Chapter 11
Upstream–Downstream Linkages of Hydrological Processes in the Nile River Basin

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Abstract The various used of water in large transboundary river basins like the Nile River will require an understanding of the upstream–downstream hydrological linkages and impacts for better planning and management of the shared resources. Related to this understanding, the hydrological processes in the three broadly classified zones (headwaters zone, transitional zone and depositional zone) have paramount importance in the decision-making process of basin-wide water uses. Particularly, changes in the headwater zone at the Ethiopian highlands (the Blue Nile sub-basin) will have the most significant connectivity to the downstream water uses and hydrological regimes. If we compare the combination effects of the rainfall amount received by in three sub-basins (Bahr-EL-Ghazal Blue Nile and Equatorial Lakes Basin), and their larger drainage area, the two sub-basins (Bahr-El-Ghazal and Equatorial Lakes Basin) receive much greater than that of the Blue Nile sub-basin. But the contribution of flow by the western basins is comparatively low. This study uses Geographical Information System (GIS) as the base tool and 30 m SRTM Digital elevation model, high resolution mean monthly rainfall, and multi-stations (226) mean monthly potential evapotranspiration data for analysing the hydrological upstream–downstream connectivity. With these input data, the analysis has confirmed that the upstream and downstream linkages in the Nile River Basin is largely dependent on the extent of the transitional zone, in which the

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releasing function is more characterised by the evaporation process than runoff. Thus, under the current setting, the dependency of the hydrological system for the downstream reach/zone of the Nile River basin on the processes of the Blue Nile sub-basin is more significant due to the short extent of the transitional zone in this sub-basin.

Keywords Hydrological process · Upstream–downstream river linkage · Nile river basin · Headwaters zone · Transitional zone and depositional zone

11.1 Introduction

The water resources use decision-making process is constrained by our abilities to collect the required information about hydrologic systems at various spatiotemporal scales. In a river basin, hydrological events that occur in the upper stream may have a direct influence to the downstream based on the process it goes through (Nepal et al. 2014). An understanding of hydrological processes in its upstream–downstream linkages is the basis for water balance studies in the basin and will serve as an appropriate input for effective and efficient planning and management of the river basin resources. It is particularly critical in river basins of larger in size and transboundary in nature with large altitude differences, climatic features and geological settings where water use planning and management in the upstream reach will have effect on downstream uses (Blaikie and Muldavin 2004; Rasul 2014). On the other hand, studies for hydrologic processes and events occur at a wide range of scales in space and time (Klemeš 1983; Blöschl and Sivapalan 1995), and availability of data about hydrologic processes are scarce within the basin area. Therefore, investigating the upstream–downstream linkages of the hydrological process facilitates hydrologic modelling and information transferring from upstream to downstream or vice versa. This can be used to offset data shortfall problems while practicing water use planning and management activities in the river basin hydrological systems.

Upstream impacts on hydrological processes can be broadly divided into two types: (i) human-influenced activities related to land use and (ii) natural impacts related to climate (Nepal 2014). The change or the impact of these processes is largely expressed with the quantification of the fundamental components of the hydrologic cycle, such as precipitation, evapotranspiration and runoff from which water balance of a river basin is simulated. The water balance also serves as a base for the understanding of the hydrological system of the basin (Sutcliffe and Parks 1999).

Record on the Nile River goes as far back as 3600 BC where the height of the annual flood has been recorded as the most important event of Egyptians (Lyons 1906). Though, a number of efforts had been made by scientists and travellers in the investigation and documentation of the physiographic and the hydrological features of the Nile basin (Lyons 1906), the studies and publications of Sutcliffe and Parks (1999) serve as foundation for understanding of the topographical and hydrological features of the basin. Recent investigations that use different hydrological models and data sources as remote sensing, also contribute a lot to quantify hydrological processes in the basin (Senay et al. 2009; Nile 2014; Kebede and Travi 2006; Taye and Willems 2011).

Hydrology of the Nile River basin has been studied by various researchers, These studies encompass various areas including stream flow modelling, sediment dynamics, teleconnections and river flow, land-use dynamics, climate change impact, groundwater flow modelling, hydrodynamics of Lake Tana, water allocation and demand analysis (Melesse et al. 2009a, b, 2011; Abtew et al. 2009a, b; Yitayew and Melesse 2011; Chebud and Melesse 2009a, b, 2013; Dessu et al. 2012, 2013; Dessu et al. 2014; Setegn et al. 2009a, b, 2010; Melesse 2011; Melesse et al. 2014; Abtew and Melesse 2014a, b, c).

Thus, this review focuses on synthesising the available information to build understanding on the upstream–downstream linkages of hydrological processes in the Nile River basin. Particularly, it quantifies hydrological elements in the basin and sub-basins and identifies their relative impact and contributions to the whole hydrological system.

11.2 Topography and Sub-Basins in the Nile Basin

Without the good knowledge of the complex topography and sub-basin characteristics, one cannot see the hydrological process of the basin (Sutcliffe and Parks 1999). An early detailed physiographic analysis was made by Lyons (1906) that tried to address the topography, the geology and the climate of the Nile as one system. Most of the recent studies use its topographic investigation as the basis for their work. But due to limitation in technical ability to collect good topographic information, they could not address some of the details of topographic variations of the Nile basin. This review work goes into further details using the Shuttle Rader Topography Mission (SRTM) 30 m Digital Elevation Model (DEM) and spatial analysis tools of ArcGIS.

The Nile as a large river basin holds diverse topographic features as mountainous, lakes, depressions, vast wetlands, floodplains and gorges. Most of the basin area lies in the low land ranges, which has an altitude of less than 1500 m above mean sea level (amsl). The highlands in the Nile basin are the main sources of rainwater, the plateau of Ethiopia in the east is the source of the Blue Nile River and the Equatorial plateau in the south is where the White Nile originates (Fig. 11.1).

Delineating the basin boundary and the computation of the area of the basin and sub-basins are also important issues in the Nile basin hydrology. Lyons (1906) computed the basin area as 2,867,600 km^2 using the available map at scale of 1:4,000,000 and 1:2,000,000 employing grid method. Later studies approached these issues differently. Some of the studies directly refer to Lyons (1906) for their

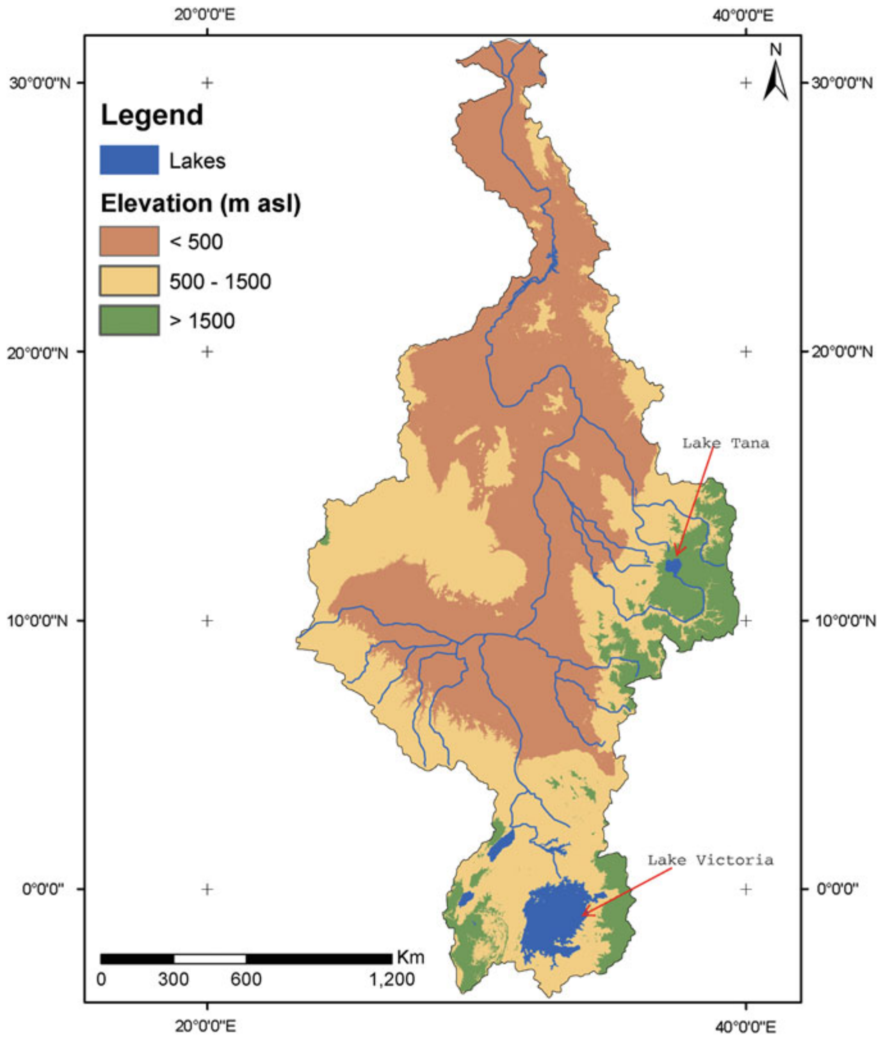

Fig. 11.1 Topographic map of the Nile basin

hydrological study (Sutcliffe and Parks 1999). Others tried to estimate the basin area differently (Zelalem 2009) as 3,112,400 km^2. Some studies only dealt with some section of the basin (Hurst and Phillips 1938; Brown et al. 1979).

Commonly, the Nile River basin is divided into three main sub-basins as White Nile, Blue Nile and Main Nile. Lyons (1906) tried to describe the Nile in six principal drainage basins; the lake plateau, the Bahr-el-Jebel, Bahr-el-Zaraf and the Bahr-el-Ghazal, the Sobat River, the White Nile and the Blue Nile and Atbara.

However, this classification also does not sufficiently describe the different topographic, climatic and other upstream–downstream linkage parameters.

Therefore, in this review work, the Nile basin is classified into nine sub-basins based on the topographic, climatic and hydrological characteristics of the respective sub-basins (Fig. 11.2). In this study, the Nile basin area is computed using GIS environment and Africa Sinusoidal projected coordinate system (Table 11.1). For large river basin like the Nile, selection of the appropriate projection system for the area computations using GIS is also essential to have good area estimation. Africa Sinusoidal projected coordinate was selected since it does not have distortion for area and distance measurement.

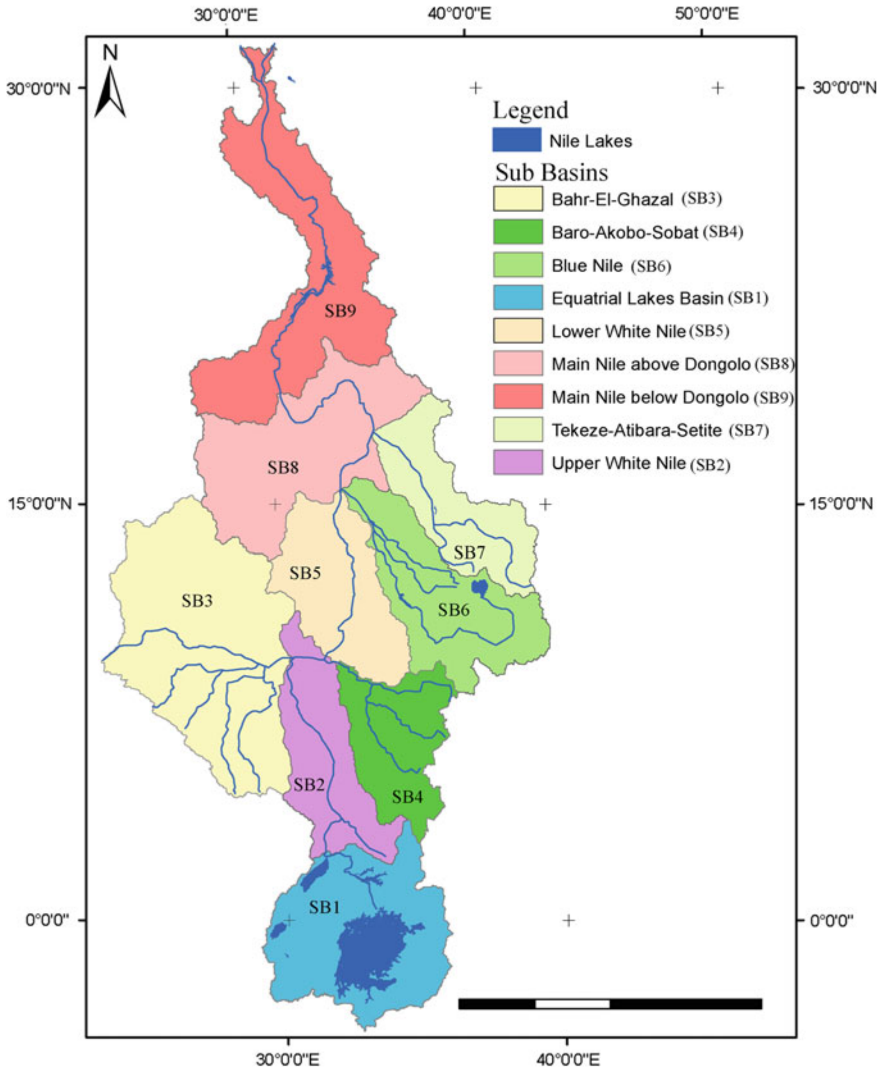

Fig. 11.2 Sub-basin map of the Nile basin

Table 11.1 Sub-basins in the Nile River basin and their drainage area

No	Sub-basin	Area (km^2)
1.	Equatorial Lakes Basin	394,147.06
2.	Upper White Nile	234,680.83
3.	Bahr-el-Ghazal	584,199.81
4.	Baro-Akobo-Pibor-Sobat	206,418.15
5.	Lower White Nile	256,040.61
6.	Blue Nile	298,382.84
7.	Tekeze-Atibara-Setite	221,685.09
8.	Main Nile upstream of Dongola	389,105.60
9.	Main Nile downstream of Dongola	443,570.58
Total basin area		3,028,230.55

11.3 River Zoning in the Nile Basin

Analysis of the longitudinal profile of streams and categorising them into different zones is the basis for upstream–downstream linkage study of a river basin. Most streams can be roughly divided into three zones (Nepal et al. 2014). Zone 1 (sources or headwaters), often has the steepest stream gradient, fast flow of water and initiation of sediment transportation. Zone 2 (transition or transfer zone,) receives some of the eroded material. It is usually characterised by wide floodplains and meandering channel patterns. Zone 3 (floodplain or depositional Zone), is primarily characterised with flatter stream bed gradient and deposition of sediments (Nepal et al. 2014).

Using the longitudinal view concept, the origin of the river channel network and the area-rainfall cumulative effect of the Nile River basin is characterised with three sources. The headwaters sections are the Ethiopian Highlands, Equatorial Lakes Plateau and the head of Bahr-El-Ghazal. These sections are the major water sources of the basin that are characterised by high altitudes and high rainfall. The middle section of the river basin is commonly known as the swamp and the Sudd area which is considered as the transitional zone of the river. Finally, part of the Nile basin around and downstream of Khartoum down to the Mediterranean Sea is grouped to be zone 3. This zone is identified as the dry zone with almost no contribution to the inflow and includes the fertile land of the delta in which maximum water use is recorded so far (Fig. 11.3). This river zoning is implemented based on the weighted overlay of annual rainfall and the gradient (limit of slope) of the land in the basin.

11.4 Rainfall in the Nile Basin

The hydrological process in downstream of a basin is highly dependent on the timing, intensity and the magnitude of rainfall in its upstream. To determine the upstream–downstream linkages of a given basin, accounting the spatial–temporal

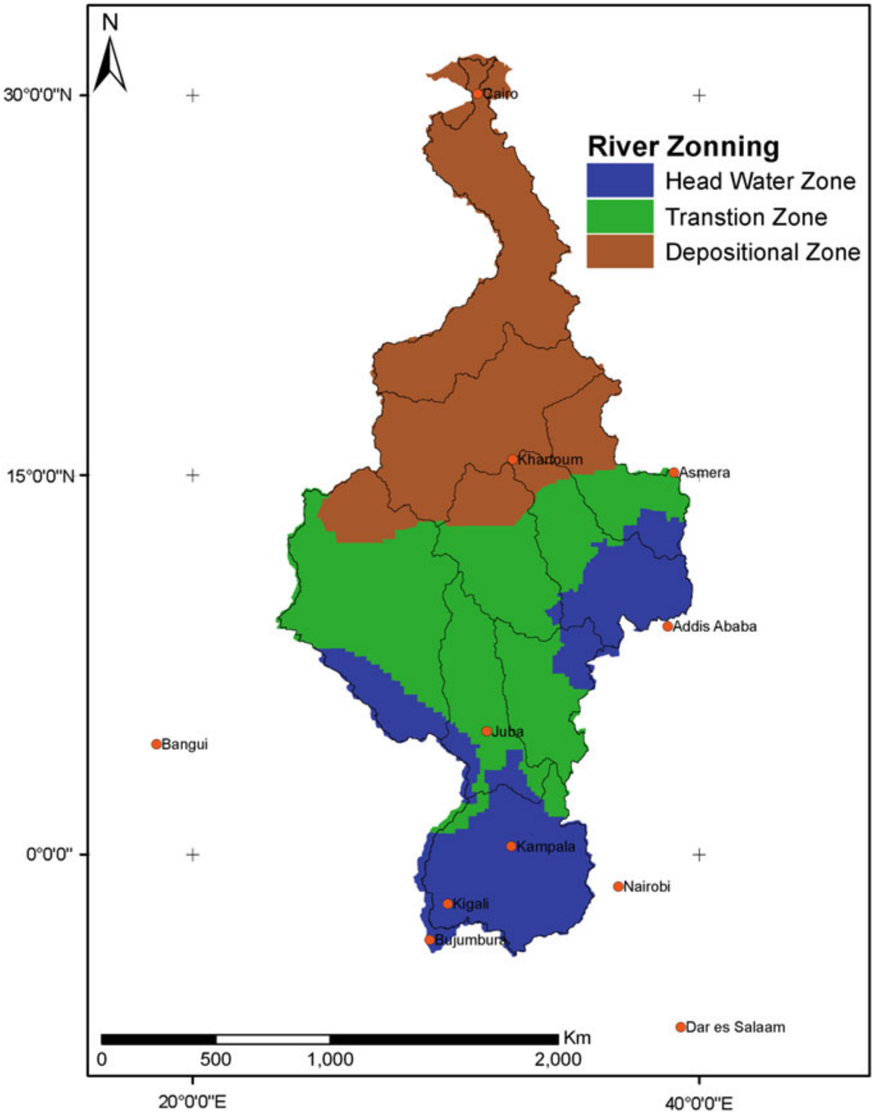

Fig. 11.3 Three broad river zones in the Nile basin based on river zoning

variation of rainfall in the basin would have a significant role. Rainfall is an important parameter for water balance analysis and inflows into the system are dependent on this parameter. The spatial and temporal distribution of rainfall can have different impact on distinct runoff generation processes (Tetzlaff and Uhlenbrook 2005). It also influences the runoff volume, peak flow and timing of hydrological response (Krajewski et al. 1991; Ogden et al. 2000).

The rainfall in the Nile River basin ranges from high rainfall in the most upstream reaches of the equatorial lakes region and the Ethiopian highlands; about 2000 mm mean annual rainfall, to arid desert condition downstream regions that receives no rainfall in a year (Batisha 2012). This climatic variability is possibly observed due to the large extent coverage of latitude (36°) and longitude (18°), large altitudinal variation (8 m below sea level to 4567 m above sea level) and the different monsoons (the longer southeasterly and shorter northeasterly monsoons) over the basin (Sutcliffe and Parks 1999).

The mean monthly and annual rainfall data over the Nile basin were extracted from very high resolution interpolated global dataset (Hijmans et al. 2005). The data set is freely available from WorldClim global climate data site (http://www.worldclim.org/). It is bias corrected and uncertainty tested dataset, which is recommended for the use in climate mapping, modelling, regional studies and understanding of climatic variations. As presented in Fig. 11.4, the spatial and temporal variability of rainfall over the Nile basin is mapped and examined using this high resolution data set.

Annual rainfall over the Nile largely decreases from the south of the basin to the North. The high rainfall area of the basin is confined to the East African lake regions and to the Ethiopian highlands (Sutcliffe and Parks 1999). The East African Lakes region receives rainfall almost throughout the year. But the rainfall in Ethiopian highlands drops out within a single season, in which the length of the wet ranges from 9 months in Baro-Akobo sub-basin in the south to 3 months in the

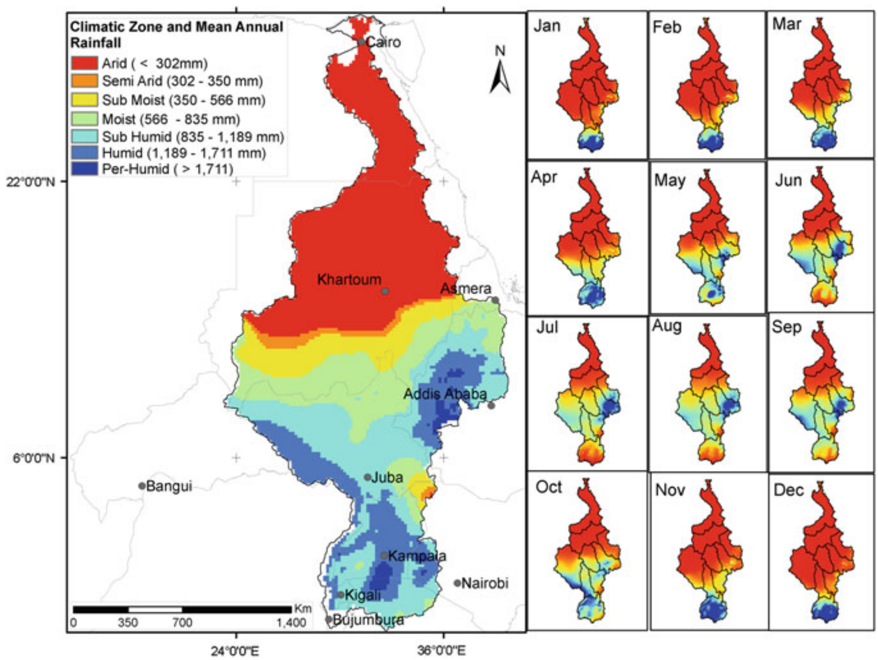

Fig. 11.4 Spatial and temporal variation of rainfall over the Nile River basin

Tekeze-Atibara sub-basin in the north. As a result of steep topography and environmentally degraded watersheds, the sub-basins in the Ethiopian highlands provide relatively quick and highly concentrated runoff to the Nile system. There is not much investigation on hydrological processes in the Bahr-El-Ghazal sub-basin. From the current review, it can be stipulated that it receives relatively considerable average annual rainfall, 835 mm. The amount of rainfall received together with the large area extent of the sub-basin, it can be anticipated that this sub-basin could have significant importance in contributing inflows to the Nile system.

Temporal variability of the wet period in the Nile basin can be categorised in three regions. The Southerly monsoon, largely located in the Equatorial Lakes region extends from October to June. The second category includes the basin area having the wet period extended from April to October. The Southern portion of the Ethiopian highlands, the Bahr-el-Ghazal sub-basin, the White Nile upstream of Malakal and the Sobat-Pibor sub-basins are likely to be included in this category. In this category, especially in the Ethiopian highlands, the wet period is limited to 3 months only towards the north direction. Large portion of the Blue Nile basin falls in this category and the Nile basin gets the largest input in terms of inflow from this sub-basin. The third category, largely located downstream of the Dongola station, is characterised as a dry spell as it receives almost no rainfall. As a result, this category of the Nile basin has no clear wet season period.

The isohyets derived from the mean annual rainfall data was used for the computation of the weighed mean annual areal rainfall of the sub-basins in the Nile system. Accordingly, the Equatorial sub-basin receives the highest mean annual rainfall (1201 mm). It is followed by the Blue Nile sub-basin (1017 mm) and the Upper White Nile sub-basin (1003 mm). These sub-basins are located on the windward side of the Ethiopian highland and East African lakes mountainous regions of the Nile system which receive high rainfall and make significant flow contributions to the Nile system. Similarly, the seasonal areal wetted rainfall for the sub-basins was also computed by the same approach. The seasonal variability of rainfall in the basin helps to compute the potential runoff in each sub-basin (Fig. 11.5).

11.5 Evapotranspiration Over the Nile

Evapotranspiration is an important part of the hydrologic cycle that describes the effect of land cover in the river basin. However, quantifying the actual evapotranspiration with space and time is challenging in water resources system analysis. Alternatively, its amount is computed with potential evapotranspiration (PET), calculated indirectly from climatic parameters and reference land covers with ample water in the area. On a global scale, evapotranspiration accounts for the loss of about 60 % of annual land precipitation and its amount increases to more than 90 % in dry-land ecosystems (Alemu et al. 2014). It is also considered as one of the largest components of the water balance of the Nile basin and accounts about 70 % of the incoming precipitation in the basin (Nile 2014).

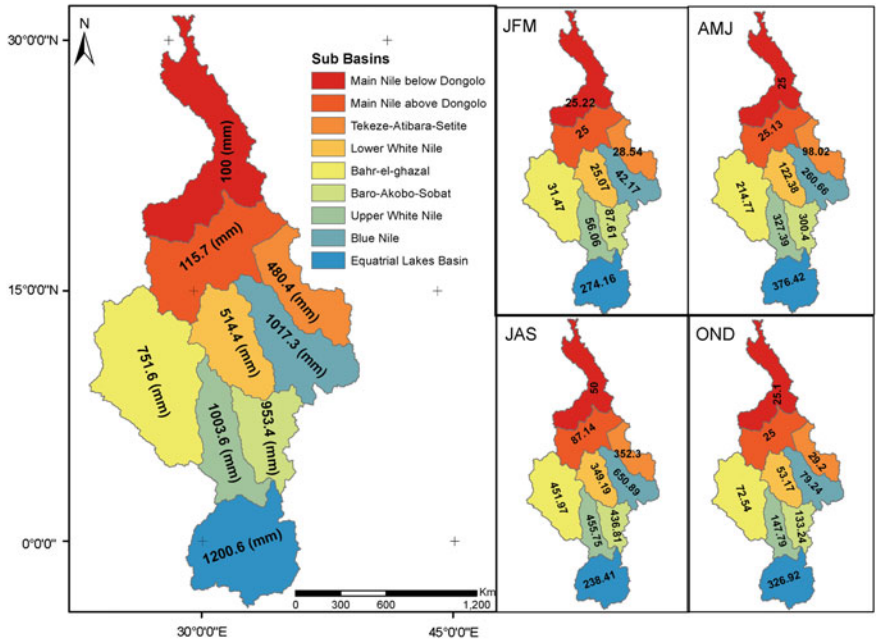

Fig. 11.5 Area weighed annual and seasonal rainfall of sub-basins in Nile River basin

For this review work, the long-term mean monthly potential evapotranspiration for 226 stations in the basin was accessed from FAO ClimWAT climate dataset (Grieser 2006). The spatial distribution of the annual, seasonal and monthly PET was interpolated using inverse distance weighted (IDW) method and shown in Fig. 11.6 to show the spatial and temporal variability of PET over the Nile basin. Accordingly, most of the Nile River basin is covered with the warm and hot thermal zone, which has high mean annual potential evapotranspiration that exceeds 1737 mm. Comparing Figs. 11.5 and 11.6, there are vast areas where PET is greater than rainfall. During period when these areas are not wet, the energy which would have been used for evapotranspiration is used to heat up the land surfaces resulting in dry and hot weather.

To understand the effect of evapotranspiration in the water balance of Nile River basin, the areal weighted annual and the seasonal potential evapotranspiration of each sub-basin was computed using the areal average of the iso-PET lines in each sub-basin. Based on analysis in this work, the downstream sub-basins, Main Nile above Dongola, Main Nile below Dongola, and the Tekezie-Atibara-Setite, show mean annual potential evapotranspiration of 2716, 2486 and 2189 mm, respectively (Fig. 11.7). In the contrary, the upstream sub-basins along the main Nile stem that constitute the main Nile above Dongola station, the mean annual potential evapotranspiration, Equatorial Lakes Basin (1434 mm) Baro-Akobo-Sobat (1603 mm) and Blue Nile (1703 mm). The annual potential evapotranspiration of

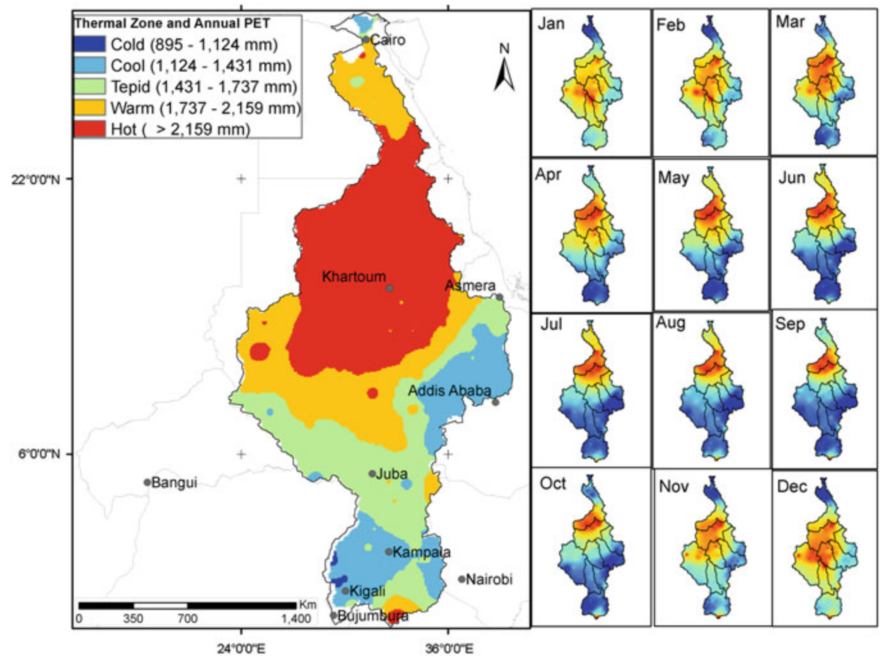

Fig. 11.6 Spatial and temporal variation of potential evapotranspiration over the Nile River basin

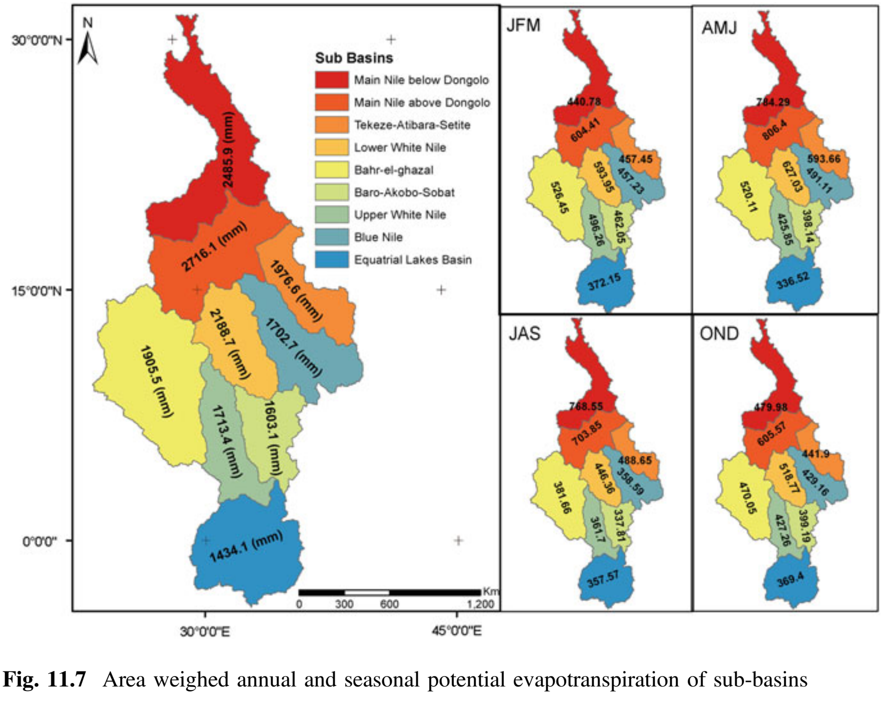

Fig. 11.7 Area weighed annual and seasonal potential evapotranspiration of sub-basins

the sub-basins is much more than the mean annual rainfall of the sub-basins which indicate the evaporation in general is the driving force for the hydrological processes of the Nile hydrosystem. But when moisture is not available for evaporation, the potential evapotranspiration would not be reached.

11.6 Runoff in the Nile River Basin

Runoff and flow characteristics of a river basin is the cumulative effect of the temporal and spatial scale changes of the hydrological process which is important for the understanding of the effect of upstream changes on the downstream system (Conway 2005). Thus, to identify the upstream–downstream linkages of the Nile River basin, basin-wide runoff was computed using the difference of the seasonal weighted areal rainfall and potential evapotranspiration over the basin. Although the water balance of a given watershed includes other variables like groundwater flow, interception, interflows, surface detention and other losses, the runoff is computed by considering the three basic hydrological elements (precipitation, evapotranspiration and runoff) as the major parts of the water balance of basin (Senay et al. 2009). As depicted in Fig. 11.8, runoff in the basin has seasonal and spatial variations. Rainfall in the upstream reach is relatively high with longer wet

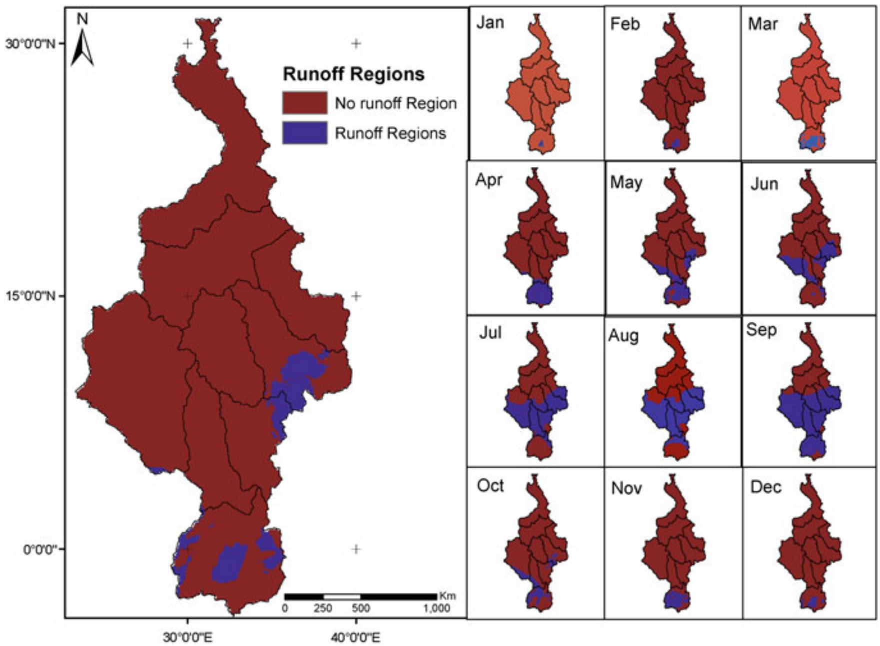

Fig. 11.8 Spatial and temporal variation of runoff over the Nile River basin

period and it is largely believed that this rainfall is the source of runoff for river flows in the basin. This further indicates the significance of the influence of hydrological process changes in the upstream to the downstream reach of the basin.

11.7 Upstream–Downstream Linkages of Processes in the Nile Basin

The different water uses in the transboundary large river basins like Nile River basin is subjected to upstream–downstream hydrological changes that might be associated with the changes in the hydrological process (Beyene et al. 2007). Despite the complex hydrologic processes in transferring flow from upstream to the downstream reach, the primary functions of a river basin can be simply characterised with three main functions: collection, storage and discharge (Black 1997). The three functions of the river basin which are responsible for the upstream–downstream linkages can be characterised by the dynamics of four elements of the hydrological cycle, precipitation, evaporation, storage and runoff (Fernandez and Sayama 2014).

The collection function describes the process of receiving precipitation from the atmosphere and channelizing the runoff supplying the storage zone. The storage zone in the river basin with its different hydrological conditions serves as the linkage between the collection and discharging zones by producing changes in the flow hydrograph base times and amount of releasing. The discharge function addresses the processes of releasing of water from the storage in the form of evaporation or runoff as surface and subsurface components.

The upstream of the basin, particularly the three headwater zones, are the major water sources for the basin river flow. The runoff generated in the headwater zones forms river inflow which leads the water to flow through the transitional zones of the basin. Due to the climatic and topographic nature of the basin, the transitional zones in the Nile River basin are mainly characterised with high rate of evapotranspiration. The high proportion of the water released into this zone is lost by evaporation. Thus the influence of the transitional zones in widening the base hydrograph time of the inflow hydrograph supplied from the headwater zones and loses of water happening in this transitional zone through evaporation describes the existing linkage of the hydrological process between the headwater and deposition zones. This further indicates the impact of changes in the hydrological process at the headwater zones to the successive transitional and deposition zones indicating existence of hydrologic connectivity between the three zones of the basin. This concept can be more illustrated by simulating water balance of the river basin at all important nodes.

The three headwater zones (Equatorial Lake basins, Blue Nile and Bahr-El Ghazal) have different levels of influences on the downstream flow system of the basin. Particularly, the changes in the headwaters zone at the Ethiopian highlands (the Blue Nile sub-basin) are contributing the most significance impacts on the

Table 11.2 Potential rainfall volumes in sub-basins of Nile River basin computed in this review work (order of list of sub-basins is as in Table 11.1)

	Sub-basin name	Sub-basin area	Mean annual rainfall	Rainfall volume in sub-basins
		(km^2)	(mm)	(km^3)
1.	Equatorial Lakes Basin	394,147	1201	473
3.	Bahr-El Ghazal	584,769	752	440
6.	Blue Nile	298,383	1017	304
2.	Upper White Nile	234,181	1004	235
4.	Baro-Akobo-Sobat	206,418	953	197
5.	Lower White Nile	256,041	514	132
7.	Tekeze-Atibara-Setite	221,685	480	107
8.	Main Nile above Dongola	389,106	116	45
9.	Main Nile below Dongola	443,580	100	44

Table 11.3 Historical flows of the Nile and contributing sub-basins (modified from Abtew and Melesse 2014; original data source Sutcliffe and Park 1999)

Reach	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
Sobat at Malakal	9.9

downstream water uses and hydrological system (Zachary et al. 2012). Although, they receive comparable amount of annual rainfall and covering larger area, the influence of the other headwater zones (Equatorial Lakes and Bahr-EL-Ghazal sub-basins) is comparatively low (El Bastawesy et al. 2014). Sub-basin area and mean annual rainfall combination in the Bahr-El-Ghazal and Equatorial Lake Basins is much greater than that of the Blue Nile sub-basin (Table 11.2), but the downstream effect of the changes in the Blue Nile sub-basin is much greater. This is demonstrated by historical flows at different reaches of major rivers of sub-basins and the Nile River (Table 11.3). Over 80 % of the Nile River flows are generated in the Blue Nile and Baro-Akobo-Sobat sub-basins.

11.8 Conclusions

The Nile basin is the longest river in the world that has strong upstream–downstream hydrological linkages. The Nile river flow per unit area of watershed is small (77 m^3 d^{-1} km^{-2}) compared to the Congo River (887 m^3 d^{-1} km^{-2}). Flow is significantly influenced by the process of the upstream of the basin. Particularly, the extent of the transitional zone, which is mainly characterised by evaporation, has governed the water release to the downstream. In this review work, the spatial and temporal variations of the major hydrological processes (precipitation, evapotranspiration and runoff) in the basin are mapped and used to identify the sub-basins which have significant effect on the downstream water use. Although, the three headwater zones (Equatorial Lake Basin, Blue Nile sub-basin and Bahr-El-Ghazal sub-basin) have equivalent annual rainfall volume over the basin, changes of the hydrological processes in the Blue Nile sub-basin has strong impact on the downstream of the basin. The major reason attributed to this influence is because the transitional zone of the Blue Nile sub-basin has limited storage effect; rather it serves as a hydraulic link to the lower section of the basin. Floodplains and wetlands are insignificant in the storage zone of this sub-basin. Further to this, the cause of this significant influence on the downstream reach is also clearly identified as the extent of its transitional zone is much smaller than the others. The release function in the Blue Nile sub-basin is more dependent on the runoff process than the evaporation process. Thus, upstream–downstream linkages of hydrological processes are stronger in the Blue Nile sub-basin.

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