomagnetic activity. Other researchers have also shown evidence connecting solar activity and the earth's climate (Friis-Christensen and Lassen 1991). Association in the 11-year sunspot cycle and peak water level in Lake Victoria has been reported and similar patterns also occurred in five other East African lakes (Stager et al. 2007). Increase in rainfall in the basin occurred 1 year before the solar maxima.

Changes in climatic patterns as the ENSO have been correlated to civil conflicts in the tropics. Based on data from 1950 to 2004, it was shown that the probability of civil conflict is double during El Niño years than La El Niña years (Hsiang et al. 2011). Further, the relationship was quantified in a recent study across major regions of the globe that one standard deviation increase in temperature or rainfall on the average increases frequency of interpersonal violence and intergroup conflict increases by 4 % and 14 %, respectively (Hsiang et al. 2013).

33.7 Case Study

The relationship between ENSO and South Florida hydrology has been determined. Dry season (November–May) rainfall and flows are higher than average during El Niño years and lower during La Niña years (Abtew and Trimble 2010). The relationship is strongest when the ENSO event is strong. ENSO prediction has more certainty than hydrologic prediction for a region. Identifying ENSO and hydrologic relationships can aid water management decision making by providing a lead time of months to mitigate drought or flood impacts. The new ENSO tracking index is not affected by short-term fluctuations in SST anomalies. The method is shown to be fully dependable in predicting ENSO events before June when the wet season starts. Since critical water management decisions are related to storage in the wet season (June–October) and water supply in the dry season (November–May of following year), the prediction is useful. Several years of ENSO successful tracking are presented and compared to traditional methods. PDO, NAO, AMO, AO, and ENSO status and developments are tracked on a weekly basis, and water management decisions are supported based on rainfall prediction. Water management decisions are made for flood control, agricultural and urban water supply and estuarine, wetland, and lake ecology management.

33.7.1 South Florida Water Management System

The South Florida Water Management District is a 46,000 km^2 coastal region with elevations ranging from about 25 m to sea level. It is in the subtropical region (24°30′–28°30′N and 80°07′–82°07′W) with rainy season from June through October (64 %) and dry season from November through May of the following year. Naturally, low relief wetlands have been developed for agriculture and settlement. The water management system consists of lakes that also function as reservoirs, impoundments (shallow storage and wetland combination), thousands of km of canals, 1,200 water control structures with 69 pump stations. The system is very sensitive to wet and dry weather. During droughts, if enough water is not stored in the lakes, impoundments, and shallow aquifers, both urban and agricultural water supply shortage is experienced. During wet conditions, if enough storage for runoff is not available in surface and subsurface storage and canal capacity is not maintained by pre-draining, then flooding occurs. Also, due to the location of south Florida, Atlantic, Caribbean, and Gulf of Mexico, tropical systems affect the hydrology. Rainfall from tropical depressions, tropical storms, and hurricanes is of high intensity and large volume. The drainage system is always tested with these events and many times shown that good prediction and preparation with lowering canals and storage facilities are essential for flood control. In El Niño years, strong westerly winds shear Atlantic tropical systems reducing the number and intensity of storms. La Niña years are favorable for tropical storm development and intensity.

33.7.2 Organizational Structure and Decision Making

Climatic and short-term weather prediction is a critical part of the water management system. Where it is essential to have both a climate prediction personnel and a weather-forecasting personnel in the decision making team. The water management decision-making team has representatives of agencies involved in water management decision making, meteorologist, climatologist, biologists, ecologists, water managers, water supply personnel, and representatives of regulatory agencies (Fig. 33.8).

A group of water managers, scientists, and engineers, from all agencies involved in water management, meet weekly in a conference room and some via telephone to discuss the state of the water management system, climate, and weather predictions and possible operational scenarios. The focus is on making recommendations of operational decisions that consider environmental impacts, water shortage, and flooding potentials. Environmental impacts of water management decisions include: (a) too much or too little fresh water releases to estuaries, (b) too high or too low water level in lakes and wetlands, (c) specific needs of endangered species such as the snail kite, (d) wading birds and migratory birds, (e) water management structures, levees and canals safety, and (f) water quality.

The meeting starts with weather reports that include the previous week's rain amounts, seasonal, and year-to-date rainfall spatial distribution, followed by upcoming week's rain forecast. In addition, longer-term climatic outlooks for rainfall produced by National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Center (CPC) are reviewed. This report includes all the relevant climatic indices to the region, such as PDO, AMO and ENSO. Reports on the ecological and hydrological status of different areas of the system, such as the Kissimmee Basin, Lake Okeechobee, stormwater treatment constructed wetlands, the estuaries, and the Everglades, are presented by staff who are knowledgeable of each system. Water management system modeling results projecting reservoir levels with predicted climate inputs are presented to guide decision making on retaining or releasing water from storage. Water managers brief on the weekly operation decisions, such as release from reservoirs, canal stage maintenance, water control structure settings, and operations of the whole system. Considering all the reports and predictions, an operational recommendation for the week is prepared by the team and submitted to managers for their approval. Recommendations for projected extreme events such as droughts will include water use restrictions and conservations measures.

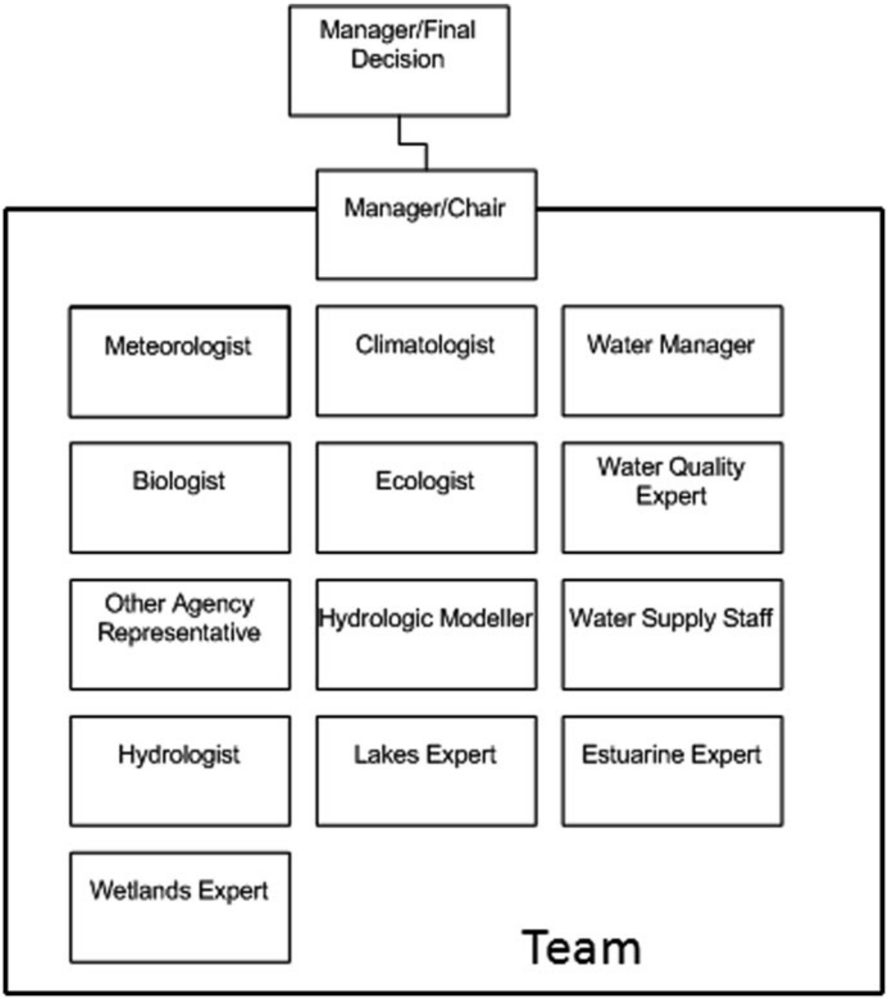
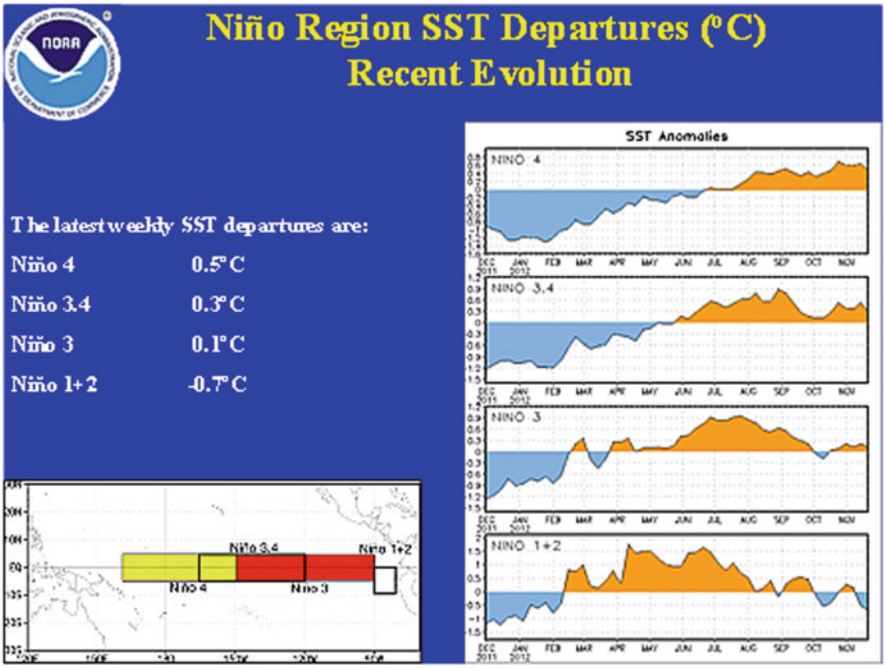


Fig. 33.8 Organizational structure for forecast based water management decision making

33.8 Climate, Weather Prediction, and Resources

A week is a good time interval for regional water management decision making. The report to the team should start with short-term weather prediction, 1–10 days. Resident weatherman is a requirement to provide continuous weather predictions and updates. Monthly and seasonal climate forecasts are critical for water management decision making, such as runoff storage, water conservation, draught mitigation, and flood control. There are enough free resources for major climatic indices such as ENSO. The US National Weather Service, CPC publishes on its website various products that include weekly ENSO assessment, global ocean



Niño Region SST Departures (°C)
Recent Evolution

The latest weekly SST departures are:

Niño 4	0.5°C
Niño 3.4	0.3°C
Niño 3	0.1°C
Niño 1+2	-0.7°C

Fig. 33.9 Weekly SST anomalies in tropical Pacific (CPC 2012b)

assessment, Madden–Julian Oscillation (MJO) assessment, global tropics benefits/hazards assessment, hurricanes, African seasonal rainfall, and climate assessment (http://www.cpc.ncep.noaa.gov/products/expert_assessment/, Accessed 26 November 2012). The climate forecast for Africa is using Canonical Correlation Analysis (CCA), a statistical technique that uses SSTs. Like in the USA regional rainfall forecast, the product is probability estimates for average, below, and above average rainfall. Figure 33.9 depicts weekly SST anomaly in eastern and central tropical Pacific at four regions for tracking ENSO development reported weekly by NOAA. The Niño 3.4 weekly values are averaged and used for generating Figs. 33.4, 33.5, Table 33.3, and Fig. 33.10 to track ENSO development using the cumulative SST ENSO tracking method.

33.9 Application to the Upper Blue Nile Basin

The Blue Nile River drainage basin is approximately 324,530 km^2 (Peggy and Curtis 1994). The Upper Blue Nile River basin is 176,000 km^2 in area (Conway 2000). The major tributaries in Ethiopia are Gilgel Abbay, Megech, Ribb, Gumera, Beshlo, Woleka, Jemma, Muger, Guder, Chemoga, Fincha, Dedessa, Angar, Dura, and Beles. The Upper Blue Nile basin is relatively wet with annual mean rainfall of 1,423 mm and standard deviation of 125 mm (1960–2002). The annual rainfall range

Table 33.3 Upper Blue Nile monthly rainfall, SST, and cumulative SST anomaly for 1971 (wet year) and 1982 (dry year)

	1971 (La Niña)			1982 (El Niño)		
Month	SST anomaly (°C)	Cumulative SST anomaly (°C)	Rainfall (mm)	SST anomaly (°C)	Cumulative SST anomaly (°C)	Rainfall (mm)
Jan	– 1.42	– 1.42	10.99	0.0	0.0	24.35
Feb	– 1.24	– 2.66	0.80	– 0.1	– 0.1	12.93
Mar	– 1.17	– 3.83	36.19	0.1	0.0	60.62
Apr	– 0.84	– 4.67	20.36	0.4	0.4	43.29
May	– 0.65	– 5.32	151.88	0.8	1.2	85.75
Jun	– 0.65	– 5.97	246.02	1.0	2.3	160.54
Jul	– 0.48	– 6.45	388.73	0.8	3.1	258.03
Aug	– 0.54	– 6.99	375.58	1.0	4.1	300.86
Sep	– 0.62	– 7.61	231.63	1.5	5.6	162.83
Oct	– 0.68	– 8.29	104.02	2.1	7.7	124.71
Nov	– 0.73	– 9.02	45.01	2.2	9.9	27.17
Dec	– 0.85	– 9.87	8.65	2.4	12.3	1.42
Annual			1,620			1,263

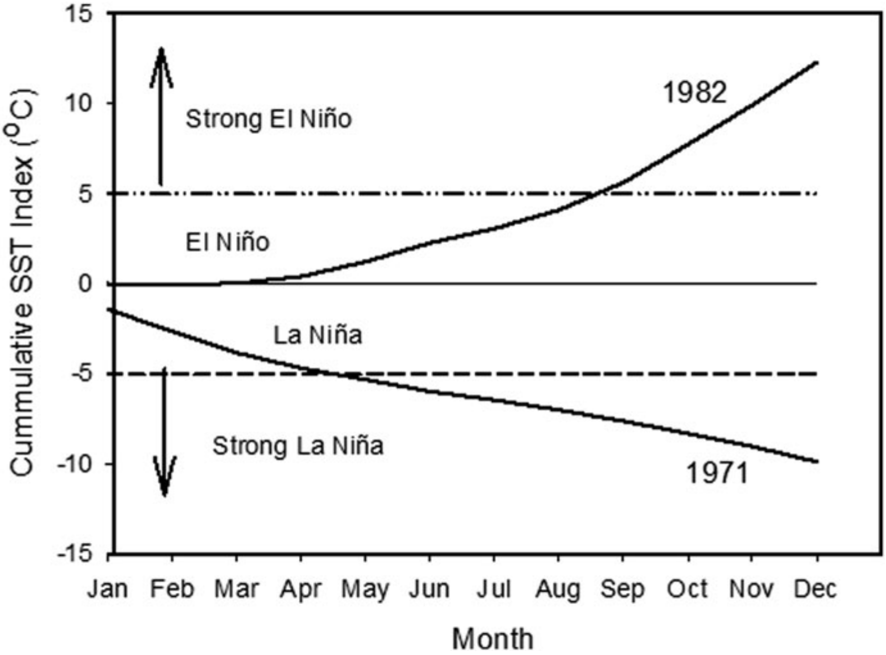


Fig. 33.10 Cumulative SST index for 1971 (La Niña year) and 1982 (El Niño year)

was 1,098–1,694 mm (Abtew et al. 2009b). In 1971, a wet year, the annual rainfall was 1,620 mm during a La Niña event. In 1982, a dry year, the annual rainfall was 1,263 mm, below average, in an El Niño event. Table 33.3 depicts the monthly mean SST, cumulative SST, and monthly rainfall in 1971 and 1982.

Based on the cumulative SST anomaly shown in Table 33.3, the graphic monthly ENSO tracking is shown in Fig. 33.10. Both the slope and direction of the cumulative SST plot indicate whether La Niña, El Nino, or neutral condition is developing before the rainy season starts. From the figure, we can see that 1971 started early on as a La Niña and by March it has become clear that La Niña is developing. Planning and water management related decisions can be made for the expected wetter than average rainfall and flows. 1982 started as neutral but positive anomaly started developing at a fast pace. By May and June, El Niño development has become clear, and this observation can aid water management decision for the potential drought that follows.

33.10 Conclusion

Advancement in the science of weather and climate monitoring is not yet fully exploited into applications in daily lives. Primary reason is the lack of recognition of the potential gain from the application, secondary reason is not having the right organizational structure and needed skills,and the third reason is risk taking with respect to uncertainties in forecast and negative outcomes from decision making. In societies where risk of failure result in increased risk of persecutions, chances of fully incorporating forecasting to resource management will be hampered. Through year-to-year observations of various climatic indices and regional meteorology, increased knowledge and confidence can be gained. With increasing populations and unfavorable climate change, alternatives are limited except for optimal management of water resources.

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