Chapter 4
Climate Change and Freshwater Resources: Current Observations, Impacts, Vulnerabilities and Future Risks

Anthropogenic influences have affected the global water cycle since 1960 which has led to various climatic changes over land regions however changes in the hydrological system is not always attributed to anthropogenic climate change. Parts of documented changes are however not solely due to natural variability. Anthropogenic climate change is also one of many stressors of water resources. Observed changes in terms of hydrological changes are mainly attributed to climatic drivers, not all which are necessarily anthropogenic, due to the difficulty and uncertainty regarding attribution.

Numerous observations of varying intensities or significance have been made during the past century and climatic drivers in combination with non-climatic drivers of climate change will continue to have an impact upon the world's hydrological system in varying ways and degrees. Projections show that climate change will decrease renewable water resources in some regions and increase in others with large uncertainties in many of these areas. The implementation of adaptive approaches into water management is encouraged as it can be used to address uncertainties caused by climate change.

4.1 Brief Background

The IPCC (2014) states that it is likely that anthropogenic influences have affected the global water cycle since 1960 which has led to increased atmospheric moisture content, global changes in precipitation patterns over land as well as the intensification of heavy precipitation over land regions. These observed changes in the world's water cycle can lead to diverse impacts as well as risks as they are conditioned by and interact with non-climatic drivers as well as water management responses.

Water acts as an agent who delivers climate change related impacts to the world's human population as well as natural systems and multiple economic sectors. The current and future influence of climate change on the world's freshwater resources is of prime importance as it will have severe consequences on the world's human

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population, natural systems and economic sectors through making them more vulnerable to water-related hazards and risks and will differ across regions as water is a locally variable resource.

This chapter consequently focuses on the evaluation of current observed changes of the water system, possible drivers or stressors, current and future impacts, vulnerabilities and risks as well as include case studies illustrating the influence of climate change on freshwater resources within different regions or contexts around the world.

4.2 Main Drivers

Observed changes in the hydrological system are not always necessarily due to anthropogenic climate change however parts of the documented changes are not due to natural variability. To determine the attribution to changes in the hydrological cycle, one needs to identify all drivers with confidence levels assigned to each. It is therefore difficult to attribute extreme hydrological events such as floods and droughts solely to climate change however climate change can alter the probability thereof.

Climatic drivers which include precipitation, temperature, sea level, carbon dioxide concentration as well as others which were described in the previous chapter, are all drivers which have an influence on the hydrological cycle. The primary climatic drivers which influence freshwater resources are potential evaporation as well as precipitation (strongly related to atmospheric water vapour content). Temperature has increased with minor changes in surface and tropospheric relative humidity being recorded. There is once again uncertainty regarding climatic drivers due to internal variability of the atmospheric system, inaccurate modelling of atmospheric response to external forcing as well as external forcing itself. It has been estimated that more intense extreme precipitation events are expected mainly due to the projected increase in humidity. Some regions especially the Mediterranean, central Europe, central North America as well as Southern Africa are predicted to have longer and more frequent droughts according to precipitation projections (IPCC 2014).

Anthropogenic climate change is therefore only one of many stressors of water resources. Non-climatic drivers include socio-economic development (population increase, economic growth and development as well as GDP), land use and cover changes (urbanisation, forests, etc.) as well as water demand changes (agricultural, industrial, energy as well as municipal and domestic water use sectors) (IPCC 2014).

Freshwater systems will be strongly impacted upon by demographic, socio-economic as well as technological and lifestyle changes which will change both exposure to hazards and water requirements. Changes in land use are predicted to be the dominant factor to affect freshwater systems in the future. An example of this may be the increase in urbanisation which will cause an increase in flood hazards and a decrease of groundwater recharge. Agricultural land use change is of particular importance especially in terms of irrigation as it accounts for most of the world's water consumption and may severely impact upon freshwater availability for humans as well as ecosystems. Population and economic growth may consequently cause irrigation to significantly increase in future and may lead to an increase in the variability of surface water supply in combination with climate change (IPCC 2014).

These non-climatic drivers will consequently affect the sustainability of resources through the reduction of water supply or increasing overall water demand. Consequent adaptations to climate change in this sector therefore needs to focus on contributing to improving water availability.

4.3 Observed Changes and Attributions

Observed changes in terms of hydrological changes are mainly attributed to climatic drivers, not all which are necessarily anthropogenic, due to the difficulty and uncertainty regarding attribution. Numerous changes have been observed in the twentieth century which has been attributed to various climatic and non-climatic drivers. Observed hydrological changes due to climate change can be grouped into six main categories namely:

- Precipitation, evapotranspiration, soil moisture, permafrost and glaciers;
- Streamflow;
- Groundwater;
- Water quality;
- Soil erosion and sediment load; and
- Extreme hydrological events such as floods and droughts (IPCC 2014).

It has been recorded globally that runoff has changed in the last four decades and have been attributed to climate change and to a lesser extent the increase of CO_2 and land use changes. Reduced runoff has been observed in the Yellow River of China mainly due to increased temperature and where only 35% of the runoff reduction can be attributed to human withdrawals. A decrease in glacier meltwater yield has also been observed and been attributed to glacier shrinkage forced by warming. The decreased dry-season discharge recorded in Peru and as well as the disappearance of the Chacaltaya Glacier in Bolivia have been attributed to decreased glacier extent and ascent of freezing isotherm at 50 m per decade over the last two decades (IPCC 2014).

Anthropogenic greenhouse gas emissions have been attributed to the more intense extremes in rainfall especially over the northern tropic and mid-latitudes. The risk of flooding in England and Wales in 2000 has been attributed to anthropogenic greenhouse radiation and the decrease in the recharge of karst aquifers in Spain during the twentieth century to decreased rainfall and possibly an increase in temperature as well as other confounding factors (IPCC 2014).

Decreased groundwater recharge within Kashmir for the period of 1985–2005 was attributed to a decrease in winter rainfall. Increased temperature as well as rainfall with other confounding factors has been attributed to the increased dissolved organic carbon in the upland lakes of the United Kingdom. An increase of anoxia in reservoirs of Spain especially during El Nino episodes has been ascribed to the decrease in runoff mainly due to a decrease of rainfall and increased evaporative demand. Water quality has also been affected by climate change over the past century. Some of the observations have included the variable faecal pollution in a saltwater wetland in California, USA mainly due to variable storm runoff and precipitation. Nutrient flushing from swamps and reservoirs within North Carolina, USA were attributed to tropical cyclones and lastly increased nutrient content of lakes in Victoria, Australia to increased air and water temperatures (IPCC 2014).

4.4 Impacts and Projected Hydrological Changes

Numerous observations of varying intensities or significance have been made during the past century and climatic drivers in combination with non-climatic drivers of climate change will continue to have an impact upon the world's hydrological system in varying ways and degrees.

The primary trend which has been established regarding freshwater-related risks and climate change is that these will become increasingly significant with the increase in GHG concentrations. Higher emissions of GHGs over the globe will have larger and stronger adverse impacts compared to lower emissions which will be accompanied with less damage and consequently cost less to adapt. For every degree increase of global warming, an estimated 7% of the world's population is projected to be exposed to a decrease of renewable water resources of at least 20% and by end of the twentieth century, 100 years' floods are projected to be three times higher due to very high emissions (IPCC 2014).

Climate change will therefore reduce renewable surface water resources but also groundwater resources in the most dry subtropical region which will consequently increase the competition between water sectors such as agriculture, industry, energy production, settlements and ecosystems. The decrease of renewable water resources as well as the intensification of competition for water resources will affect regional energy, food as well as water security and increase water-related risks for various sectors around the globe. In some cases, water resources are projected to increase especially at high latitudes.

No widespread observations have been made regarding the changes in flood magnitude and frequency due to anthropogenic climate change but projections do show variations in flood frequency. Flood hazards are therefore projected to increase especially in parts of South, Southeast and Northeast Asia, tropical regions of Africa as well as South America. The socio-economic losses from flooding have increased since the mid-twentieth century and this increase is mainly attributed to greater exposure as well as vulnerability across the globe. The risks of floods will consequently increase across the globe partly due to climate change.

Meteorological (less rainfall) and agricultural (less soil moisture) droughts are also estimated to increase in terms of frequency across the globe, more specifically in the dry regions by the end of the twenty-first century. These regions will also experience an increase in the frequency of short hydrological droughts (less surface water and groundwater). Uncertainties do however exist in terms of the frequency of droughts which last longer than 12 months as these depend on accumulated rainfall over long periods. There is also no conclusive evidence present which indicates that the frequency of surface water and groundwater droughts has changed over the past few decades. The impacts of drought have however increased which has been attributed to the increase of water demand by various water use sectors (IPCC 2014).

Streamflow and water quality will also be negatively affected by climate change and cause the degradation of freshwater ecosystems. Ecological impacts of climate change have been expected to be higher than historical impacts mainly due to anthropogenic alterations of flow regimes through water withdrawals as well as the construction of reservoirs. Raw water quality is also estimated to be reduced due to climate change which will pose risks to drinking water quality even with conventional treatment. This will be mainly caused by increased temperature, increased sediment, nutrient and pollutant loadings from heavy rainfall, reduced dilution of pollutants during periods of droughts as well as the disruption of treatment facilities during floods (IPCC 2014).

Snowfall regions have observed alterations in streamflow seasonality due to climate change. These alterations as well as others will increasingly be observed in future due to climate change. Increasing temperatures have reduced the spring maximum snow depth in recent decades in all snow regions except in very cold regions. The reduction in spring maximum snow depth has caused maximum snowmelt discharge, smaller snowmelt floods, increased winter flows as well as reduced summer low flows. The increase in temperature has also caused river ice in the Arctic to break up sooner than in the past (IPCC 2014).

Glacial regions have also been affected by the increase of temperature. Due to nearly all glaciers being too large for equilibrium in terms of the current climate, a water resource change has occurred during most of the twenty-first century. Changes beyond the committed change are expected with continued warming. Glacial-fed rivers and total meltwater yields from stored glacier ice will also increase in numerous regions in the next decades but decrease thereafter. The continued loss of glacial ice entails a change of peak discharge from summer to spring (excludes monsoonal catchments), and may possibly also reduce summer flows in downstream parts of glacial catchments (IPCC 2014).

In terms of soil erosion and sediment loads, little to no observational evidence is present to indicate that these factors have been altered by climate change. The increase in heavy rainfall as well as temperature has however been projected to change soil erosion and sediment yield in future but the extent of these changes is highly uncertain and will largely depend on rainfall seasonality, land cover as well as soil management practices.

Further projected impacts, vulnerabilities as well as risks in terms of the world's freshwater resources now follow to enable the identification of relevant adaptation or mitigation strategies which can be implemented to minimise further impacts accompanied with climate change.

4.5 Projected Impacts, Vulnerabilities and Risks

Projections of freshwater-related impacts vulnerabilities and risks are largely based on the comparison of historical conditions and are mostly helpful in trying to estimate the human impact on the environment and support adaptation to climate change. Existing climate models show that approximately half of the world's population will be living in high water stress areas by 2030, which includes between 75 and 250 million people in Africa. Additionally, water scarcity will also be exacerbated in some arid and semi-arid regions which will displace between 24 and 700 million people around the world (IPCC 2014).

Current projections estimate that for each degree of global warming, up to 2.7 °C above preindustrial levels, renewable freshwater resources will decrease by at least 20% for an additional 7% of the world's human population. The total number of people who have access to renewable groundwater resources is also projected to decrease quite significantly. The portion of the world's human population which live in river basins will experience an increase of new or aggravated water scarcity which will increase with water scarcity. Projections indicate an increase of 8% at an increase of 2 °C to 13% at 5 °C (Gerten et al. 2013). It is therefore of prime importance that future impacts, vulnerabilities and risks be identified to minimise the effects on the already stressed freshwater resources of the world. The following sections will focus on projected impacts, vulnerabilities as well as risks in terms of water availability as well as water uses which include agriculture, industries or energy production, municipal services or domestic use, freshwater ecosystems and other uses.

4.5.1 Water Availability

Current estimates show that approximately 80% of the world's population is already facing serious threats to its water security according to water availability, water demand and water quality indicators (Vörösmarty et al. 2010). Climate change will exacerbate these threats due to causing the alteration of water availability around the world.

The effects of climate change on future water demand vary and are spread wide across climate and hydrological models. This is mainly due to varied climate models and patterns of projected rainfall changes. Strong consistencies do however exist and these include the following:

- There will be a reduced availability of water resources in the Mediterranean as well as parts of Southern Africa. Much greater variations in terms of projections exist for South and East Asia.
- Runoff may increase in some water-stressed areas and may experience a reduction in the exposure to water resources stress.
- Increase in global mean temperature around 2 °C, above preindustrial and changes in population, will have a greater effect on changes in resource availability than

climate change. Humans will therefore have a greater effect on water availability than climate change over the next few decades however climate change will regionally exacerbate the effects of population pressures.

- Projections of future water availability are sensitive to climate, population projections, population assumptions as well as the choice of the hydrological impact model which is used to measure stress or scarcity (Schewe et al. 2013).

Projections show that climate change will decrease renewable water resources in some regions and increase in others with large uncertainties in many of these areas. Majority of projections do however show a decrease in many mid-latitude and dry subtropical regions and an increase in high latitude and many humid mid-latitude regions. Even though some projections show an increase in some regions, it should be noted that short-term shortages may occur due to reduced snow and ice storage especially in high latitude areas.

The availability of "clean" water can also be reduced due to the negative impacts of climate change on water quality. The use of groundwater to try and lessen the impacts of water stress should not be considered to be a viable option especially in regions which are projected to experience a decrease in groundwater recharge or renewable groundwater resources. It is projected that more than 10% of the world's population will suffer from a decrease of renewable groundwater resources and it is estimated to rise with an increase in temperature.

4.5.2 Impacts on Water Use Sectors

Agriculture

The agricultural sector is the primary user of water across the world. The water demand and use in terms of food and livestock feed production are governed by crop management and its efficiencies as well as the balance between soil water supply and atmospheric moisture deficit. As a result of these dependencies, changes in climate in terms of precipitation, temperature and radiation will affect the water demand of crops grown through irrigated and rainfed systems.

According to a global vegetation and hydrology model, climate change will barely affect global irrigation demand by 2080 of major crops in regions currently equipped by irrigation systems (Konzmann et al. 2013). There is however a high certainty that irrigation demand will significantly increase in areas which include more than 40% across Europe, USA and some parts of Asia. Other regions which include major irrigated areas such as India, Pakistan and South East China, may experience a slight decrease in irrigation demand mainly due to higher rainfall but only according to some climate change scenarios. Once again it needs to be highlighted that effects on the agricultural water sector will vary largely across regions and will be very heterogeneous.

In terms of soil, it has been estimated that poor soil may not be a limiting factor. The physiological and structural crop responses to CO_2 fertilisation may partly cancel out the adverse effects of climate change through potentially reducing global irrigation water demand (Konzmann et al. 2013). However even though this optimistic trend has been projected, increases in irrigation water demand by more than 20% are still projected in some regions such as Southern Europe. The general trend for future irrigation demand is projected to exceed water availability in numerous areas and should therefore receive attention (Wada et al. 2013).

The increasing variability of rainfall across the globe will especially affect rainfed agriculture and will consequently increase yield variability and differences between rainfed and irrigated land. Water demand of these agricultural water uses should therefore be managed more effectively and inefficiencies should be addressed to limit further water losses especially in terms of irrigated crops. The water demand for rainfed crops should also be reduced through improved management practices. It should be highlighted that unmitigated climate change may however counteract these efforts and places emphasis on addressing future climate change as the continuation thereof at current trends will counteract efforts.

Industries and Energy Production

As indicated in the previous chapter, energy production, especially hydroelectric and thermal power plants as well as the irrigation of bioenergy crops will require large amounts of water. Hydroelectric power generation will be affected by climate change through changing mean annual streamflow, seasonal flows, increase of streamflow variability as well as increased evaporation from reservoirs and changes in sediment fluxes. Impacts of climate change on hydropower plants will largely depend on local changes in these mentioned hydrological characteristics as well as on the type thereof and seasonal energy demand. Regions which are characterised by high electricity demands for heating or for summertime cooling may face challenges due to seasonal streamflow shifts and may require the development and implementation of adaptation of operating rules due to climate change.

In terms of water availability for cooling of thermal power plants, the number of days with a reduced useable capacity is projected to increase in Europe and the USA, owing to increases in stream temperatures and the incidence of low flows.

Municipal Services

Climate change will also cause many challenges for water utilities. The problems with which water utilities may be confronted with include the following:

- The increase in ambient temperatures will reduce snow and ice volumes, increase evaporation rate from water bodies and consequently decrease natural storage of water unless precipitation increases its availability. Water demand will also increase with higher ambient temperatures in conjunction with the competition for this resource.
- Changes in timing of river flows as well as possible more frequent or intense droughts will increase the need for artificial water storage.
- The increase in water temperatures, which encourages algal blooms and increases risks from cyanotoxins and natural organic matter in water resources, will force water treatment facilities to implement additional or new treatment of drinking water.

- Possible drier conditions will increase pollutant concentrations. This is a major concern as some groundwater sources are already at low quality even when pollution may be natural.
- The increase in storm runoff will increase the loads of pathogens, nutrients as well as suspended sediment.
- The rise in sea level which consequently increases the salinity of coastal aquifers will cause a decrease in groundwater recharge (Bates et al. 2008; Jiménez 2008; van Vliet and Zwolsman 2008; Black and King 2009; Brooks et al. 2009; Whitehead et al. 2009; Bonte and Zwolsman 2010; Hall and Murphy 2010; Mukhopadhyay and Dutta 2010; Qin et al. 2010; Chakraborti et al. 2011; Major et al. 2011; Thorne and Fenner 2011; Christierson et al. 2012).

As indicated previously, climate change will also affect water quality indirectly. Numerous cities rely on water from different forested catchments which do not require a lot of treatment. However, an increase in the frequency and severity of forest wildfires may degrade water quality quite significantly. Numerous drinking water treatment facilities are not designed to handle more extreme effluent variations which are expected to increase under climate change. This will consequently place additional demands on these facilities or even require the development of different infrastructure which is capable of operating for longer which will render the treatment of wastewater to be very costly especially in rural areas. Sanitation technologies vary in terms of their resilience towards climate impacts and the following climatic conditions are of interest. First, wet weather especially heavier rainstorms which cause an increase in amounts of water and wastewater combined in systems for short periods. This is of concern as current designs are based on critical "design storms" of historical rainfall data and will have to be modified. New strategies will also have to be developed in terms of adaptation and the mitigation of urban floods which consider climate change as well as urban design, land use, the heat island effect and topography.

Second, drier weather is also a concern especially in terms of the shrinking of soil which causes water mains and sewers to crack or break, making them very vulnerable to infiltration and exfiltration of water and wastewater. The combination of increased temperatures as well as pollutant concentrations, longer retention times and sedimentation of solids will possibly increase corrosion of sewers, decrease asset lifetimes, increased drinking water pollution and higher maintenance costs.

Lastly, sewer systems are also concerned with a rise in sea levels mainly in terms of the intrusion of brackish or salty water into sewers which necessitates processes that can handle saltier wastewater. The increase in storm runoff also implies that there will be a need to treat additional wastewater when combined sewers are used. Increased storm runoff will therefore add to sewage and the resulting mixture will have a higher pathogen and pollutant content.

Drier conditions will have higher concentrations of pollutants in wastewater and any other type will have to be dealt with. The cost thereof may cause low-income countries to not address this in future. The disposal of wastewater or faecal sludge is a concern that is just beginning to be addressed in the literature and further research is needed for treatment facilities and regions as a whole to be able to adapt accordingly (Seidu et al. 2013).

Freshwater Ecosystems

Freshwater ecosystems include biota (animals, plants, and other organisms) and their abiotic environment in slow-flowing surface waters such as lakes, man-made reservoirs, or wetlands; in fast-flowing surface waters such as rivers and creeks; and in the groundwater. These systems have been heavily affected by human activities than have marine and terrestrial ecosystems.

Climate change will therefore be an additional stressor which will affect these systems not only through increased water temperatures but also through altering stream flow regimes, river water levels as well as the extent and timing of inundation. Wetlands which are located in dry environments are hotspots of biological diversity and productivity, and their biotas will be at great risk of extinction if runoff decreases and the wetland dries up.

These freshwater systems are also affected by water quality changes which may be induced by climate change. Human adaptations to climate change-induced increases of streamflow variability and flood risk, such as the construction of dykes and dams. The effects of climate change on freshwater systems need to receive attention as it supports a wide variety of biota upon which some human livelihoods depend. The degradation of these systems by climate change as well as human activities may have wide-ranging effects on the environment itself as well as the world's human population.

Other Uses

Hydrological changes will also have indirect impacts on navigation, transportation, tourism and urban planning (Pinter et al. 2006; Koetse and Rietveld 2009; Rabassa 2009; Badjeck et al. 2010; Beniston 2012) and may cause social and political problems. An example of this may be where water scarcity and water overexploitation may lead to an increase of risks of violent conflicts and nation-state instability (Barnett and Adger 2007; Burke et al. 2009; Buhaug et al. 2010; Hsiang et al. 2011).

The rise in snowline as well as the shrinkage of glaciers has been estimated to have a very likely environmental, hydrological, geomorphological, heritage and tourism resources impacts in cold regions (Rabassa 2009), as already observed for tourism in the European Alps (Beniston 2012). It should be noted that even though most impacts will have adverse effects, some might be beneficial if managed correctly.

Climate change will therefore be an important influence and constraint of water availability across the globe in the future. We can conclude out of this section that climate change has and will have further negative effects on the hydrological cycle due to continued warming over the recent decades. Changes have included increased atmospheric water vapour content, changes in rainfall patterns including extremes, reduction in snow and ice cover especially in high latitudes and lastly changes in runoff and soil moisture. Substantial changes will therefore be accompanied with future climate change especially under future scenarios of GHG emissions although there are some uncertainties in projected patterns of precipitation on a regional scale.

The relationship between climate and water resources does not exist in isolation and is further influenced by socio-economic and environmental conditions which vary over regions. Multiple human activities especially agriculture, changes in land use, construction as well as water pollution negatively influence water availability. Water demand is also highly variable and is determined by population as well as levels of development. We therefore have to take a closer look on a regional scale in order to determine more specific influences of climate change in certain regions for these regions to be able to develop relevant cost-effective adaptation or mitigation strategies. A brief description regarding the main influences of climate change on freshwater resources in different regions around the world as well as discussion of three case studies to illustrate the wider influence of hydrological changes due to climate change now follows.

4.6 Regional Outlooks and Case Studies

The influence of climate change on the world's freshwater resources will pose significant challenges in terms of adequate future water availability and may pose different risks for socio-economic development as well as environmental sustainability. The impacts of climate change are heterogeneous in nature and will vary according to a region or area's environmental and socio-economic characteristics which in turn determines the degree of vulnerabilities and risks as highlighted throughout. Anthropogenic climate change will pose the biggest challenges to the globe's society and will force decision-making bodies such as governments, to incorporate climate-related risks into their decision-making processes.

This section will focus on providing brief descriptions of the impacts of climate change in terms of regions across the globe and provide detailed case studies for Africa, Pacific Islands as well as Portugal to illustrate various vulnerabilities and risks which may be accompanied with climate change in terms of freshwater resources as well as the different implications thereof on socio-economic as well as environmental systems.

Europe: The European region will experience an increase in the demand for irrigation purposes but also an increase in the frequency of droughts as well as warmer day temperatures. Water made available from runoff will decrease. Some regions are projected to experience a decrease in river flooding however it is projected that the United Kingdom might experience increases. The region is expected to experience an increase in its average crop yields however it should be noted that these projections have a high degree of uncertainty and also assumes that there will be an adequate supply of water for irrigation in the region. Importantly, Europe is an exporter of wheat and maize as well as an importer of all four major crops which will interlink it with climate-related impacts in the Americas as well as Asia in particular which should consequently also be taken into account when looking at future food security within the region.

Middle East and Africa: As indicated previously, the northern regions of Africa as well as the Middle East are already experiencing water stress. The region around the Mediterranean is estimated to experience some of the largest increases in the number of drought days of all regions across the globe. It will experience a decrease in annual water runoff and the warmest days are projected to become even warmer in the already hot climate. The Middle East and Northern regions of Africa are major importers of wheat, maize and rice which will link them to climate-related impacts in major production regions of these crops, namely North America, South America, Russia, Australia as well as Northern Europe.

In terms of the *sub-Saharan region of Africa*, extremely large relative population increases are projected along with decreases in average annual water runoff. This will consequently increase pressure on food and water demand in a region which already suffers from high levels of food insecurity and water stress. The region is also characterised by governance issues where a number of countries have scored high on the Fragile States Index between 2005 and 2013. In terms of future climate in the region, it is expected that the temperatures of warmest days, number of drought days as well as the frequency of flood events are projected to increase across the whole sub-Saharan region which will exacerbate current vulnerabilities such as food insecurity and water stress if adaptation strategies are not developed and implemented.

Asia: For the purpose of describing the effects of climate change in the Asian region, it will be divided into South, East and Southeast Asia. The southern region of Asia is characterised by high population density and the continued population growth will increase demand for food and water resources in a region which is already experiencing water stress and food insecurity. Additional pressure will be placed on the region's already insecure food supply with a predicted decrease in the average yields of wheat and maize. There will be a small increase in rice which is the main export crop for the region. It should be noted that the range spans from 16% decrease to 19% increase in the average yield. The region will also experience an increase in the frequency of flood events in the future as the region is exposed to tropical cyclones along with rising sea levels. The combination of these effects may consequently have adverse effects on the region's population as millions of people may be flooded per year along the coasts.

The eastern region of Asia imports a high proportion of crops which include wheat, maize and soybeans. Over 40% of the world's soybeans are imported by China to try and meet the growing demand for animal feed within the country. These factors consequently link the Eastern Asia region with climate impacts in major production and export regions of these mentioned crops, primarily the Americas. It is also estimated that the region will experience an increase in the frequency of flood events. The region is also exposed to tropical cyclones and characterised by high population near the coast. Rising sea levels will therefore have the potential to affect millions of people as the case in the Southern Asia region. Furthermore, the predicted increase of sea temperatures and ocean acidification may also threaten the region's important fishing industry and place additional pressure on its food supply.

The densely populated south-eastern region of Asia is already exposed to flooding as well as storms. The region is projected to experience considerable increases in population as well as rising sea levels and an increase in the frequency of inland flooding. The increase of sea surface temperatures as well as ocean acidification is also predicted for the region and may threaten fish stocks in this major fishing region. The Southeastern Asia region is also important in terms of rice exports and a major producer of maize. Projections show a slight increase in average rice yield and a decrease in average maize yield. These projections however did not account for increasing water demand for irrigation, decreasing water runoff, increases in drought days as well as the effect of storms.

Australasia: The region which comprises of Australia, New Zealand and New Guinea as well as the neighbouring islands of the Pacific Ocean, is low in population density and has a high level of self-sufficiency in terms of food. The region is however a major exporter of wheat and there are currently mixed and uncertain projections regarding changes in future average yields which depend on adequate water supply for irrigation purposes. The water demand for irrigation has been projected to increase and large increases in the number of drought days and temperature of the warmest days have also been projected. A decrease in water runoff is also projected which may be concerning as it will influence water availability and may place the region's water resources under stress with the increase in water demand especially by the agricultural sector.

North America: This region is very important in terms of crop production as it is the primary source of wheat, maize and soy bean exports to the world market as well as the second largest exporter of rice after Asia. Projections related to future crop yields are currently very uncertain. The region has however shown some increases in the yield of wheat, soybean and rice and decreases in maize yields. Once again, these estimated changes assume sufficient water supply for irrigation as the water demand of the agricultural sector increases. The number of days in drought is also expected to increase as well as the temperature of the warmest days. Projections in terms of flooding are uncertain due to the variability of precipitation estimates.

South America: This region is also very important in terms of crop production, particularly maize and soybeans. Projections show decreases in yield for both these crops as well as wheat in Brazil and northern South America. The more southern regions may have a slight projected increase in these crops. The whole region is however expected to experience reductions in water runoff, increases in the number of drought days as well as higher temperatures, combined with increases in water demand for irrigation (Met Office 2016).

Therefore, the effects of climate change will be heterogenic in nature across regions as indicated above. However, most regions will experience an increase in drought days, decrease in runoff, increase in temperatures of warmest days and an increase of water demand, especially irrigation, as they attempt to achieve future food security. Current vulnerabilities such as water stress as well as food insecurities will exacerbate the effects of climate change, especially in developing regions such as Africa, and may inhibit growth or worsen current socio-economic development and future quality of its natural resources, especially water. The following sections will provide case studies to further illustrate the heterogeneous nature of the impacts of climate change and also highlight the effects thereof on natural resources, specifically water as well as a region or country's socio-economic development and future growth.

4.6.1 Africa: Vulnerable Rivers and Economies

Africa as a region is of a growing concern as its water resources are particularly vulnerable to climate change due to already suffering disproportionately from water-related hazards, primarily floods and droughts (WWAP 2003). The exact magnitude of current water issues on the continent is still not clear however estimations by Vörösmarty et al. (2005) are that approximately 25% of the continent's population experiences water stress and 69% live under conditions of water abundance. These estimations do not consider actual water availability and the relative abundance shows low water consumption which results from limited water supply infrastructure and a further one-third of the continent's population live in drought areas (WWF 2000). Droughts and floods are exacerbated by the relatively low level of economic development and the sub-Saharan region is the only region in the world which has become poorer in the last generation.

The low level of economic growth is clearly shown in terms of the poverty statistics on the continent. The continent makes up 13% of the world's population but holds 28% of the world's poverty, is home to 32 of the 38 indebted poor countries of the world and did not achieve most of the MDGs. The challenge of poverty as well as relatively low economic growth is further intensified through rapid population growth which places further pressure on the continent's natural resources and socio-economic development. The resultant poverty and underdevelopment across Africa has been created by numerous factors such as the difficulty coping with climate variability and changes in terms of frequent droughts, floods, high temperatures, land degradation as well as being dependent on rainfed agriculture which in turn emphasises the need for a clearer understanding regarding the possible changes in the hydrological cycle over Africa related to climate change to inform relevant decision-making. Future general projections of impacts related to climate change for the African continent include the following:

- Warming of more than the global annual mean warming with the drier subtropical regions warming more than the moister tropics.
- Precipitation is likely to decrease over the majority of the Mediterranean region of Africa as well as the northern Sahara. A decrease in winter rainfall over western southern Africa and a likely increase of annual mean rainfall over East Africa.
- Most projections show that annual river runoff will be reduced over North Africa and most of Southern Africa. Increased annual runoff is projected in East Africa.
- The continued increase of the population will result in more water stress in North, Eastern and Southern Africa and the combination of climate change will further increase water stress issues over most of the continent.

These projected changes and impacts will vary within different regions across the African continent due to varying natural or physical characteristics as well as socio-economic elements such as demographics and level of economic development. Climate change will have a variety of impacts on natural and human systems as described throughout. The projected impacts as well as possible socio-economic consequences for the different regions across the continent also need to be considered to determine what adaptation strategies will be necessary. The impacts as well as their socio-economic effects in terms of the main African regions include the following:

- *West Africa*: Predicted impacts include the risk of rising sea levels and coastal floods to coastlines. These impacts will cause economic damages as well as be associated with rising costs. Changes in terms of disease burden/vector-borne diseases will cause rising health costs. Changes in ecosystem services are also predicted for the region and will negatively affect forestry and fisheries.
- *North Africa*: This region will also be threatened by rising sea levels and coastal floods to coastlines and be accompanied by economic damages and rising costs. Most of the costs will have to be invested in coastal protection as well as identified long-term risks and migration especially in the Nile Delta. The predicted increase in temperature will cause rising summer electricity use as the use of cooling aids increase which will cause higher energy costs. The region is also expected to experience reduced water availability and be accompanied by losses of increased costs of supply. The reduction in agricultural yields and increased irrigation costs will also be accompanied with economic losses. Lastly, the increased health effects of more frequent or intense heat waves will cause an increase in health costs.
- *Central Africa*: The region will experience an increase in health costs due to changes in disease burden or vector-borne diseases. Forestry and fisheries ecosystem services will also be affected.
- *East Africa*: This region will also experience an increased risk of rising sea levels or coastal floods of coastlines such as the Mombasa region. The predicted changes in the frequency and magnitude of extreme events such as floods and droughts will cause economic damages in the region. Changes in disease burden, specifically malaria, may spread to highlands and cause increased health costs. Changes in water availability as well as linkages with lakes and other ecosystems are expected. Predictions also show a potential decrease in agricultural production and there may be a loss of ecosystems as well in the region which may include forests as well as wildlife and tourism which include parks and coral.
- *Southern Africa*: The region will experience increased risk of sea level rise, coastal floods as well as the erosion of coastlines which will cause increased economic damage and costs. The possible decrease in water resource availability will also cause losses and further economic costs for sectors such as agriculture where irrigation is predicted to increase. Changes in disease burden or vector-borne diseases will also cause an increase in health costs. The region is also expected to experience an increase in the risk of forest fires, negative effects on agricultural production as well as the loss of ecosystems or natural resources which could potentially negatively affect wildlife and tourism revenues.

Climate change will therefore have numerous environmental impacts which will consequently lead to various socio-economic costs if proper mitigation or adaptation strategies are not developed. It has been estimated that in the event of no adaptation taking place in the African continent, the total cost may be quite significant. Current estimations regarding the cost to Africa's GDP include a cost range of 1.7% in the event of a 1.5 °C temperature increase, 3.4% in the event of a 2 °C temperature increase and lastly 10% in the event of a 4 °C temperature increase. Cost ranges with adaptation for the region have been estimated to be a minimum of US$10 billion by 2030 and possibly up to US$30 billion a year directly in response to climate change. Africa can therefore not afford to ignore the future effects of climate change and avoid the development of appropriate mitigation and adaptation strategies within different regions and countries (Boko et al. 2007).

Consequently, we need to look on a basin scale to achieve appropriate decision-making especially in terms of smaller basins as global scale analyses only provide a coarse resolution. Basin-scale hydrological models supply more explicit representations of available freshwater resources as well as water demand, providing more detailed evaluation of water availability. Two examples namely the Okavango Delta wetland in Botswana and the Mitano River basin in Uganda will be used to illustrate the importance of basin-scale analysis of climate change and show how a region's characteristics such as the size of the population as well as hydrology influence its vulnerability towards future climate-related changes.

4.6.2 The Future of the Okavango Delta Under Climate Change

The Okavango Delta, one of the most significant hotspots in the Kalahari region of Southern Africa, is an alluvial fan where the river terminates and is one of the major water resources in the region. The Okavango River is one of the largest river systems in Africa and spans over three riparian states of Angola, Namibia and Botswana. The delta is maintained by annual flooding of the Okavango River which consequently creates the second largest inland wetland in the world. The delta is unique and constitutes of a variety of dynamic habitats with exceptionally high beta diversity. It is one of the World Wildlife Fund's top 200 ecoregions, is the world's largest RAMSAR site and became the 1000th UNESCO heritage site in 2014. The delta plays a huge role in the region's hydro-climatology and may therefore be very sensitive to future changes in climate (Murray-Hudson et al. 2006).

The delta supports life in an otherwise inhospitable environment and is home to approximately 150,000 people who live within and around it and depend on the extraction of natural resources either directly or indirectly. Its rich wildlife diversity as well as permanent water resources has consequently been attracting more land users with variety of land use activities. Increased human activities together with the impacts of climate change have caused tremendous environmental stress in the region and raises concerns regarding its future sustainability. Climate change predictions for the Okavango Delta indicate the following:

- Changes in climate even by the middle of the twenty-first century may be potentially very large in the basin and could exceed very substantial natural variability experienced in recent decades;
- Uncertainty exists in terms of the magnitude and signs of climate change but the signal of climate change is clear within the basin; and
- Future variability of precipitation within the basin is still largely uncertain however toward the latter decades of the twenty-first century, there is a convergence of projected responses and shows a drying of the system due to increased temperature and evapotranspiration losses starting to dominate.

The Okavango River basin is one of the least developed river basins in Africa but the increased socio-economic needs of the growing population will change this situation in future and has been identified as a basin which has the potential for water-related disputes (Wolf et al. 2003). Water resources in Angola are particularly exploited and future developments in the country such as increased urbanisation, hydropower schemes as well as increased irrigation will have significant consequences for the water availability in downstream countries especially Botswana and other negative impacts such as the degradation of water quality (Pinheiro et al. 2003; Ellery and McCarthy 1994; Green Cross International 2000; Mbaiwa 2004). Developments in downstream areas must also be kept in mind as the increased water demand will also be an issue. The planned pipeline from the Okavango River to Grootfontein, in an attempt to connect river systems with Windhoek in Namibia, will also exacerbate water demands on the river basin. Developments therefore need to be carefully considered as these will occur within the context of climate variability and change and should be accompanied with the development of appropriate adaptation strategies. The three riparian states which share the water resources of the Okavango River basin also importantly need to have shared accountability regarding future water demands and developments which may affect the future of the river basin's water availability and to ensure its future sustainability under climate variability and change as well as human activities.

4.6.3 Future of the Mitano Basin, Uganda Under Climate Change

The Mitano basin in Uganda, in comparison to the Okavango Delta's surface river flow and wetland flooding, is characterised by groundwater recharge. Groundwater is an important water source for drinking and irrigation around the world and supplies 75% of all improved sources of drinking water in sub-Saharan Africa (Foster et al. 2006). The impacts of climate change on groundwater are however poorly understood and most predictions of the effects of climate change on freshwater resources are defined in terms of mean annual river discharge or runoff. An understanding of both is however required for the development of proper climate change adaptation strategies.

This is particularly important for Uganda as the country has a substantial dependence on rainfed agriculture and has a heavy reliance on localised, untreated groundwater as a source of potable water. The Mitano River basin is relatively small and drains areas of relatively high elevation and the groundwater from the weathered overburden and fractured bedrock discharges into the River Mitano drainage network.

The East African region which includes Uganda is one of the few regions in the world which has consistent projection of future precipitation change, with most models showing increased precipitation in the future (Meehl et al. 2007). The main concern is however regarding its future water resources due to projections showing that the population will nearly double between 2005 and 2025. This significant increase in the region's human population will be accompanied with numerous land use changes as well as increased water demands by different sectors which will place immense pressure on the region's surface and groundwater resources. It is therefore of prime importance that climate change related impacts on freshwater resources are projected and considered in an attempt to ensure future sustainability within the region. The following effects of climate change on freshwater resources have been projected for the region:

- An annual increase of 17% is predicted for rainfall except during January and an increase of 4.2 °C in temperature which may give rise to a 53% increase in annual evaporation.
- It is also predicted that these mentioned changes above may lead to a 49% reduction in recharge and 72% increase in runoff.
- Simulations show an increase in the occurrence of large precipitation events (above 10 mm). This increase in intensity under future climate change substantially increases recharge and runoff by overcoming evaporation on individual days and enable more frequent infiltration and recharge.
- Results related to groundwater recharge do however differ between the daily precipitation transformation approach (projected increase) and projections using monthly "change" factors (projected decrease). These results therefore indicate that groundwater recharge is very sensitive to the used projected method.

The projected increase in recharge give a promising outlook for the region's future populations, however the increases in demand due to very rapid population increase will exert significant pressure on its finite water resources. Currently, the country is already experiencing increased motorised groundwater developments which have expanded since 2003 and the main urban area in the Mitano River basin has already been singled out as an area which does not have adequate water supplies to meet the current water demand of the town. Future urban expansions will consequently lead to further intense groundwater abstraction as the country tries to provide safe drinking water to growing urban populations. The uncertainties related to the future development of intensive irrigation under climate change with increased dry-day frequency also poses an additional problem for future water demand in the country.

Socio-economic changes will therefore have a larger effect on the basin's water resources rather than direct climate change impacts. For the country to try and achieve future sustainability of its water resources, it needs to focus on conservative development of groundwater resources especially in terms of intensive groundwater abstraction for town water supplies and irrigation. A full range of possible hydrological responses to future climate change therefore needs to be accounted for when developing future adaptation strategies to be implemented within the Mitano River basin and ultimately Uganda.

4.6.4 Pacific Islands

The Pacific islands is a region constituting of three major island groups in the Pacific Ocean namely Polynesia, Micronesia and Melanesia. The water supplies of islands within the region which are small and low lying will be considerably vulnerable to extreme events such as droughts and may also be threatened by saltwater inundation caused by high tides.

Most of the Pacific islands make use of rainwater catchments as well as shallow wells for drinking water and other uses. On some of the atoll islands, the freshwater layer is thin and very vulnerable to contamination from saltwater below especially in the event of excessive freshwater abstraction. This region has also been affected by El Niño events which have caused severe droughts and water shortages on most of the islands which were accompanied by health effects such as dehydration, drought-related skin disease as well as respiratory infections. Large reverse osmosis water purification systems were consequently invested into address some of the human health concerns. Seawater was therefore treated to assist in alleviating water shortages in conjunction with groundwater withdrawals. Concerns however started to develop during the 1997–1998 drought regarding increased groundwater withdrawals due to the potential impact of saltwater intrusion on different crops such as bananas and breadfruit and groundwater monitoring was implemented. Despite the increase in groundwater withdrawals, saltwater intrusions did not affect crops but emphasised the importance of groundwater monitoring programmes (Keener et al. 2012).

The freshwater resources on the atoll islands are therefore very vulnerable and monitoring data are required to manage both rainwater and groundwater resources conjunctively and increase adaptive capacity of low lying islands to meet challenges from climate variability and change. The predicted temperature increase due to climate change for the region is estimated to be between 2 and 4 °C which will cause immense water stress especially on poor rural people which are dependent on water resources for their livelihoods. The total projected economic loss amount is estimated to be US$1 billion in damages to water resources and will intensify current water problems within the region (Keener et al. 2012).

The major impacts related to projected changes in temperature and rainfall as well as sea level rise will include accelerated coastal erosion, saline intrusions into freshwater lenses as well as increased flooding from the sea which may have large effects on human settlements. Even though it is predicted that rainfall may increase during certain months, the scarcity of freshwater is still a limiting factor in terms of social and economic development. Deteriorating infrastructure is common and results in leakages as well as water pollution and ultimately higher costs.

The population's reliance on rainfall significantly increases their vulnerability in the region to future changes in rainfall distribution. Current estimations indicate that a 10% reduction in 2050 is possible and is expected to correspond to a 20% reduction in the size of the freshwater lens on islands namely Tarawa, Atoll and Kiribati. The declining size of low lying islands due to sea level rise is expected to result in land losses and may also reduce the freshwater lens on atolls by as much as 29% (Keener et al. 2012).

The projected decrease in rainfall as well as accelerated sea level rise would compound together as a great threat to the region's freshwater and groundwater resources as well as its human population. Climate change threatens both natural as well as human systems of the Pacific Islands and will be accompanied with an increase in water stress as well as economic losses in the region. It is therefore of vital importance that the region invests in the implementation of rainwater and groundwater monitoring strategies which may inform the development of appropriate adaptation strategies to ensure future sustainability of the region's water resources but also protect its already vulnerable population against future threats on their livelihoods.

4.6.5 Portugal

Portugal, located in Southern Europe or the Mediterranean region, will also be particularly negatively affected especially in the Iberian Peninsula, located south of the Tagus River. The region is expected to experience a considerable increase in temperature and a reduction in both rainfall and runoff by 2100. Once again, in order to evaluate the impacts of climate change on the region's water resources, one has to focus on changes in runoff and not just temperature and rainfall. Projections show the following for the region:

- A general decrease in the region's water availability;
- An increase of seasonal and spatial asymmetries;
- An increase in flood risk; and
- An increase of water quality problems.

The estimated decrease of runoff in the Spanish part of the transboundary river basins is predicted to accentuate the expected decrease in water availability in Portugal. The influence of climate change on sea levels is also likely to affect groundwater levels as well as quality which will further negatively affect the country's water resource availability (da Cunha et al. 2005).

Some research has already shown small changes regarding the inflow to reservoirs which may cause significant changes in the reliability of water yields from these reservoirs. Changes in operating rules may therefore be required to improve the ability of these systems to meet delivery requirements. The expected changes in rainfall amount and distribution will also have a direct impact on hydropower generation in the country and may also require changes to be made in operating rules. The total impact on the country's agricultural sector will depend on a variety of factors which influence varies for different regions and for different crops. General consensus is however that relatively small changes in water availability could have rather large impacts in the agricultural sector and consequently influence future food security.

Water management in Portugal is therefore likely to become more and more challenging and the impacts of climate change on water demand should be an object of attention as changes in temperature will also have impacts on water demand. The predicted decrease of water availability and increase of hydrological seasonal asymmetries will be associated with increased stressing conditions which relate to water quality and flood risks. Water management policies which are based upon sound and in-depth knowledge of the country's water resources as modified by climate change are therefore of vital importance. Further research related to the impacts of climate change on the region's water resources should be encouraged to enable the consideration of climate change in water management practices. The estimated decrease of river flow in southern Portugal is of primary concern as it may have dramatic consequences on the country's available water resources and emphasises the fact that impacts of climate change on the country's water resources cannot be ignored in terms of planning and management (da Cunha et al. 2005).

Therefore, it is quite clear that climate change will be associated with a wide variety of impacts which need to be considered with an increased attention on the country's water management strategies and policies. Currently, it is said that water managers have not yet fully perceived the current changes and do not assume the need to take climate change into account for long-term planning and the management of their complex water systems. However, some water professional organisations have already perceived the new reality and have consequently made appropriate recommendations to water planners and managers to take climate change into full consideration.

4.7 Conclusions and Future Adaptation

There are numerous opportunities for anticipatory adaptation especially in developing countries and most of the global cost of water sector adaptation will be necessary here. Local level adaptation costs have not been fully established and more research is required.

The implementation of adaptive approaches into water management is encouraged as it can be used to address uncertainties caused by climate change. These adaptive techniques can include scenario planning and experimental approaches which consist of learning from past experiences as well as the development of flexible and low regret solutions which are resilient to uncertainty. Barriers to these approaches do however exist and include the lack of human and institutional capacity, financial resources, awareness and communication.

The increased variability of surface water availability will influence the reliability of water supply which is expected to suffer as a consequence. Increased groundwater abstractions may however assist in continued reliable water supply and may be considered as an adaptation technique but will be limited in regions where renewable groundwater resources are expected to decrease due to climate change.

Certain measures which are aimed at reducing GHG emissions may have risks for freshwater resources as well. Examples of this may include the following. In the event of bioenergy crops being irrigated, these crops make water demands which other mitigation measures might not. Hydropower may also have negative impacts on freshwater ecosystems but can be reduced by appropriate management methods. The capture and storage of carbon can lead to a decrease in groundwater quality and in some regions, afforestation can lead to the reduction of renewable water resources but also flood risks and soil erosion.

Climate change will therefore have varying impacts on freshwater resources as well as at different intensities around the world. The intensity and significance of impacts will largely vary due to different characteristics of regions. Projections show that climate change will decrease renewable water resources in some and increase in others. Uncertainties regarding the actual impact on freshwater resources do however still exist and more research is needed. The development and implementation of various adaptive approaches are however encouraged to try and minimise and address the uncertainties which may be caused by climate change.

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