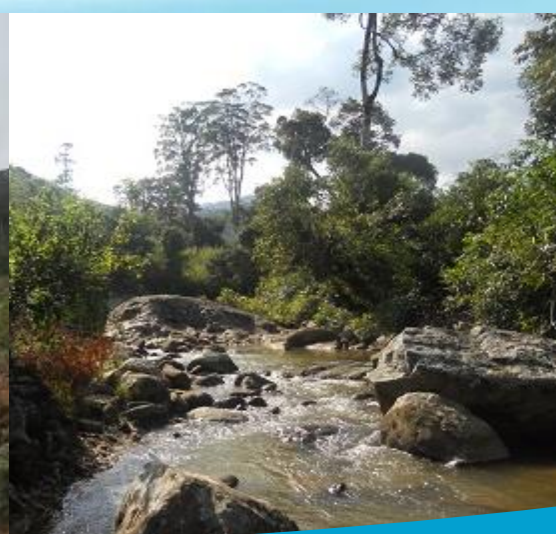
Climate, Forest Cover, and Water Resources Vulnerability

Wami/Ruvu Basin, Tanzania


Tanzania Integrated Water, Sanitation and Hygiene (iWASH) Program

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Wami/Ruvu Basin, Tanzania

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Cover Photographs:

Front Cover from left: Headwater catchments of various tributaries of the Wami and Ruvu rivers in the Eastern Arc Mountains having a mosaic of primary forest and cleared land; a stream in the Eastern Arc foothills and a lake in the floodplains of the Wami.

Back cover from left: Locally-relevant environmental education in schools, high valley in the Eastern Arc Mountains,.livestock in the Ruvu Basin.

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Acronyms and Abbreviations

AET	Actual Evapotranspiration
ESRI	Environmental Systems Research Institute
EAM	Eastern Arc Mountains
ET	Evapotranspiration
FIU	Florida International University
GCM	General Circulation Models / Global Climate Models
GPS	Global Positioning System
iWASH	Integrated Water, Sanitation and Hygiene
ITCZ	Inter- Tropical Convergence Zone
IUCN	International Union for Conservation of Nature
Masika	Heavy and long rainy season from March to May
masl	Meters above (mean) sea level
PET	Potential Evapotranspiration
SLR	Sea Level Rise
UDSM	University of Dar es Salaam
URT	United Republic of Tanzania
Vuli	Short rainy season from October to December
WADA	Water and Development Alliance
WRBWO	Wami-Ruvu Basin Water Office

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Discussions with more than 50 people from villages and farms represented by the Mkindo Water User Association helped to illuminate the various links between water resources, human activities, and climate variability in the Basin. Stanislaus Kizzy of TANESCO has provided perspectives on water requirements for power plants as well as on water balance for the region.

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About the Vulnerability Report Series

This report composed by Amartya Saha and Valeria Perez Guida describes a climate study for the Wami/Ruvu Basin, and discusses the implications of climate change and forest cover change on water resources in the Basin from both availability and demand perspectives, and identifies sector-specific areas of adaptation.

A second report in this series describes the vulnerability of water resources at a catchment scale, involving village communities and other stakeholders of the Mkindo River Catchment in the Wami Basin. This report is titled "Climate and Landscape-related vulnerability of water resources in the Mkindo River Catchment, Wami River Basin, Tanzania".

These reports form part of the documentation of the Tanzania Integrated Water, Sanitation and Hygiene (iWASH) Program initiated in 2010. The goal of the Program is "to support sustainable, market driven water supply, sanitation and hygiene services to improve health and increase economic resiliency of the poor in targeted rural areas and small towns within an integrated water resources management framework".

Executive Summary

Assessing vulnerability of water resources to climate/forest cover change at the basin level

Climate change is one of the factors influencing water availability to society and ecosystems. Forest/wetland cover and anthropogenic water demand/use are other major factors. Adaptive strategies for water resource management are necessary at both the basin-level (e.g. Wami/Ruvu Basin Water Office) and at individual stakeholder levels (e.g. communities, large farms, and industries). This report examines the implications of climate change and forest cover change upon water availability, use, and demand in the Wami/Ruvu Basin that includes the catchment areas of the Wami, Ruvu, and coastal rivers around Dar es Salaam in Tanzania.

Current climate characteristics and future climate projections for Wami/Ruvu Basin

The overall climate predictions over the 21st century for the Wami and Ruvu Basins are:

- Rising temperatures across the seasons, with an increase in the number of very hot days (> 32°C) and a decrease in cold days.
- Rising evapotranspirative demand and soil moisture deficits, especially in the semi-arid western part of the basin (Kinyasungwe catchment).
- Increasing uncertainty in the onset, regularity, and amount of rainfall. Occurrence of sizeable rain events in what has been usually considered dry season.
- Increasing frequency of extreme events, including high rainfall events, floods and long periods of scanty or no rainfall leading to droughts.
- Rising sea level, whose negative effects can be exacerbated by decreases in freshwater river inflows to estuaries

It is to be noted that predicting precipitation is far more complex than predicting temperature, as reflected by the wide variability in rainfall projections amongst regionally downscaled General Circulation Models (GCMs). Hence, water resources management strategies aimed at buffering water supply from climate uncertainty are more realistic than an approach that overtly relies on projected rainfall increases or decreases by a selected few models, even if these models are regionally downscaled and calibrated to match their hindcasts to past data.

Forest cover change in the Wami/Ruvu Basin (2000-2012)

The maps of forest cover extent and change (loss, gain) for the Wami/Ruvu Basin generated from the global forest cover mapping project indicate a very high rate of deforestation over the past decade in the lowland savannah woodlands in the eastern part of the basin, with a lesser extent of forest loss in the Eastern Arc Mountains (Nguru, Nguu, Ukaguru, Uluguru and Rubeho blocks). The loss of forest cover significantly increases runoff following rain events causing flash floods and soil erosion. At the same time, the decreasing infiltration results in earlier drying up of springs/rivers and lesser groundwater recharge. Effective implementation of laws that protect primary forests (Forest Reserves), especially in headwater catchments and riverbanks are absolutely essential for buffering water resources in the basin against the vagaries of climate change and increasing demand. This fundamental task needs the cooperation of all stakeholders: ministries of water, forests and agriculture along with local communities, NGOs, and academic institutions. Soil and water conservation practices (terraces, bunds, check dams, and strip mulching) are necessary especially in steep terrain that has been deforested. Wetlands such as those present in the Mkata plain, Wami Dakawa, and the river floodplains provide water storage that feeds rivers in the dry season, and hence require protection and management.

Vulnerability Assessment (VA): exposure, sensitivity and directions for adaptation

Surface water for irrigation represents the biggest water use in the Basin, with the highest use being in the Mkondoa, Wami, Upper Ruvu and Kinyasungwe sub basins. Domestic use ranks second in the Basin, drawing upon comparable proportions of both groundwater and surface water, and is by far the largest in the Coast sub-basin including the major metropolitan area of Dar es Salaam. Other water sectors are industry, livestock, fisheries/aquaculture, energy, mining, and commerce. Directions for developing adaptive strategies for each water use sector in coping with the often unknown changes from the worst-case scenario perspective are identified in this report.

The increasing uncertainty in rainfall, higher possibility of droughts/floods, and decrease in water retention capacity of the catchments necessitates consideration of the following aspects in the development of active management plans:

- *A basin-scale accurate water availability analysis, including*:
  - additional river discharge monitoring, hydrological data management and analysis, monthly and annual water balance of the entire basin and sub-basins.
  - extending a groundwater monitoring network especially in the Coast and Kinyasungwe Catchments where groundwater use is high, as well as a better understanding the local connection between rainfall and recharge.
- *Water re-use assessment and strategies for municipal/industrial wastewater and increased irrigation efficiency, and other demand management strategies.*
- *Headwater catchment forest, riparian gallery forest, and wetland protection* aiming at water harvesting, maintenance of natural flow regime, and water quality; as well as *provisions to increase groundwater recharge by terracing and check dams.*
- *Community awareness* on the need for individual water storage, and community/school water monitoring programs.
- *Extreme event preparedness*: an increase in the possibility of heavy rainfall events and floods necessitate maintaining locks and gates in dams and water control infrastructure, as well as the development of early warning systems and disaster management programs.

Each of these sectors will need to draw up their own adaptive management plans taking into account the vulnerability of water as well as the different stakeholders involved. The present report tries to contribute to this aim. Finally, vulnerability assessment is a continuous process to provide feedback for adaptive management of water sources, catchment ecosystems, and sectorial water demand.

1 Water Resources Vulnerability in the Wami/Ruvu River Basin

Water resources vulnerability

Apart from direct human consumption, water underpins every economic activity. Ecosystems that ensure our survival also have water as their lifeline. The inadequate provision of freshwater, an ecosystem service, threatens the health of ecological systems and human wellbeing. The amount of water available in a basin at any point in time is determined by the interaction of various supply and demand factors. Water inputs in the form of precipitation are determined by climate and are thus subject to uncertainty from climate change. Forests and wetlands regulate water flow and storage; hence, deforestation and wetland drainage in the humid tropics leads to higher river flows following rains and rivers drying up earlier (e.g. Bruijnzeel 2002, Yanda and Munishi 2007, Krishnaswamy *et al.* 2012). Furthermore, water quantity and quality is at increasing risk of being compromised given increasing domestic and industrial pollution, deforestation and the lack of soil conservation in catchments, as well as rainfall uncertainty. These changes in water availability go together with a growing human water demand following rising water needs in domestic, agriculture, industry, and power sectors accompanying increasing populations and economic development. There is also the necessity of maintaining the natural flow regime in rivers and estuaries to preserve aquatic ecosystems and fisheries (Poff *et al.* 1997). Taken together, the net effect of these supply and demand changes affects the vulnerability of water resources (Gain, Giupponi, and Renaud 2012).

Vulnerability assessments

Given the complexity associated with water resources and their management, i.e. large numbers of possible alternatives usually characterized by high uncertainty arising from the numerous and often unknown interactions between a changing climate and the biophysical landscape, different geographical and temporal scales, and conflicting interests of multiple stakeholders (Hyde, Maier, and Colby 2004), water resources vulnerability assessment is a complicated endeavor. Furthermore, there is no universally accepted concept for vulnerability; this plurality in definitions leads to a very diverse range of assessment frameworks and methodologies (Gain *et al.* 2012).

Figure 1-1 illustrates the heuristic model used to develop the vulnerability assessment of water resources for the Wami and Ruvu Rivers Basins, hereafter referred to as the Wami/Ruvu Basin. The model is based upon the USAID (2007) framework of exposure, sensitivity and adaptation. The main factors affecting water availability and water needs in the Wami/Ruvu Basin are assessed. For water availability, climate determines the amount of precipitation while land cover regulates water storage and flow. Water needs are spread over an array of human activities as well as ecosystem water requirements to maintain their structure and function. The intersection of water availability and water needs, both of which vary seasonally and inter-annually, determines the vulnerability of water resources for this particular basin. An accurate understanding of these vulnerabilities can be used by stakeholders to discuss and develop adaptation strategies for each water use and sector (e.g. domestic, agriculture, livestock, and ecosystems).

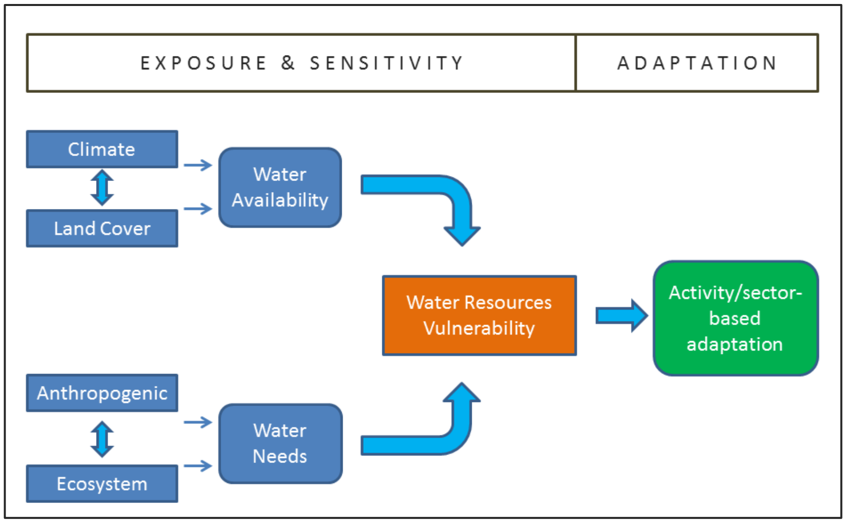


Figure 1-1: A comprehensive heuristic model of vulnerability assessment of water resources.

The Wami/Ruvu River Basin

The Wami and Ruvu rivers originate in the Eastern Arc Mountains in central Tanzania, and flow eastwards through some of the country's major agricultural, industrial, and urban areas before discharging into the Indian Ocean north of Bagamoyo. A series of smaller coastal rivers such as Mkusa, Mpiji, Msimbazi, Kizinga, Mzinga, Mbezi, and Luhute arise in the low-lying coastal hills around Dar es Salaam. Water resources in the Wami, Ruvu and coastal river basins are jointly managed by the Wami Ruvu Basin Water Board of the Ministry of Water and, hence, referred to as the Wami/Ruvu Basin (Figure 1-2). The large urban centers of Dar es Salaam, Morogoro, and Dodoma are located in the Basin. A large climatic diversity exists within the Basin; including humid plains along the Indian Ocean coastline, the Eastern Arcs Mountains with high rainfall, and the arid areas around Dodoma further west that lie in the rain shadow of the mountains. Climate and biogeographic history has resulted in a stunningly large variety of biodiversity-rich ecosystems, notably the montane forests in the Eastern Arc Mountains; the savanna woodlands, famous worldwide for their wildlife; and coastal mangroves, seagrass beds, and coral reefs that form nurseries for marine life. A wide range of livelihoods exists in the Basin encompassing rain-fed and irrigated agriculture, livestock herding, forest base production, and leading industries of Tanzania. Such a diversity of water availability and demands present within the basin poses an ever-widening challenge for sustainable water resource management. How this challenge is starting to be addressed with the involvement of all stakeholders in the basin, from village communities and schools to large water users and the Ministry of Water, can form a model for other regions of Tanzania, East Africa, and developing nations worldwide.

Figure 1-2: The Wami/Ruvu Basin (orange boundaries).

Objectives and organization of this report

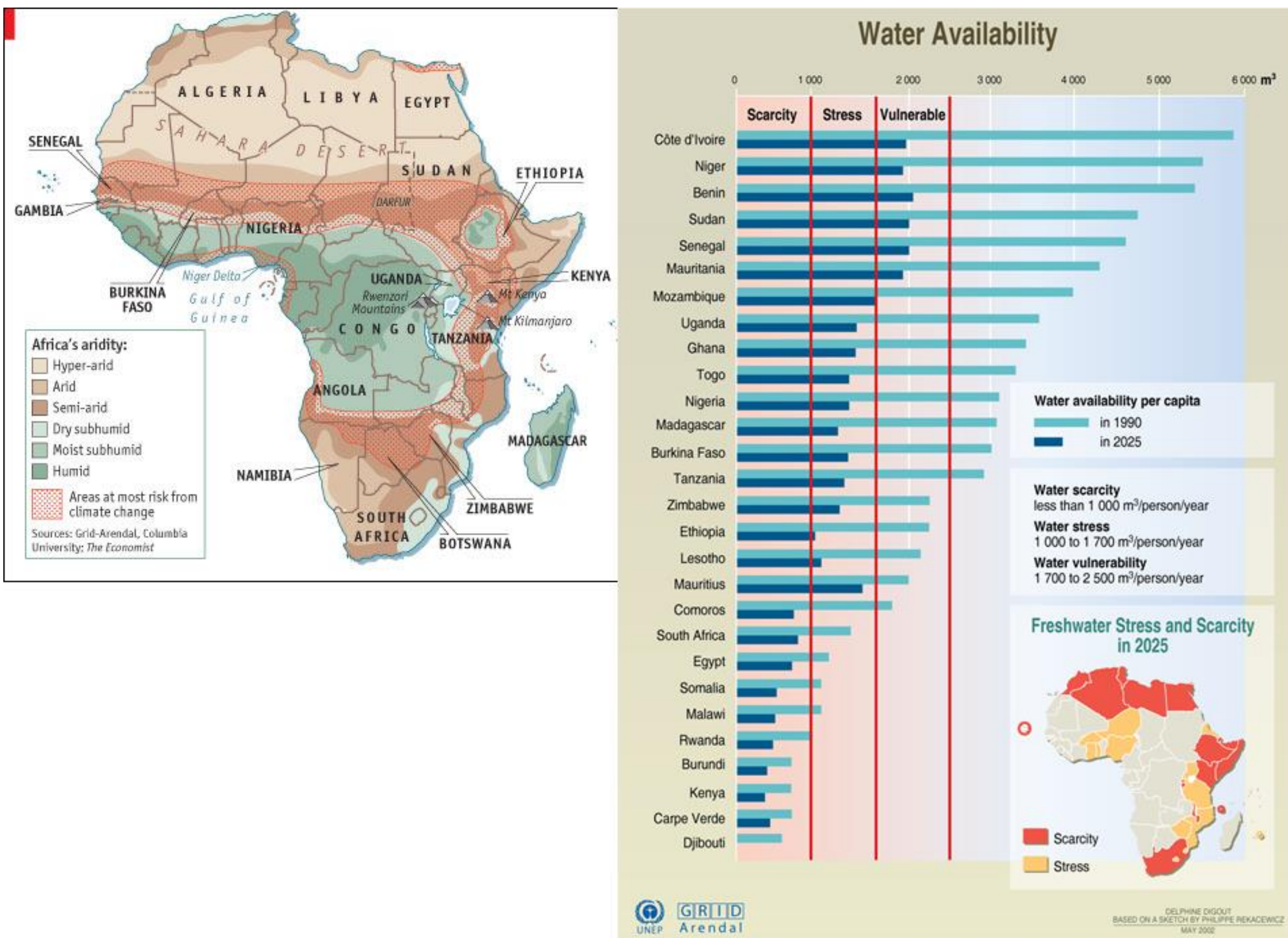
The primary objective of this report is to present information and analyses that can enable a better understanding of the impact of climate change and forest cover change upon water resources in the Wami/Ruvu Basin. Understanding the natural variation in water sources (rainfall) and water storage/flow regulation by land cover can help develop and implement water resources management strategies ensuring sustainability, social equity, and functioning ecosystems buffered against climate uncertainty. Accordingly, the report describes the factors that affect water supply (climate and forest cover) as well as the sector-specific water demands in the Basin. Viewing water availability and demand though the same lens brings into focus the possible trajectories in both, thus enabling the development of basin use and management plans. The report also includes guides to run and interpret climate models. High-resolution images of the climate maps in this report are available at http://glows.fiu.edu.

After this introduction, Chapter 2 describes the climate of Tanzania and the Wami/Ruvu Basin over the 20th century, in terms of seasonality, spatial characteristics, and effects of large-scale climate teleconnection patterns. It is followed by climate predictions by 16 General Circulation Models that were run using ClimateWizard under three greenhouse gas emission scenarios (A2, B12 and B2). The parameters predicted are temperature, precipitation, evapotranspiration, and soil moisture deficit/surplus. The annex includes resources on how these predictions are obtained. Chapter 3 considers the change in forest cover over 2000-2012 along with a discussion of the possible impacts of deforestation on water resource availability. Chapter 4 shifts to the water demand side, with a sector-wise look at water use, sources, and projected demands. This section draws upon the extensive water sector use (as of 2011) and demand projection (2015, 2025 and 2035) study by JICA and WRWBO (2013). Finally, in Chapter 5, water availability and demand are considered together to identify a set of thematic guidelines that can enable water resource management to cope with the dual challenges of increasing uncertainty in availability/quality and increasing levels of water demand.

2 Climate of the Wami/Ruvu Basin, Tanzania

2.1 Climate change – impacts on water resources, livelihoods and public health

The Intergovernmental Panel on Climate Change (IPCC) states that "Africa is one of the most vulnerable continents to climate change and climate vulnerability" (IPCC 2007) and that by the 2050s, 350–600 million Africans will be at risk for increased water stress, predominately in the northern and southern parts of the continent (Arnell 2004, IPCC 2007). The primary dependence on rain-fed agriculture and livestock means that African farmers are especially vulnerable to precipitation changes that can result in over-farming, degradation of land resources, increased pressure on wild game species, and exposure to zoonotic diseases (Fields 2005). Figure 2-1 (left) indicates that the semi-arid belt between the moist tropics and deserts faces the highest risk to climate change. Figure 2-1 (right) shows the expected decrease in limited freshwater per capita all across Africa in 2025.



Source: United Nations Economic Commission for Africa (UNECA), Addis Abeba ; Global Environment Outlook 2000 (GEO), UNEP, Earthscan, London, 1999.

Figure 2-1: (Left) Sub-humid to arid zones around the moist regions of central Africa face high risk to climate change. [Source: The Economist 2007]. (Right) Predicted decrease in per capita freshwater availability from 1990 to 2025. [Source: UNECA 1999]

In the case of the Wami/Ruvu Basin it is expected an increase between 2.1 and 4 °C in annual temperatures, together with an increase in rainfall in two rainy season areas and a decrease in rainfall in areas with just one rainy season (Ngana *et al.* 2010). Furthermore, these authors also mention a sharp loss of vegetation cover and shrinking of cloud bases in the Eastern Arc Mountains (EAM), and the necessity of further studies on the impact of this on river hydrology and soil erosion. In their report on climate change, agriculture, and food security in Tanzania, Kilembe *et al.* (2012) mention that climate change holds the potential to threaten the gains attained in relation to nutrition and literacy in the region. Warmer temperatures have been linked to a higher incidence of malaria up in tropical highlands (Siraj *et al.* 2014), while increases in flooding spread waterborne diseases such as cholera (Shemsanga *et al.* 2010). In primarily rural areas, where residents are dependent on agriculture/livestock and poverty rates are as high as 95%, vulnerability to climate variability is higher.

Under this scenario, a key challenge in planning adaptation strategies will be related to the increasing uncertainty about future climate, and thereby uncertainty in water availability. Thus, adaptive strategies require an understanding of the current climate and then consider climate predictions under varying scenarios of greenhouse gas emissions. Given the climate dynamics, in order to understand microclimates, e.g. the climate of the Wami/Ruvu Basin, it is necessary to consider the climate of a broader geographical region, e.g. Tanzania, and how it is influenced by broader scale elements i.e. the Indian Ocean. After this introduction, the Chapter includes a description of Tanzania and the Wami/Ruvu Basin climate patterns over the past decades. It also synthesizes recent literature on climate predictions for Tanzania and discusses the results of downscaled model outputs for both Tanzania and the Wami/Ruvu Basin. Local topography and land cover also influence local microclimates, these factors are considered in Chapter 4.

2.2 Past and present climate in Tanzania and in the Wami/Ruvu Basin

2.2.1. Climate of Tanzania – the past century

Tanzania lies just south of the Equator, at 1-12°S, with a tropical climate and regional variations arising from elevation and topography. A narrow coastal strip (<200 masl) leads to a central plateau of around 900-1800 masl with the Eastern Arc Mountains (EAM) rising up to 2600 masl. The mountains intercept moisture-laden easterly trade winds coming from the Indian Ocean, resulting in adiabatic cooling and higher precipitation in these mountains (average annual rainfall greater than 2000 mm) relative to other parts of the country. The spatial distribution of rainfall is seen in Figure 2-2 with the highest rainfall present along the EAM, followed by the coasts along the Indian Ocean (east) and Lake Victoria (northwest), then the southern highlands around Mbeya and Lake Nyasa, and finally the semi-arid central plateau lying in the rain shadow of the EAM. The most arid zones are around Dodoma.

In terms of the Tanzanian cities, Dar es Salaam, on the Indian Ocean coastline, gets around 1000 mm precipitation annually, Mwanza on the Lake Victoria shoreline, around 700 mm, while Tabora in the central plateau sees less than 500 mm (Jack 2010). The northern parts of Tanzania have a bimodal rainfall pattern consisting of 'long' rains (*Masika*) between March to May and 'short' rains (*Vuli*) between October to December (Shemsanga *et al.* 2010). The central and southern regions have one rainfall season between December to May, and a long dry season from May to December (GoT 2003).

Precipitation

The influence of regional pressure systems

Seasonal rainfall in Tanzania is driven by the migration of the Inter-Tropical Convergence Zone (ITCZ), a relatively narrow belt of very low pressure and heavy precipitation that forms near the Earth's Equator. The ITCZ is the point of convergence of easterly trade winds from the northern hemisphere (northeast trades) and the southern hemisphere (south-east trades) in a zone of low pressure that brings rainfall. The exact position of the ITCZ changes over the course of the year, migrating southwards through Tanzania in October to December, reaching the south of the country in January and February, and returning northwards in March, April, and May, causing the two distinct wet periods characteristics of the north and east. The southern, western, and central parts of the country experience one wet season that continues from October to April or May. The amount of rainfall falling in these seasons is usually 50-200 mm per month but varies greatly between regions (Alusa and Ogallo 1992), and can be as much as 300 mm per month in the wettest regions and seasons.

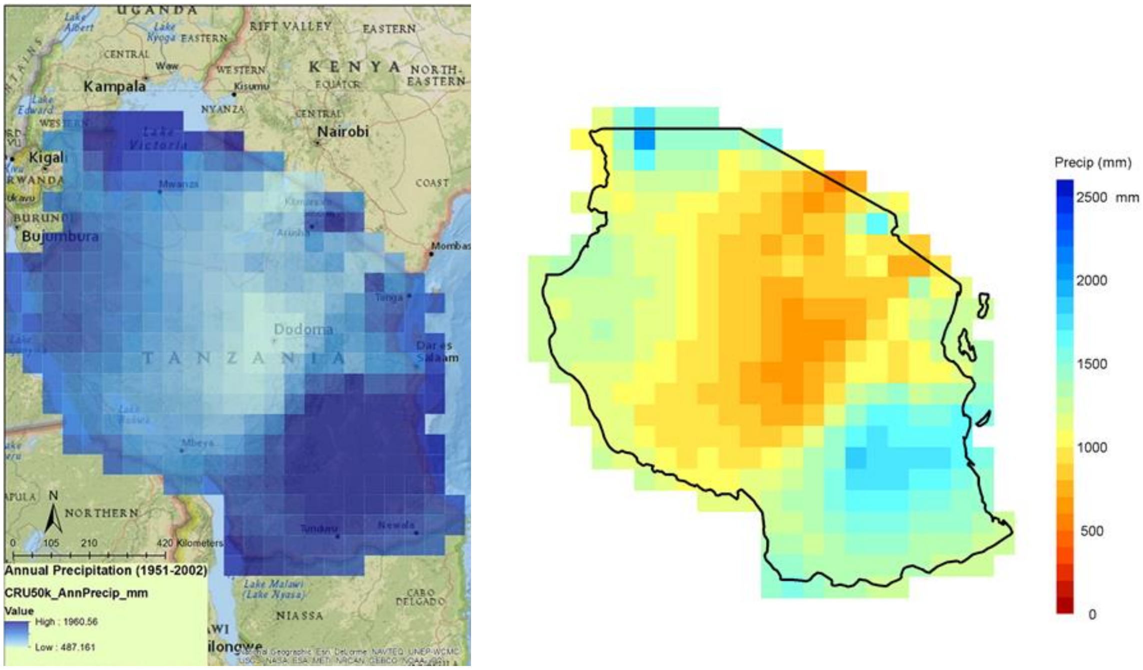


Figure 2-2: Average annual precipitation (1951 – 2002) in Tanzania (50 Km grid scale). (Left) Regional context. (Right) Rainfall scale. [Data Source: ClimateWizard]

The influence of climate teleconnection patterns

The movements of the ITCZ are sensitive to inter-annual variations in sea surface temperatures in the Indian Ocean, known as the Indian Ocean Dipole or IOD Figure 2-3. Therefore, the onset, duration and intensity of rainfall in Tanzania varies considerably from year to year (Liu *et al.* 2011). Another well documented ocean influence on rainfall in this region is the El Niño Southern Oscillation or ENSO (Indeje *et al.* 2000, Matayo *et al.* 2000, Kijazi *et al.* 2005, Godwin 2005). El Niño episodes usually cause greater than average rainfalls in Tanzania in the short rainfall season (October-December), whilst cold phases (La Niña) bring a drier than average season. Climate teleconnection patterns can also work synergistically.

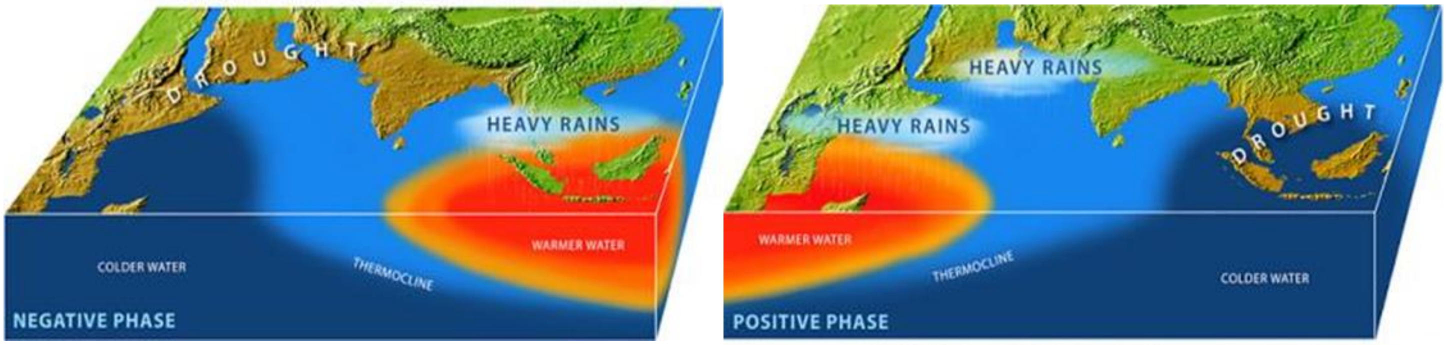


Figure 2-3: Association between Indian Ocean Dipole (IOD) and rainfall in East Africa. [Source: Paul Oberlander, Woods Hole Oceanographic Institute, Massachussetts, USA, and shown here with permission from author]

For example, in December 1997, the combination of the positive phase of the IOD (Figure 2-3) with the strong 1997-1998 El Niño was associated with extremely heavy rainfall (Liu *et al.* 2011). This situation exacted a heavy toll on human economic activity and loss of life, but also contributed significantly to recharging aquifers in central semi-arid Tanzania (Taylor *et al.* 2013).

Figure 2-4 shows the rainfall anomaly (departure of annual rainfall from the period 1961-1990 mean annual rainfall) expressed as a percentage and averaged across Tanzania. The large changes year to year, between 10-40%, indicate the high inter-annual variability of rainfall, suggesting the need for taking this variability into account when designing adaptive management strategies, such as enhanced storage at the community level, monitoring groundwater and surface water at the basin level, crop selection for wet and dry years and the secure maintenance of food grain storage.

The inter-annual variation in annual rainfall is typically greater than the inter-decadal variation; however, knowledge of inter-decadal variation (associated with teleconnection patterns like the IOD and ENSO) is useful in predicting wet and dry multi-year phases. This inter-decadal variation is evident in both the annual rainfall on a large spatial scale such as rainfall averaged over the entire country (Figure 2-4, left) and for monthly rainfall over more local scales such as rainfall over Zanzibar (Figure 2-4, right). Water resource managers are concerned with both forms of variation. Inter-annual variations reflect variation in the actual availability of water, while inter-decadal patterns indicate chances that there may be wetter or drier than normal periods extending over several years.

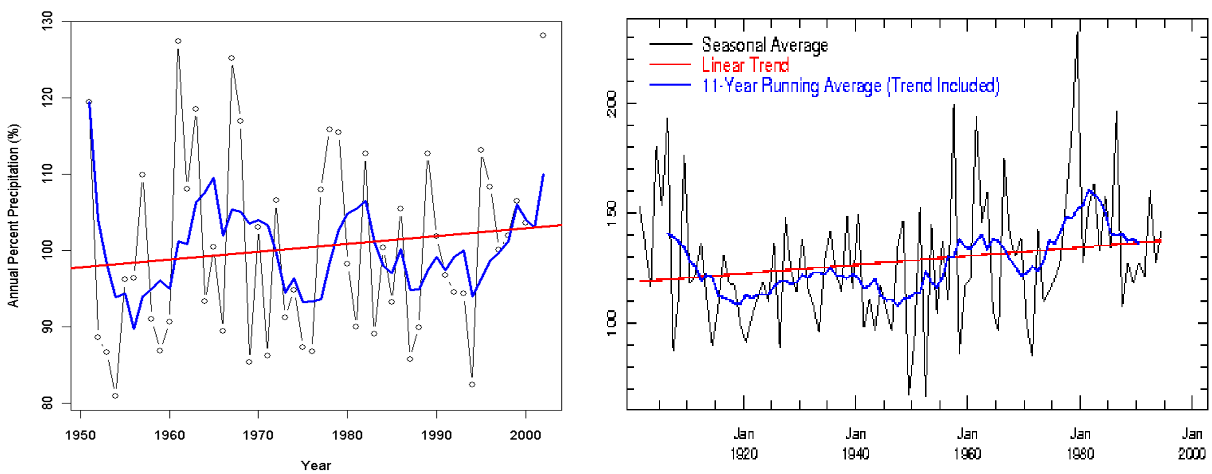


Figure 2-4: (Left) rainfall anomaly (departure of annual rainfall from the 1961-1990 mean annual rainfall expressed as a percentage) averaged across Tanzania. (Right) Monthly precipitation at Zanzibar (1901-1995). For both the blue line depicts the 5-year moving average while the red line indicates a linear trend (insignificant here). [Data Source: ClimateWizard]

Time series plots of rainfall illustrate consecutive years of low or high rainfall which can result in extreme events like droughts or floods, such as the wet years 1935-1940 followed by a drier period in 1941-1946 (Figure 2-4 right). The blue line indicates the 11-year running average, suggesting decadal periods of high rainfall that are specially marked from 1959-1970 and then from 1970-1990. Again, note that the inter-annual variation in monthly rainfall maxima and minima (peaks) is much higher than inter-decadal variation.

Temperature

Tanzania has a variety of temperature regimes (Figure 2-5 left). Mean daily temperature on the humid coasts ranges between 24°C - 34°C, in the central plateau between 21°C - 24°C, and in the highland areas between 15°C - 20°C depending on the elevation. The regions differ markedly in seasonal variation, with little difference between summer and winter on the coast (2-3°C), while larger seasonal differences in the interior (8-12°C). Generally, the hottest months are December to February while the coolest months are June to August (GoT 2003).

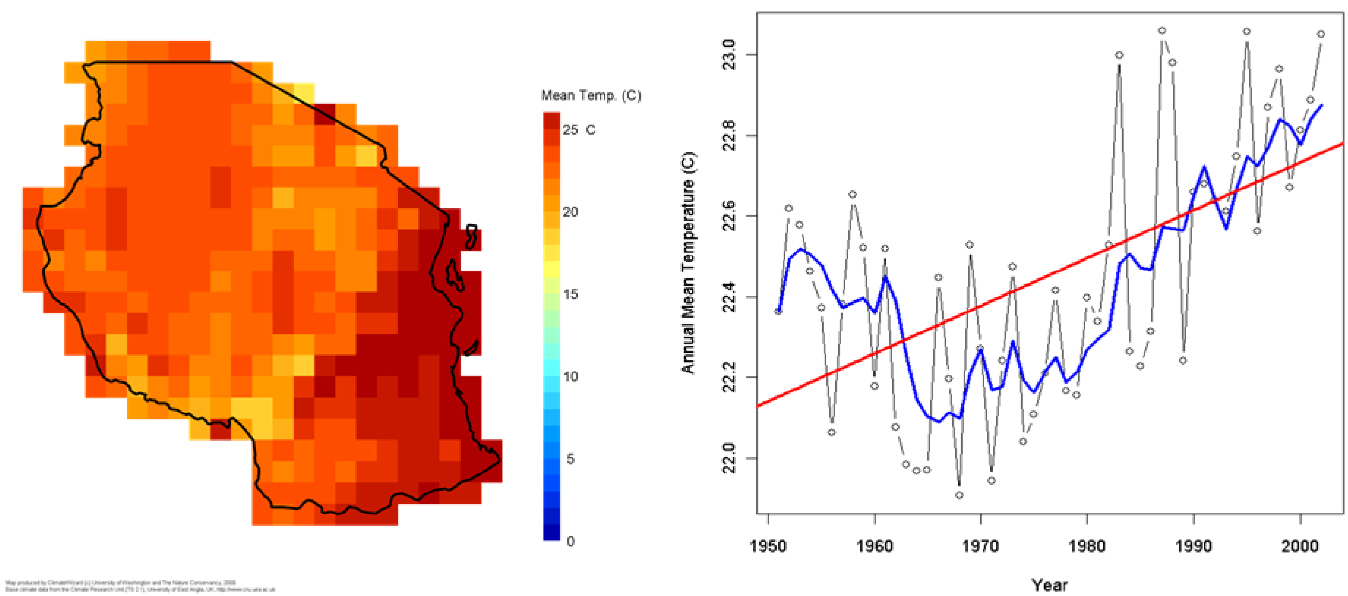


Figure 2-5: (Left) Annual mean temperature averaged over 1951 – 2002 at 50 km grid scale across Tanzania. (Right) Annual mean temperature across Tanzania during 1950-2002. [Data Source: ClimateWizard]

Globally, the average annual temperature has been increasingly rising over the past five decades, and Tanzania is no exception. Images of the shrinking glacial ice cap on Mount Kilimanjaro have emerged as an iconic representation of glacial melting. Figure 2-6 indicates that the interior plateau and highlands of Tanzania have been warming at a faster rate (trend up to 0.02 °C/year) than the coast which is tempered by the presence of the Indian Ocean.

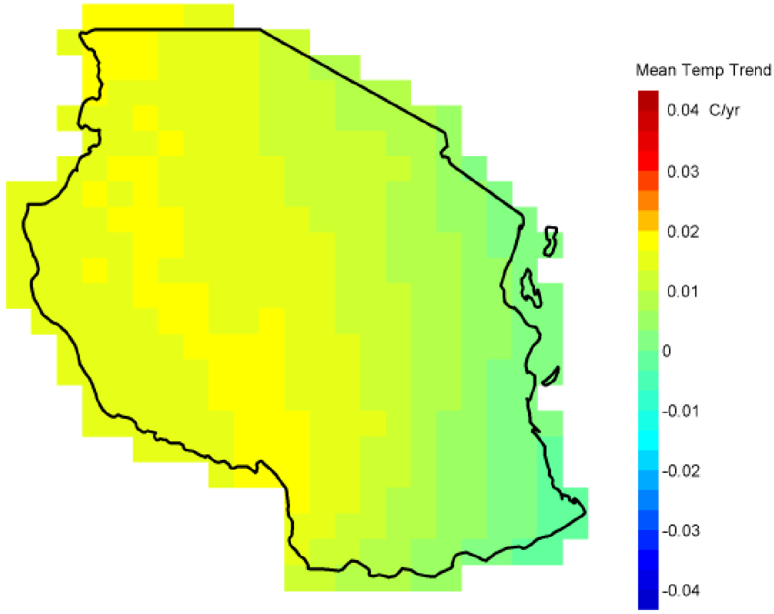


Figure 2-6: Mean annual temperature change trend (°C/year) over 1951-2002 for Tanzania [Data Source: ClimateWizard]

2.2.2. Climate of the Wami/Ruvu Basin – the past fifty years

The Wami/Ruvu Basin encompasses a stunningly wide variety of ecosystems that are governed by different climatic regimes prevalent in the basin. Examples of these ecosystems include: evergreen montane cloud forests, lowland evergreen broadleaf forests, deciduous *miombo* woodlands, savanna, freshwater wetlands, mangroves, and coral reefs. The availability of water and fertile land makes this region Tanzania's breadbasket. At the same time, the presence of major urban, industrial, educational, financial, political, and international tourism centers makes this region host the economic powerhouse of Tanzania. Given the role water plays for ecosystems and in every one of these sectors, this study analyzes the links of past and future climate projections with water resources for the Wami/Ruvu Basin.

Rainfall is a significant climate factor in the Wami/Ruvu Basin. The main economic activities in the Basin are agriculture, livestock, and forest production, which are all highly vulnerable to the timing, amount, and distribution of rainfall. The high levels of biodiversity and endemism in the ecosystems of the EAM, Mikumi, and Saadani National Parks are also intricately connected with rainfall. Air temperature is another climate parameter affecting economic activity that is especially significant in the dry season. There also is a close link between air temperature and saturation vapor pressure of water that in turn influences rainfall (Allen and Ingram 2002). The widespread concern over increasing uncertainty in the timing of rainfall makes imperative to understand both seasonal and spatial climatic patterns, and how they may change.

Examining the climate of a region requires firstly to consider the seasonal and inter-annual variation in current climate (Jack 2010). Rainfall and temperature records in the recent past are examined for seasonal patterns, spatial patterns and inter-decadal patterns. An understanding of past and current climate forms the basis of interpreting climate predictions in the near future. This knowledge can then be utilized in natural resource as well as sectorial management plans to create adaptive strategies safeguarding climate-sensitive economic activity against floods, droughts, and related problems. In addition, there are other factors such as fires and the spread of infectious diseases (Patz 2005) that are linked to climate variability.

Rainfall is strongly affected by dynamic systems of pressure and wind patterns that operate on larger spatial scales, from regional to inter-continental. Hence it is instructive to examine available literature on climate patterns for Tanzania, predominantly over the latter half of the 20th century.

The Wami/Ruvu Basin witnesses a wide range of rainfall and temperature regimes, broadly falling under coastal (humid), EAM block (high rainfall and altitude-dependent temperature), and the interior western highlands (arid, with high seasonal temperature variation). The headwaters for both the Wami and the Ruvu Rivers are located in the EAM. Because of their elevation the EAM consistently experience the heaviest rainfall in the basin (>2000 mm annual), twice the amount of the Indian Ocean coast (1000mm), thrice the amount of the lowlands (Dakawa ~700mm), and four times the amount of the semi-arid region (~500 mm). Both rivers then flow through wetlands, farms, and savanna woodlands to the Indian Ocean.

Precipitation

Rainfall in the Wami/Ruvu Basin is strongly influenced by global climate cycles such as IOD and ENSO (as discussed in section 2.2) as well as local topography and land use. Heavy and long rains (*Masika*) prevail from March to May while short rains (*Vuli*) occur from October to December, the timing of which depends upon global circulation patterns and varies year to year (Ngana *et al.* 2010). The location of the Wami/Ruvu Basin lies within the meteorological transition zone of Tanzania, between the northern bimodal and southern unimodal rainfall regimes. As a result, the river flow regime varies between slightly bimodal in some years like 1966-1967 with abundant *Vuli* rains to typical unimodal in other years, particularly dry years like 1972-1973 with La Niña related failed *Vuli* rains (Valimba 2007). The dry season (*Kaskazi*) occurs from July to October.

Spatial heterogeneity - the influence of basin topography

The topography of the basin ranges from flat low-lying land along the coast to the interior plateau with an elevation of 500-1000 m, and the EAM, scattered between the coast and the highland plateau, rising up to 2600 m above sea level in the Uluguru Mountains and up to 2300 m in the Nguru Mountains (Yanda and Munishi 2007, Gomani *et al.* 2010). Moisture-laden winds blowing westward from the Indian Ocean lose much of their moisture over the EAM in the form of orographic precipitation when forced to rise and undergo adiabatic cooling. The western part of the basin lies in the rain shadow and is thereby semi-arid, as seen in Figure 2-7. The annual rainfall is around 550-750 mm in the western semi-arid highlands near Dodoma and 900-1000 mm in the central areas near Dakawa and in the estuarine and coastal areas (Nobert and Jeremiah 2012). The EAM (Ulugurus and Ngurus) witness a mean annual rainfall over 1500 mm (Mwandosya *et al.* 1998, Bracebridge 2005), and the eastern windward slopes get > 2500 mm with almost some rainfall every month produced from cloud condensation (Ngana *et al.* 2010). Communities living in mountain villages located below cloud forest-covered mountain catchments in the Ngurus mention that springs, which are their main sources of water, run through all the year.

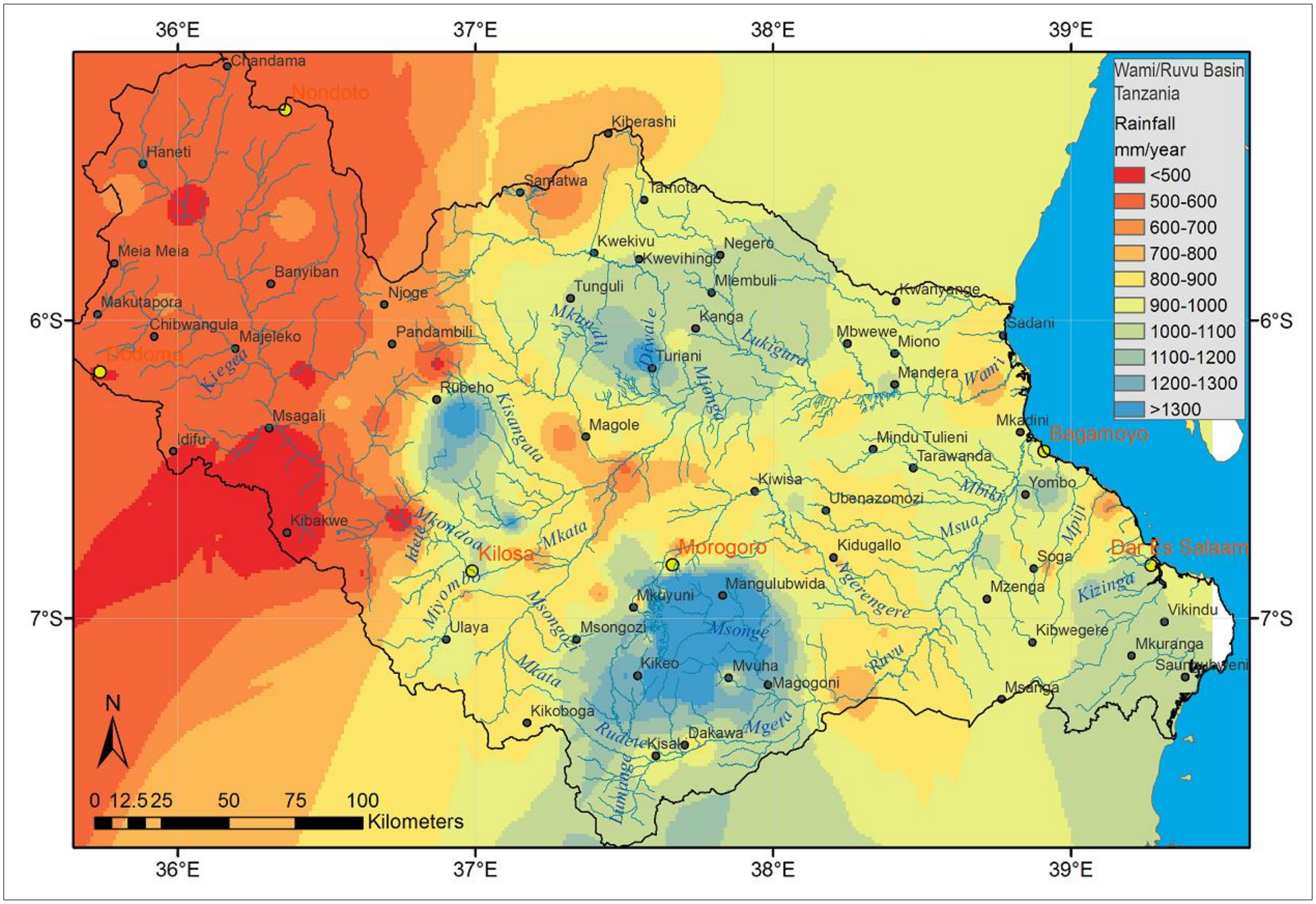


Figure 2-7: Rainfall distribution in the Wami/Ruvu Basin, depicted as isohyets from rainfall station data (1962-2011). [Data Source: WRBWO]

This spatial rainfall pattern is evident in Figure 2-7 that depicts isohyets generated from rainfall monitoring station data collected over 5 decades. The arid zones are in brown while high-rainfall zones are in blue. This spatial pattern is also seen in Figure 0-1 that utilizes the CRU TS2.0 historical dataset (see Annex 2), representing the annual precipitation over the available data from the period 1961 to 2002, spatially homogenous over a 50 km grid scale. The general spatial patterns of rainfall in the Basin are also evident in this projection, such as higher rainfall over the Eastern Arcs Mountains (Ulugurus and Udzungwas, the latter in the Rufiji Basin further south) and the coast, with the lowest rainfall in the western part of the Basin. Note however that the squares represent 50km * 50 km, hence high rainfall in the Ngurus which occupy a much smaller area than the Ulugurus, gets averaged out with lower rainfall in the surrounding lowlands, and therefore does not appear to have as high a rainfall as the Ulugurus.

Figure 2-8 depicts the annual rainfall averaged over 1901-2010 that is available from different rainfall stations across the Basin, indicating a wide range from 500 mm to over 2500 mm. The spatial heterogeneity in basin rainfall is also evident on a monthly time scale (Figure 2-9), which shows the monthly rainfall at 42 stations. Monthly rainfall at each station has been averaged over the time period of available whole-year data (with no missing data). Many stations have data going back to the 1950s with some stations as far as 1901; thus indicating the magnitude of seasonal and spatial rainfall variation over the 20th century.

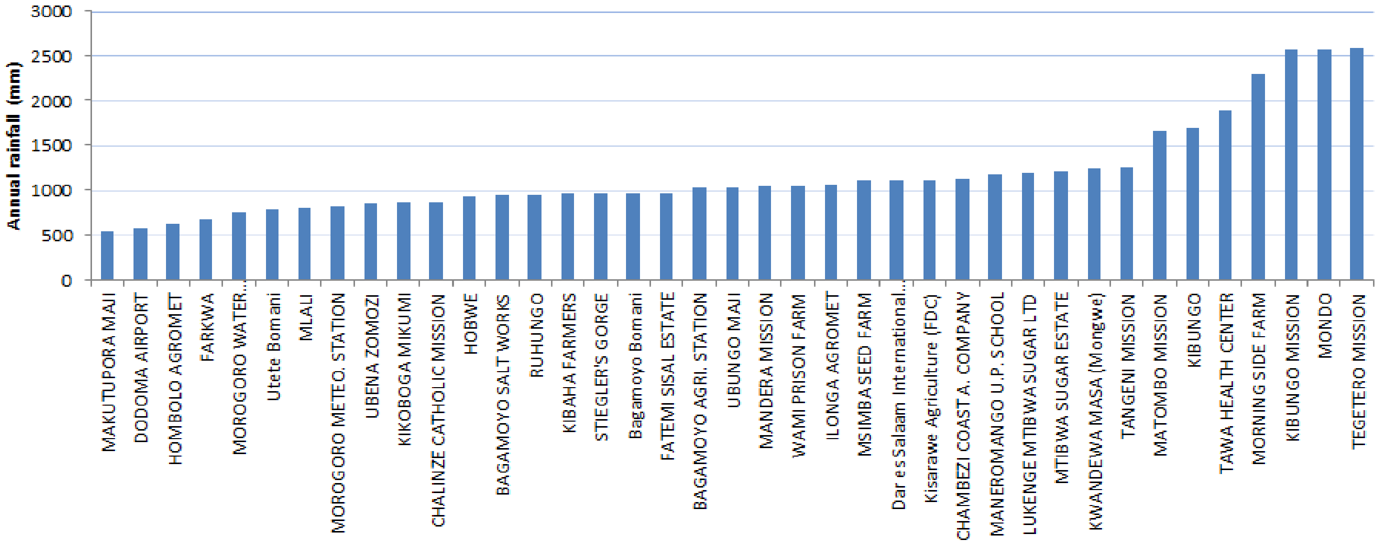


Figure 2-8: Rainfall across the Wami River Basin (1901-2010). [Data Source: WRBWO]

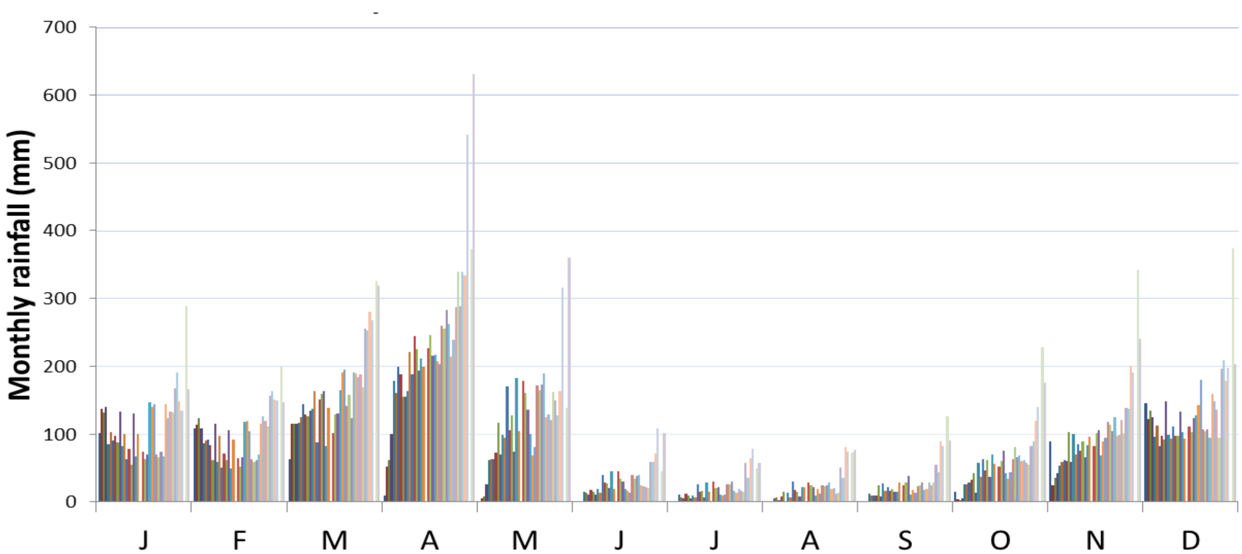


Figure 2-9: Monthly rainfall across the Wami River Basin averaged for the period 1901-2010. [Data Source: WAMI/RUVUBWO]

Figure 2-10 displays annual rainfall at five stations in the form of time series. Stations vary in the periods of available data. The years with missing data have been left out, which explains the gaps in the time series. The five stations were chosen to represent the Basin rainfall gradient – Dodoma in the semi-arid west, Morogoro City and Futama Sisal Estate in the central Wami/Ruvu Basin, Morningside (1200 masl. up in the Ulugurus) and Bagamoyo on the coast by the Indian Ocean. It is clear that the amount of rainfall recorded at Morningside (in orange) is much higher throughout the almost five decades of data collection as compared to the other stations, while Dodoma (in red) has consistently the lowest rainfall.

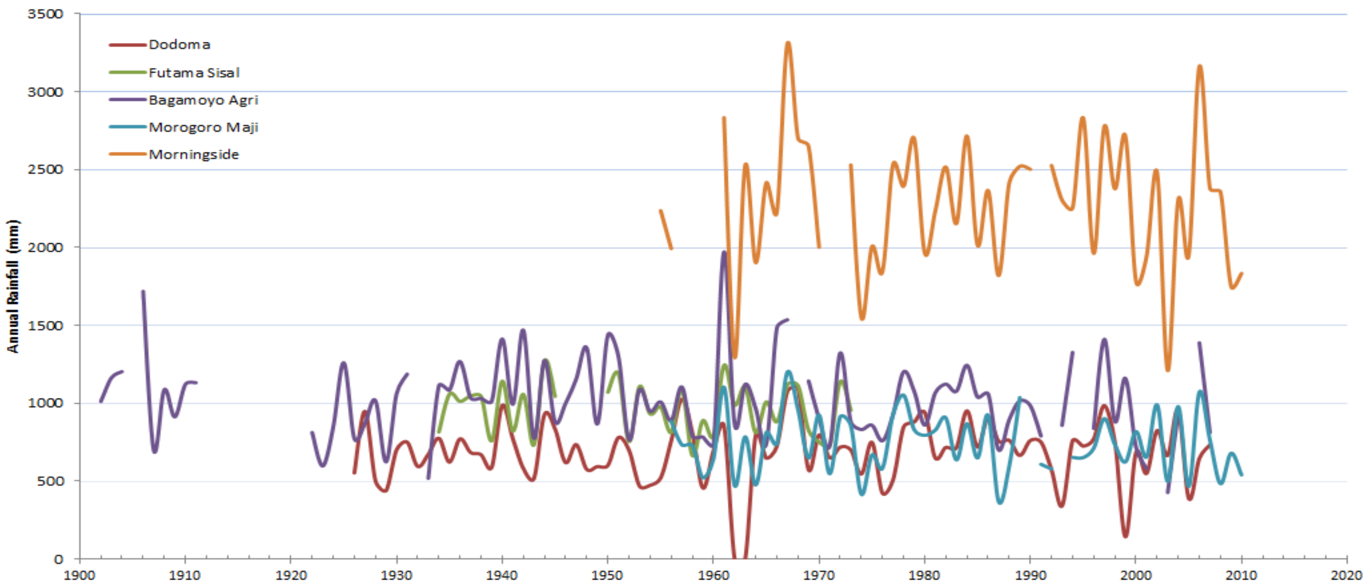


Figure 2-10: Time series of annual rainfall from 1902 – 2010 as available for 5 stations in different rain zones of the Wami/Ruvu Basin. [Data Source: WRWBO]

Interannual differences - the influence of climate teleconnection patterns

There is substantial variation in annual rainfall from one year to another. This inter-annual variation in annual rainfall is evident in Figure 2-10 for each of the five rainfall stations. By examining the increases and decreases in rainfall in the individual time series, it can be seen that most of the peaks (increases) and troughs (decreases) happen at the same time for all five stations. This pattern indicates a basin-wide rainfall increase or decrease in annual rainfall that is caused by some regional forcing effect.

Figure 2-11 depicts the annual rainfall time series 1901-2002 (the dots) averaged spatially over the Wami/Ruvu Basin along with a five-year moving average shown as a blue line[1]. Interannual rainfall difference can be 400-500 mm and as high as 700 mm between 1958 and 1960 and even higher in the EAM (~1200 mm at Morningside station, Figure 2-10).

[1] The figure on the left depicts the annual rainfall time series from 1901-2002 (the dots) averaged spatially over the Wami/Ruvu Basin along with a five-year moving average shown as a blue line. The moving average for each year is the average of 5 years centered around that year (two years prior, the year in focus and two years ahead). Moving averages make it easier to visualize the periodic fluctuation of annual mean precipitation. The fluctuation in this case appears to be shortening from a 35-year cycle earlier in the 20th century to a 20-year cycle. The amplitude or approximate difference in inter-decadal periodicity in precipitation is about 200-300 mm. The figure on the right is the difference of the rainfall in a year from the mean rainfall calculated over a certain range of years. This is called the rainfall departure and is expressed as a percentage. Blue bars indicate annual rainfall in a certain year being more than the mean over the period, while red bars indicate the opposite, that is, annual rainfall in a particular year being lower than the period mean annual rainfall.

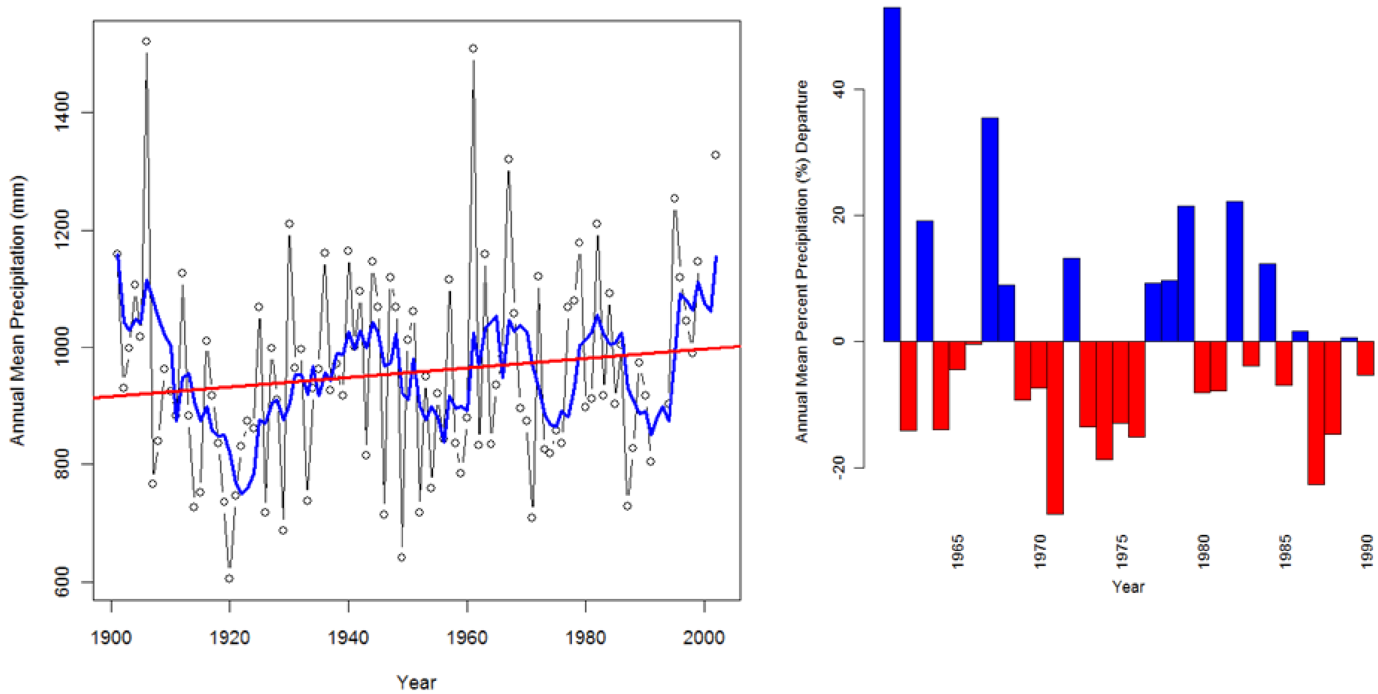


Figure 2-11: (Left) Annual rainfall time series from 1901 to 2002 for Wami/Ruvu Basin. (Right) Rainfall anomalies during the period 1961-1990. [Data Source: ClimateWizard]

Another way to visualize the variation is to depict the departure of a particular year's rainfall from the average rainfall over a certain period. Figure 2-11 (right) shows this departure from a baseline average over 1961-1990. There are certain periods where the rainfall is consistently below the mean rainfall baseline value, e.g. the 1969-1975 period in this Figure. Except for 1972, this long period of below-normal rainfall can indicate conditions of prolonged drought that is often associated with La Niña phase in the Pacific.

The seasonality and timing of rainfall events differs within the basin, on account of the Wami/Ruvu Basin lying along the climatic convergence zone. **Figure 2-12** the average quarterly rainfall at a 50 km grid scale. Between March and May, the coast and the EAM witness the heaviest rainfall, while the semi-arid Dodoma region sees more rainfall in the period December – February. It is also remarkable that between December and February, the most arid areas in Tanzania receive more rainfall than the Bagamoyo coastal region. The EAM continue to receive the highest rainfall in the basin every quarter. However, spatially averaging over a region (in this case 50 km grid) can mask the higher or lower interannual variability that might be inherent in certain locations as seen in Figure 2-10.

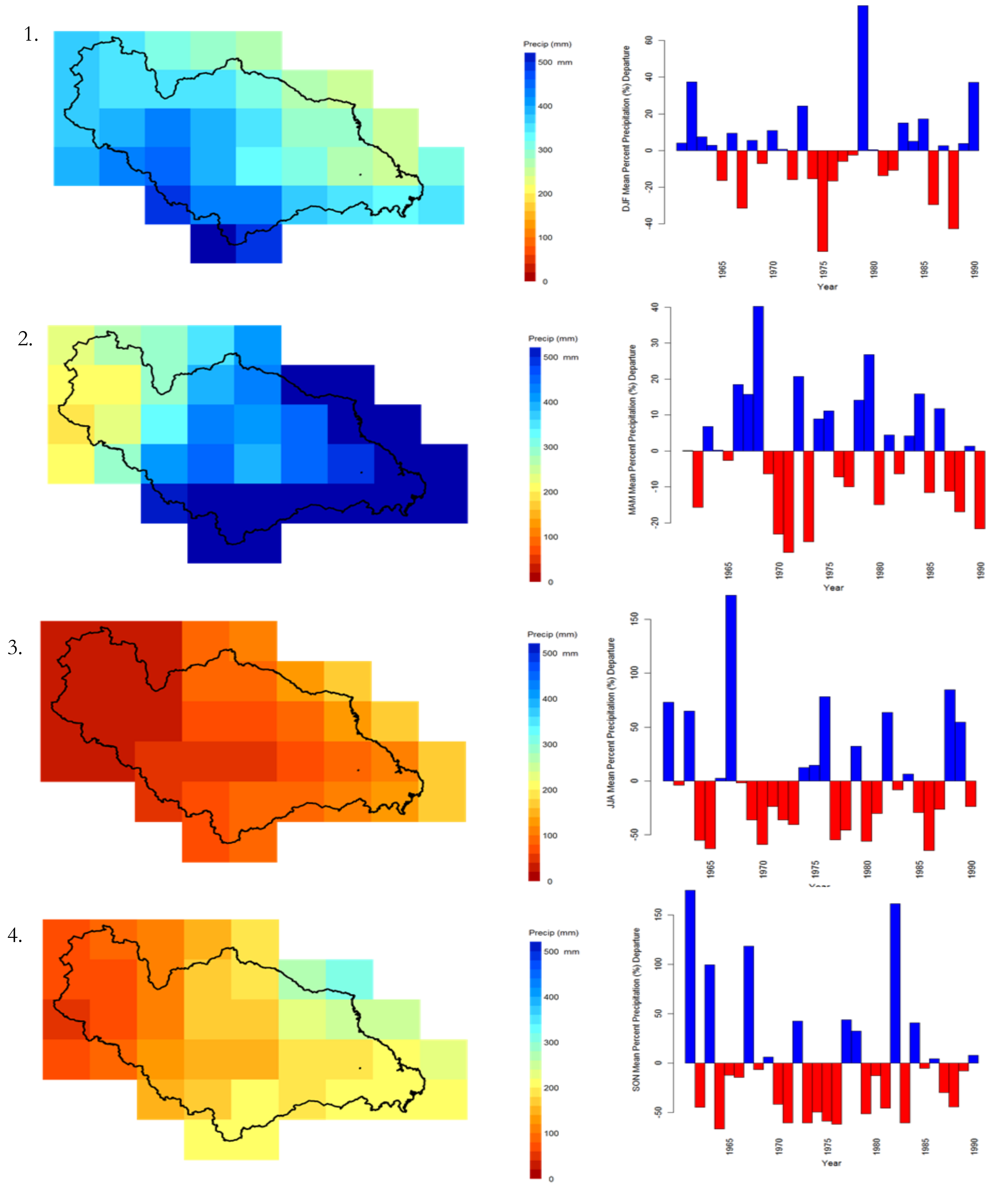


Figure 2-12: Mean seasonal precipitation averaged over 1961-1990. (Left) Pattern at a 50 km grid. (Right) Mean percent precipitation departure. (1) December-February (2) March-May (3) June-August (4) September-November. Data Source: ClimateWizard]

Temperature

The annual mean temperature varies spatially across the Wami/Ruvu Basin as seen in Figure 2-13 ranging between 22°C in the interior (lighter squares) and 26 °C in coastal areas (deeper red squares). The EAM that reach up to 2600 m have considerably cooler temperature (mean annual 12-24°C (Ngana *et al.* 2010) that decreases with elevation. Cooler microclimates allow the cultivation of temperate fruits and vegetables (Yanda and Munishi 2007) such as strawberries commonly grown in the Uluguru Mountains near Morogoro.

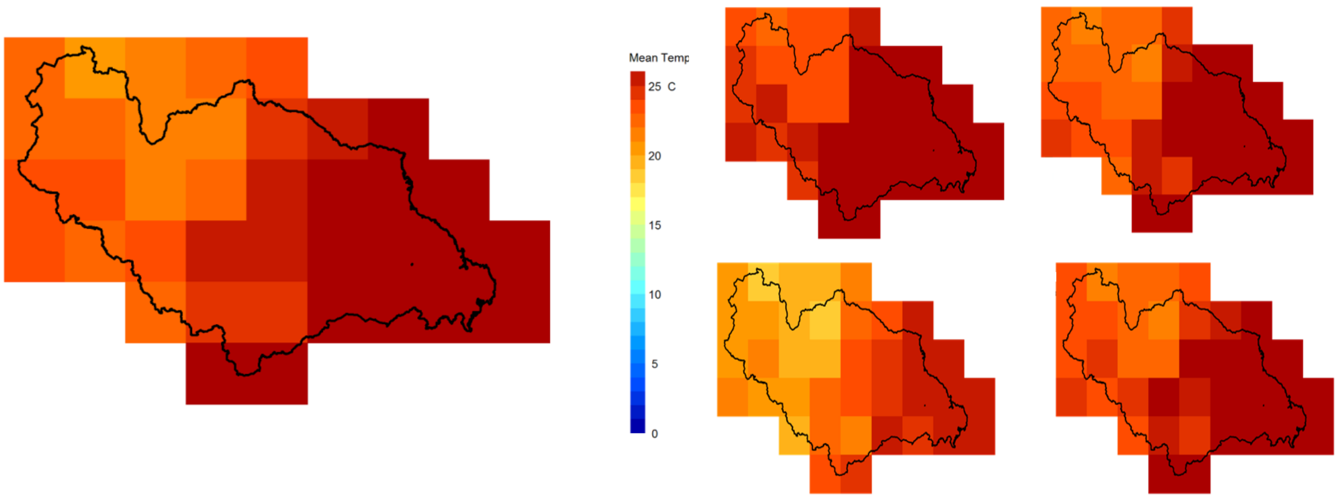


Figure 2-13: (Left) Average annual mean temperature in the Wami/Ruvu Basin (1901-2002) at a 50 km grid scale. (Right) Seasonal patterns in average quarterly temperature (1901-2002). Clockwise from top left: December-February, March-May, June-August, and September-November. [Data Source: ClimateWizard]

The coastal areas have the highest annual temperature. This annual average masks the fact that the humid coastal areas have a smaller seasonal range than the less humid interior (Figure 2-13 right). In the interior, summer daytime temperatures exceed those on the coast while winter temperatures are many degrees cooler due to the higher elevation of the interior plateau as well as absence of the moderating effect of the ocean. For instance, Dodoma is situated at an elevation of 1137 masl and has witnessed a record high temperature of 36 °C between October and February, and a low of 8 °C in July. Also, the diurnal temperature range in the interior in any part of the year can exceed the seasonal range in high or low temperatures (ClimateData EU). Basin wide, the highest temperatures occur in the period December- February (33°C) while the lowest temperatures occur during the period May-July (18°C) (Ngana *et al.* 2010).

Evapotranspiration

Evapotranspiration (ET) refers to the loss of water from the earth's surface into the atmosphere via evaporation from soil surfaces and water bodies, plant canopy, and transpiration by plants. Potential Evapotranspiration (PET) refers to the maximum amount of water that can possibly leave the earth's surface into the atmosphere at a certain level of net solar radiation (incoming – reflected); PET assumes that water supply is unlimited. On the other hand, Actual Evapotranspiration (AET) takes into account water limitation. AET is usually less than PET, but can approach or equal PET under conditions of ample water availability in the soil. Thus AET/PET ratio can indicate the relative status of water availability in a region.

While ET can be measured for grasslands and croplands using lysimeters, there is as yet no way to measure ET over forests and woody vegetation, which can be quite heterogeneous depending on species, vegetation type, and season (Saha *et al.* 2012). There is an array of methods to estimate ET at the landscape scale (Lu *et al.* 2005), each with its own assumptions and uncertainties. These methods include vapor-transport models, eddy flux, tree sap flux measurement, diurnal groundwater measurement, and remote sensing. However, most methods require detailed meteorological and vegetation data that are unavailable in much of the world. The Penman-Montieth (PM) method is widely used in agriculture and recommended by FAO (Allen *et al.* 1998). The method requires four meteorological parameters: net solar radiation, wind speed, air temperature, and relative humidity, which are location-specific, and are thus available only in few places such as weather stations. Methods such as Thornthwaite and Hamon (Hamon 1960) use just air temperature that is available more easily. Zemadim *et al.* (2011) compared PM and Thornthwaite method's estimates with open pan evaporation data, and developed empirical methods for six areas in the EAM and presented a literature review of PET estimates in Tanzania. Another avenue is to use MODIS global ET dataset that has a resolution of 1 km and is obtained by validating remotely sensed spectral data with eddy flux towers (www.modis.org). Figure 2-14 shows MODIS estimates of actual ET for the Wami/Ruvu Basin while Figure 2-15 shows PET calculated values.

At certain times of the year AET can be higher than rainfall in the Wami and Ruvu Basin lowlands, especially in irrigated farms and wetlands where Penman-Montieth PET has been reported in the range of 2000 mm/year. AET is expected to be lower than rainfall in the EAM, due to perennial cloud cover and high humidity that can lower the evaporative energy demand. However, forested slopes have a higher leaf area index than lowland savannas and hence can have higher transpiration. PET estimates in the EAM have been reported in Mwandosya *et al.* (1998) as being 1600 - 1800 mm/year in the Uluguru Mountains, while Zemadim *et al.* (2011) obtained PM estimates of 1500, 2000 and 2400 mm/year for the north-eastern, southern and central EAM, respectively. Figure 2-14 indicates the highest AET occurring in the EAM as well as river valleys, and the lowest AET in the western semi-arid Dodoma region. Actual ET in the semi-arid Dodoma region is less than PET, about 200-700 mm (Zemadim *et al.* 2011), where water scarcity limits the amount of ET. AET in the central part of the Wami Basin (Dakawa) is close to PET due to the existence of wetlands and shallow groundwater table, which imply that water is not limited over much of the year. However, this can change with greater use of water resources, especially the use of groundwater for irrigation. The AET in the Ulugurus and Ngurus can be expected to be close to PET owing to the high moisture status of the region.

It is to be noted that while annual ET figures are useful for annual water balances, land cover change and plant phenology can lead to seasonal changes in ET at weekly and monthly scales. Therefore, ET data should be examined at time scales that are meaningful for any particular analysis such as crop water requirements or monthly water balance.

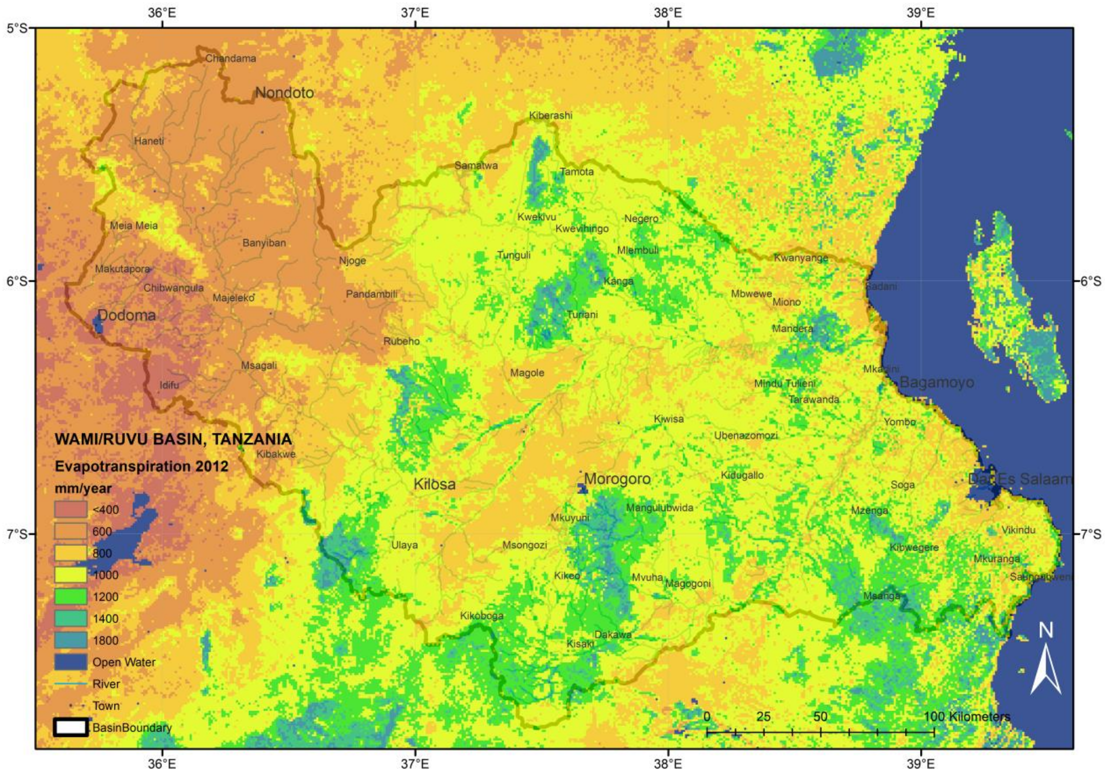


Figure 2-14: AET estimates for 2012 from MODIS Global ET dataset for the Wami/Ruvu Basin at a 1 km resolution. [Data Source: MOD16 Global Terrestrial Evapotranspiration Data Set]

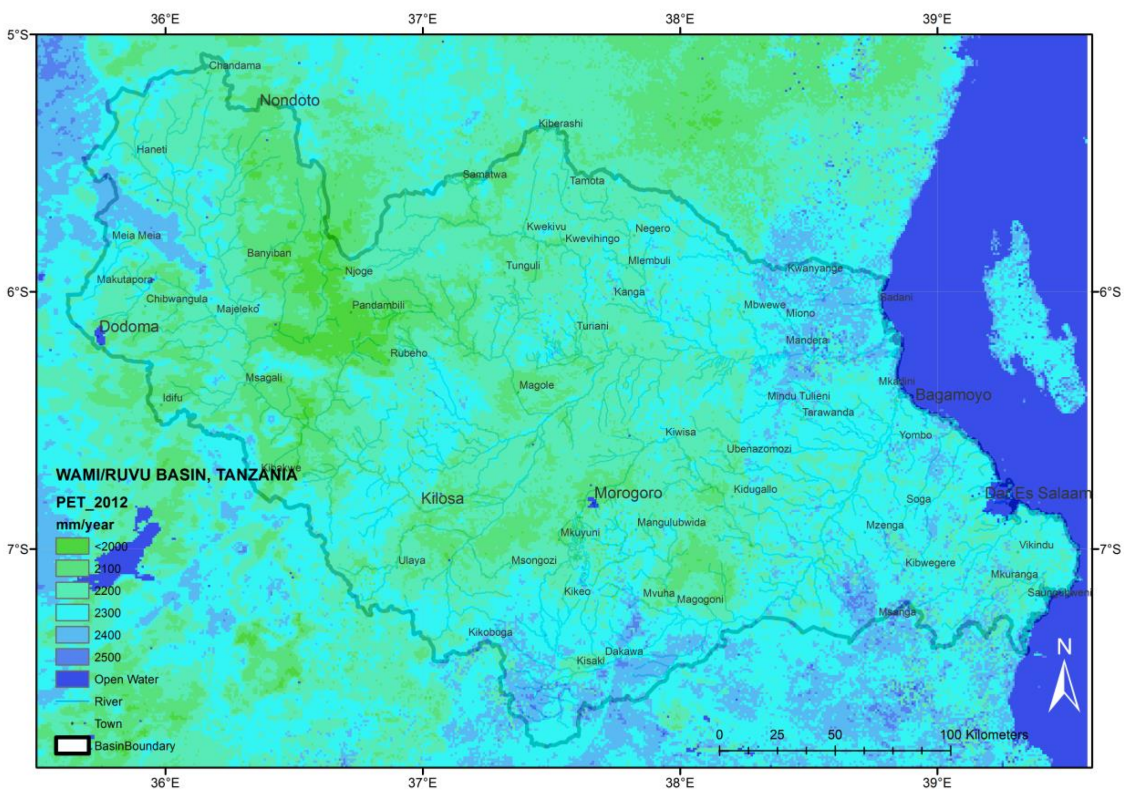


Figure 2-15: PET estimates from the MODIS Global ET dataset for the Wami/Ruvu Basin. [Data Source: MOD16 Global Terrestrial Evapotranspiration Data Set]

2.3 Climate change projections in Tanzania and in the Wami/Ruvu Basin

2.3.1. Climate forecasting procedure - a note on uncertainty

Climate is determined by the interaction of solar energy, air pressure, wind and ocean currents, water availability, topography, and land cover. Changes in atmospheric pressure half a world away affect the dynamic equilibrium of winds and currents, which in turn affect the climate in a region; this linkage is extremely complex and not well understood. This uncertainty is carried over to predictions. Climate models try to model the various physical processes that govern climate, and differ in the ways they do so. For instance, there is a fair amount of uncertainty in how to estimate evapotranspiration (ET) at the landscape level where woody vegetation is present. Hence models differ in the exact processes they consider. Furthermore, models need to be calibrated so that their predictions are close to reality; this is usually done by adjusting values of the parameters in their equations so that their predictions for a period in the recent past resemble actual data over that period. However, while forcing models can tune their predictions closer to historic reality, there is no way to ensure that such historic relationships will hold in future (e.g. Rahmstorf 2010).Temperature is relatively straightforward to predict as it is based upon an energy balance of a region. Precipitation, on the other hand, is much more difficult to predict, as it incorporates numerous processes that, as mentioned, are not well understood, or are interlinked in a complex web of feedbacks. This can be illustrated, for example in the projections for the Ruvu Basin based upon 12 GCMs being run under the A2, A1B and B1 emission scenarios and presented by the Climate Change Knowledge Portal of the World Bank. While for temperature projections, all models agree on an increasing trend in mean annual temperature, there is high variability amongst the models in relation to precipitation predictions.

General Circulation Models (GCMs), also called Global Climate Models, constitute the foundation of climate prediction (Jack 2010). These models divide the earth's surface into a grid, typically at 2.5 degree latitude by 2.5 degree longitude. For each grid cell, models perform an energy balance by considering net solar radiation, wind speed, relative humidity, temperature, and different greenhouse gas concentrations that trap heat. This allows forecasting climate (temperature, precipitation, ET) under different greenhouse gas emission scenarios (IPCC 2000). These results are uniform over the grid cell, a large area (typically 300 by 300 km), and actually work better at larger scales such as 500-1000 km (Jack 2010). However, such a large area can have big differences in climate. Therefore, in order to capture climate variability within such a large area, the model outputs have to be scaled down to include local factors that affect climate, including topography and land cover, by a process termed downscaling. Most human activities such as agriculture and water resources management occur at scales far smaller than a 300 km grid. Hence, downscaled climate predictions, even at a 50 km resolution, must be looked at as an average for a 2500 sq km area that glosses over local (topography-related) differences in climate that may exist (USAID 2007). Further downscaling to scales around 10 km and even upto 1 km are possible via using existing local meteorological and hydrological data to empirically calibrate the regional climate models (Platts *et al.* 2014).

For this study, climate predictions for the Wami/Ruvu Basin were obtained from an ensemble of GCMs run at the A2 greenhouse gas emissions scenario[2], and then downscaled to a 50 km grid. The climate models used (Table 2-1) are a subset of 16 from the 22- member ensemble used by the IPCC Fourth Assessment Report, published in

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[2] The A2 emission scenario, or the "business as usual" scenario assumes that no significant changes happen in consumption patterns and resources use to reduce emissions significantly from current rates. This scenario was selected because given the current inability of policymakers and society to curb emissions and consume fewer resources, and the upward climb of atmospheric CO2 concentration, the high emissions scenario (A2) was selected – instead of the A1B and B2 emissions scenarios. In this way, we are getting current 'worst case estimates,' so as to better prepare solutions that take into account the worst case scenarios.

2007[3].

The web-based platform ClimateWizard (www.climatewizard.org) was used to select and run models and to generate outputs in the form of maps and time series data. An ESRI shapefile for the Wami/Ruvu Basin was used to specify the region for which 16 GCMs were executed to predict temperature, rainfall, PET, AET/PRT, moisture deficit, and moisture surplus for the near future (2014-2040), mid-century (2041-2069) and end of century (2071-2099). See Appendix 1 for details on ClimateWizard. Results were downscaled to a 0.5 degree grid in latitude/longitude from the original 2.5 degree grid (Maurer *et al.* 2009 – Annex 2). In terms of surface area, this corresponds to a 50 km * 50 km grid cell from the original 200-300 km grid cell size of the GCMs. Results for temperature, precipitation, precipitation change, PET, AET/PET, moisture deficit, and surplus are available as single GCM outputs as well as a range of aggregations of the 16 GCMs (low, bottom 20%, bottom 40%, middle, bottom 60%, bottom 80% and high) in map formats. In addition, for individual models these values are plotted against time scale. Temporally outputs are available on a monthly, seasonal and annual scale. Four rainfall seasons were chosen for the further analyses; January–February (JF), the 'long rains' of March–May (MAM), June–September (JJAS) and, the 'short rains' of October–December (OND), as referred to in Matayo *et al.* (2000).

In summary, the following parameters were included in this study:

- Prediction periods: 2014-2050, 2051-2099 (or 2014-2040, 2041-2069, 2070-2099)
- Time scales: annual, seasonal (JFM, AMJ, JAS, OND), monthly
- Scenarios: A2, A1B, B1 (high, medium, low emissions scenario families as per SRES, IPCC)
- General Circulation Models (GCMs): 16 individual models as well as low, middle, high averages of model ensembles.

Table 2-1: List of GCMs that have been used for climate projections for the Wami/Ruvu basin, Tanzania.

GCM	Country	Institution
BCCR-BCM2.0	Norway	Bjerknes Centre for Climate Research
CGCM3.1(T47)	Canada	Canadian Centre for Climate Modelling and Analysis
CNRM-CM3	France	Météo-France / Centre National de Recherches Météorologiques
CSIRO-Mk3.0	Australia	CSIRO Atmospheric Research
GFDL-CM2.0	USA	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory
GFDL-CM2.1	USA	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory
GISS-ER	USA	NASA / Goddard Institute for Space Studies
INM-CM3.0	Russia	Institute for Numerical Mathematics
IPSL-CM4	France	Institut Pierre Simon Laplace
MIROC3.2(medres)	Japan	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)
ECHO-G	Germany	Meteorological Institute of the University of Bonn, Meteorological

[3] It should be noticed that these models have been developed independently by different organizations in different countries, and while they all rely upon currently known principles that affect wind circulation, water, and energy budgets, they differ in the exact manner processes are considered and parameters' values chosen. For further details on these models and results of their evaluation see Randall *et al.* (2007).

	/ Korea	Research Institute of KMA, and Model and Data group.
ECHAM5/MPI-OM	Germany	Max Planck Institute for Meteorology
MRI-CGCM2.3.2	Japan	Meteorological Research Institute
CCSM3	USA	National Center for Atmospheric Research
PCM	USA	National Center for Atmospheric Research
UKMO-HadCM3	UK	Hadley Centre for Climate Prediction and Research / Met Office

2.3.2. Climate projections for Tanzania – a brief review

There have been several studies (GOT 2003, Jack 2010, and McSweeney *et al.* 2011) that have run GCMs at various emission scenarios to predict climate in Tanzania; their results have been quoted by other studies examining the effect of climate change on specific sectors in Tanzania, such as livelihoods (Paavola 2004), hydrology and land use (Yanda and Munishi 2007), coastal ecosystems (Tobey and Mwakifanda 2008), Wami and Ruvu Basins (Ngana *et al.* 2010) and water resources (Noel 2010), as well as in numerous reports on agriculture, climate change, and adaptation.

Temperature

The climate prediction studies (Mwandosya *et al.* 1998, 2002, Jack 2010, McSweeney *et al.* 2011) all reported an expected rise in mean annual temperature within the range of 1.5°C - 2°C by 2050 and around 2°C - 4°C by the 2090s under low (B1) and high emission scenarios (A2) respectively; these results are similar to IPCC's Fourth Assessment for East Africa (IPCC 2007). McSweeney *et al.* 2012 predicted that the highest rates of warming would be in the winter season (June to September) amounting to about 4.8°C.

Figure 2-16 shows predictions for Tanzania developed for this study considering a geographical dimension[4]. The map on the left shows the difference between the predicted annual temperature (averaged over the period 2040-2069) and the average temperature that existed over the period 1961-1990. The western half of the country is predicted to see a rise in the annual temperature by 2.4 °C during the period 2040-2069 as compared to the baseline. Similarly, the map on the right depicts the departure of precipitation prediction for the period 2040-2069 from the mean precipitation over the period 1961-1990.

Both, Jack (2010) and McSweeney (2012), predict an increase in the number of hot days and nights, up to 40% of all days and 68% of all nights by the 2060s and up to 65% days and 99% nights by the 2090s. Conversely, a decrease is expected in the number of days and nights considered cold today, these are expected to become very rare by the 2090s. Hot days (defined as greater than 32°C -Jack 2010) are a variable of interest as they increase heat stress and place extra energy demands in dwellings and industry, affect crops, and can cause shifts in ecosystems and species metabolism, migration, and behavior. Platt et al (2013) describe a study of using a downscaled regional climate model to explore the possibilities in species shifts in the EAM and to explore the hypothesis that species would have to ascend with altitude to keep pace with warming temperatures. While species in the highest forests of the EAM would be expected to have nowhere else higher to go to, Platt *et al.* mention that some species may move downwards or laterally on account of changes in water availability and precipitation.

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[4] Average values of predictions of the 16 models described in Section 2.3.1. are considered.

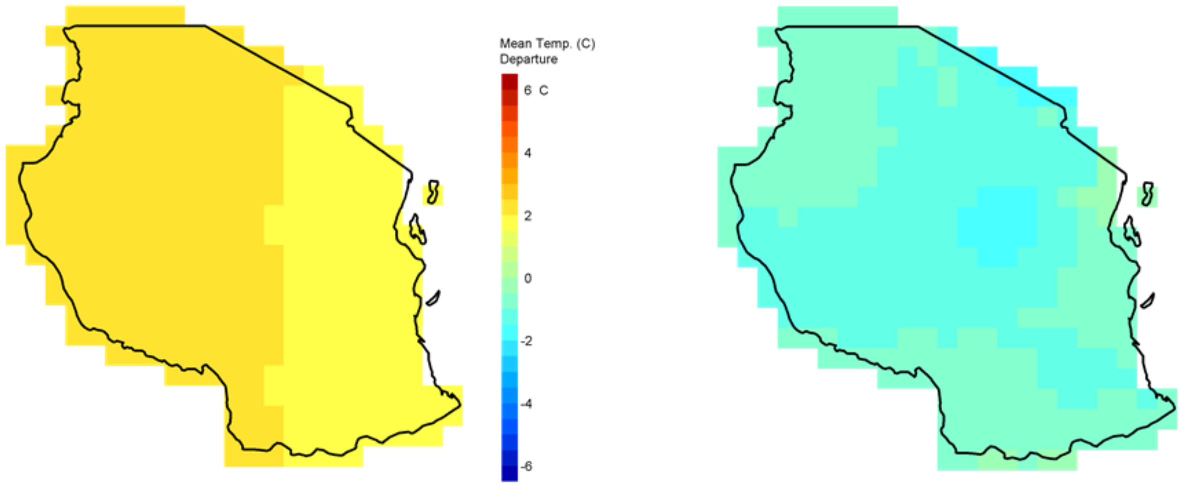


Figure 2-16: (Left) Predicted temperature anomaly (2040-2069) from (1961-1990) by an ensemble of 16 GCMs run at the SRES A2 scenario. (Right) Precipitation anomaly over the same time period. [Data Source: ClimateWizard]

Precipitation

Unlike the models' near-unanimous agreement on forecasting temperature increases, there is no clear consensus on forecasting rainfall amounts. Figure 2-17 shows hindcasted and projected precipitation by 15 widely-used GCMs. While the seasonal pattern (high rain in March-May etc.) is forecast by each model, the amplitude of variation amongst the models is greater than 100 mm/ month in the wet season months – a tremendous variation. This is expected, and is reflective of the far greater complexity of factors that affect rainfall predictions, that lead to different assumptions and parameterization between models. This complexity is also reflected by often contrasting predictions depending on which models and how many models were run. Mwandosya *et al.* (1998) indicate that some parts of the country may receive up to 45% more rainfall under various climate change scenarios and other areas, especially the central region, might receive 5-10% less. McSweeney (2012) found predictions were for a similar increase in annual rainfall across Tanzania. The complexity of predictions increases on a seasonal time scale; McSweeney *et al.* (2012) predicted increased rain in January-February, especially for the south, while increased rain during March-May in the north. June -September would see rainfall increases in the extreme north while decreasing rain in the central and southern areas. The largest increase is predicted for January-February (8-14 mm or 5-7%) by 2060 and 13-23 mm (7-11%) by the 2090s. Jack (2010) also suggested there would be a seasonal shift in rains, with less rainfall early in the season and stronger rains later in the season. These predictions agree with Hulme *et al.* (2001) on projected rainfall changes in East Africa. Paavola (2004) indicates that dry seasons especially in the central semi-arid zone could get longer.

The proportion of total rainfall that occurs in heavy single showers (expressed as the maximum rainfall occurring over 1 day or 5 days) is also projected to increase. For instance, rainfall patterns have changed during the last decade in the Pangani Basin, north of the Wami-Ruvu Basin, with an increased occurrence of high intensity rainfall events along with longer periods of low intensity or no rainfall (Valimba 2004). Such occurrences, together with land use change from forest to agriculture and increased sedimentation of river channels from soil erosion, increase the possibilities of widespread floods. This change from a more homogenous rainfall distribution to a greater discretization of events accompanies an increased uncertainty in onset of rainfall. Preparing for greater uncertainty should be the guiding star of designing adaptive strategies for water resource management at all levels, from basin scale to communities and individuals.

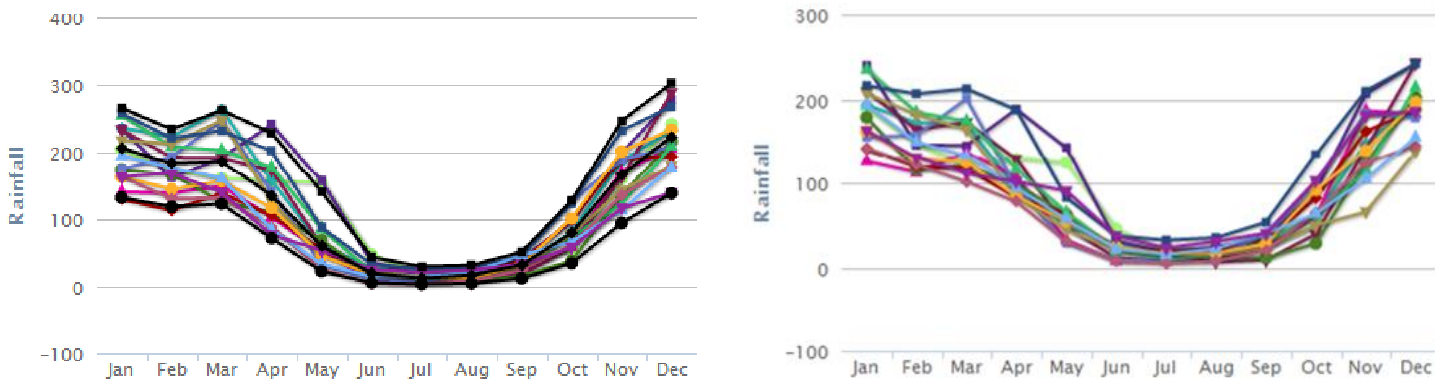


Figure 2-17: (Left) Hindcasted mean monthly rainfall (1980-1999). (Right) Mean monthly projected rainfall (2080-2099) for Tanzania by 15 GCMs. [Source: World Bank Climate Change Knowledge Portal 2014]

River Discharge

Reflecting the uncertainty in rainfall predictions, there is much less agreement amidst GCMs in predictions for runoff or river discharge. Mwandosya *et al.* (1998) predicts increased flows in the Rufiji Basin and decreased flows in the Wami-Ruvu Basin and the Pangani Basin. Noel (2010) refers to two other studies; one study (de Wit and Stankiewicz 2006) projects a rise in perennial drainage to a total of 136% in central Tanzania and 125% in northwest Tanzania by the end of this century; this is contrary to the prediction of decreased rainfall in central Tanzania as mentioned earlier in the section on precipitation. The other study by Strzpeck and McCluskey 2006 as referred to by Noel (2012), suggests that by the year 2050 streamflows nationwide will decrease to be between 80-100% of the period 1961-1990 flows and only 80-90% of the base period flows by 2100. What appears very likely is that the timing of incidence and the distribution of rainfall and river discharge will be changing in unpredictable ways. Thus policymakers and resource managers need to accept high levels of uncertainty in rainfall and runoff in designing strategies and management plans for the worst –case scenario.

Sea level rise (SLR)

There has been a net rise in sea level all over the planet over the past century (Figure 2-18), with a nonlinear acceleration (Hansen 2007) in the rate of rise (global average) from 1.7 mm/year in early 20th century (Church and White 2011) to greater than 3 mm/year (Rahmstorf 2010). While sea levels have risen and fallen up to a hundred meters over the earth's past (e.g. Lambeck *et al.* 2002), the present rise is thought to be accelerated by global climate change that is resulting in increased melting of land-bound ice worldwide as well as the thermal expansion of ocean water from warming of the earth's atmosphere. Estimates of sea level rise (SLR) for a certain rate of warming have been increasing (e.g. Rahmstorf 2010) as the estimated rate of melting of glaciers and the Greenland and West Antarctic ice sheets increase (Figure 2-18). For instance, in the 1990s the West Antarctic ice sheet melting front was thought to be restricted to the seaward ice edge and the exposed ice surface to the atmosphere. In the 2000s, another rapidly advancing melting front was discovered below the ice cap by seawater entering underneath, leading to fears of chunks of ice breaking off into the sea resulting in faster dissolution. Global warming of 4°C will likely lead to a SLR of 1 meter, and possibly more, by 2100, with several meters more to be realized in the coming centuries (Figure 2-18). However, even if global warming is limited to 2°C, global mean sea level is likely to continue to rise on account of lag effects, with some estimates ranging between 1.5 and 4 meters above present-day levels by the year 2300. SLR would likely be below 2 meters only if warming remains well below 1.5°C. It is instructive to note that the atmospheric CO_2 levels have passed the 400 ppm mark, and the last time in earth's history with a similar atmospheric concentration was in the Pliocene, more than 3 million years ago, when the sea levels are thought to be 20-25 meters higher than present (Lambeck *et al.* 2002).

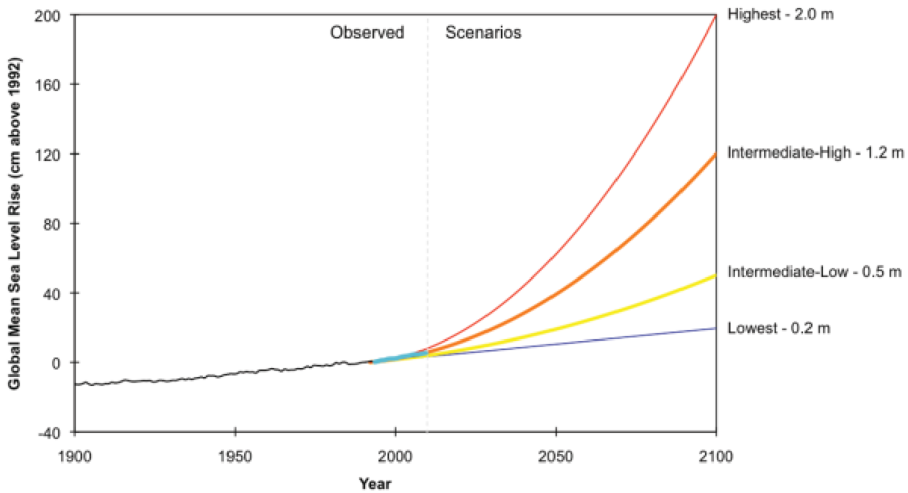


Figure 2-18: Global average SLR from the 1900s and projected SLR. [Source: Parris *et al.* 2012]

As seen in Figure 2-19 SLR is predicted to also vary regionally. For a number of geophysically determined reasons, it is projected to be up to 20 % higher in the tropics and below average at higher latitudes. In particular, the melting of the ice sheets will reduce the gravitational pull on the ocean toward the ice sheets and, as a consequence, ocean water will tend to gravitate toward the Equator (Yin *et al.* 2010). Changes in wind and ocean currents due to global warming and other factors will also affect regional SLR, as will patterns of ocean heat uptake and warming. Thermal expansion of heating sea water also adds to the rise in level. The rate of SLR is not expected to be constant either. Climate teleconnection events like the Pacific Decadal Oscillation (eg..Hamlington *et al.* 2013) raise some part of the ocean while lowering others. Figure 2-20 illustrates the heterogeneity of sea levels accompanying interannual climate variability associated with the ENSO and IOD cycles, as well as longer term changes such as the increase in sea levels in the Western Tropical Pacific due to changes in the Trade Winds. During El Niño years sea level rises in the eastern Pacific and falls in the western Pacific, whereas in La Niña years the opposite occurs (eg Boening 2012).

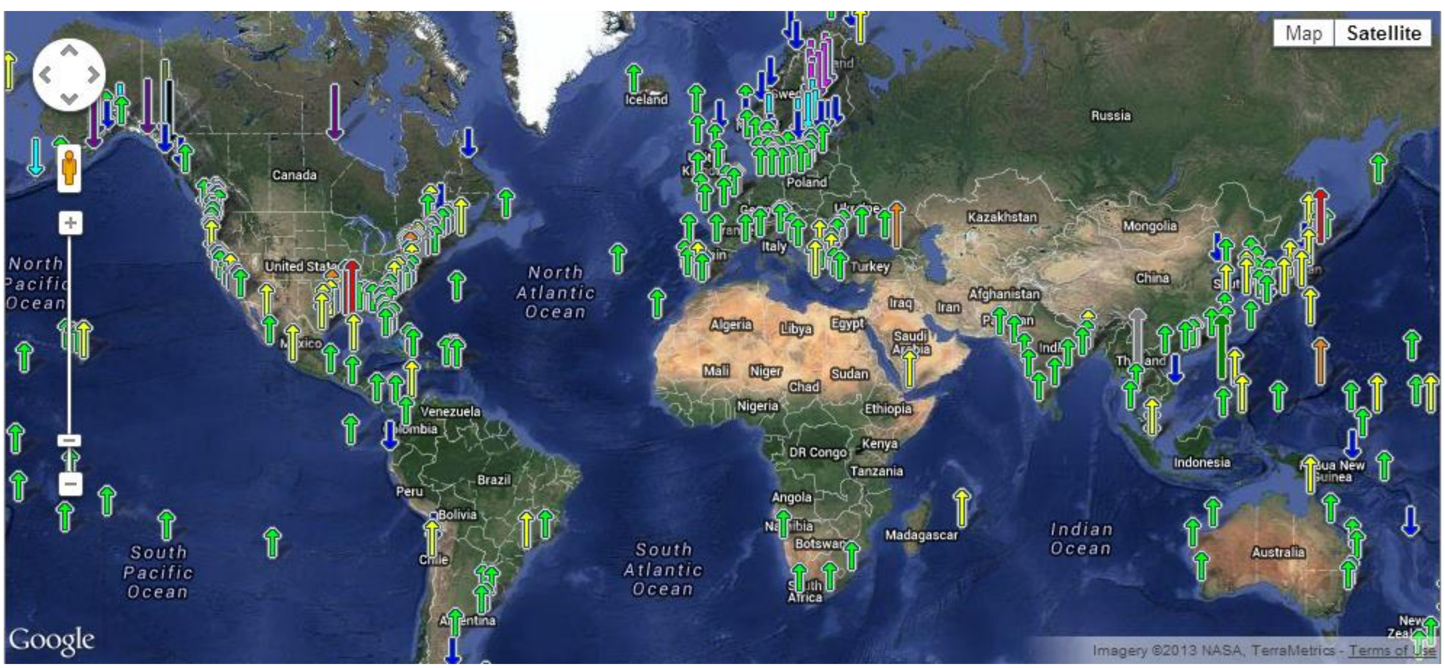


Figure 2-19: Regional variation in SLR in locations according to long-term sea level data sets. Upward arrows indicate that the sea level has risen, while downward arrows indicate a drop in sea level [Source: NOAA/NASA/Google]

It is to be realized that the impacts of SLR are felt ahead of actual inundation of land, by means of seasonal high tides that will reach further inland, sea water intrusion into aquifers that can impact coastal vegetation that depends upon freshwater lenses to survive and mangroves whose salinity tolerance can be exceeded. Seawater intrusion also poses a serious problem to the water supply in coastal settlements in Tanzania (e.g. de Witte 2012), which in most cases would imply abandoning existing wells and sourcing water inland, adding to existing pressure on water resources and transportation costs. Such problems faced by coastal areas of the Pangani River Basin are regularly in the news.

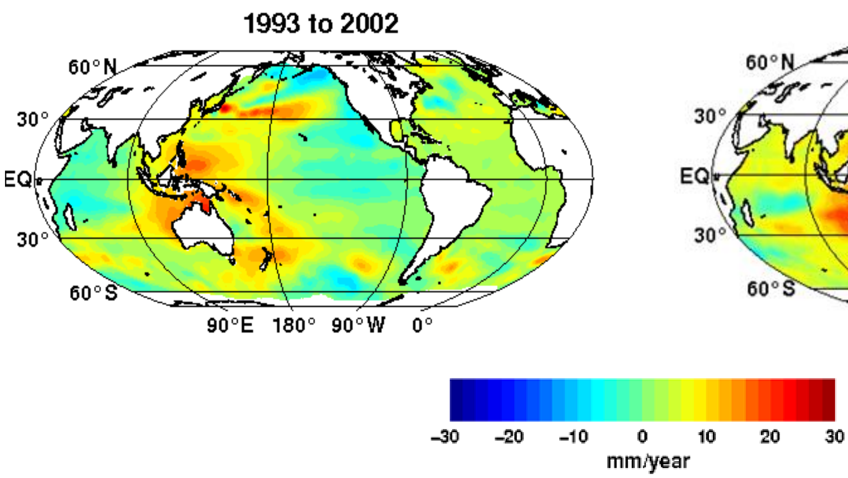


Figure 2-20: Sea levels change with wind and ocean current changes associated with climate teleconnections. [Source: CSIRO]

Even a SLR of 20 cm could increase wave-induced erosion on exposed coasts, such as those to be found in island states, and on ports in the entire region. Furthermore, spring high tides will get higher and lead to the flooding of canals and estuaries, lagoons, etc., which have far-reaching implications for agriculture, coastal ecosystems, and coastal aquifers. The combined effect of land subsidence caused by aquifer compaction following groundwater overextraction (Eggleston and Pope, 2013) and SLR leads to a relative sea level rise that is greater than SLR.

Not enough is known of the geology of coastal Tanzania in order to estimate these local effects with any accuracy (Alusa and Ogallo 1992). Tobey and Mwakifwamba (2008), Agarwala *et al.* (2003), Kebede *et al.* (2010) and McSweeney *et al.* (2012) have reported on the expected impacts of SLR on coastal Tanzania. McSweeney *et al.* (2012) refer to the IPCC Assessment Report (IPCC 2007), which estimates a rise between 0.4 and 0.7 meters by 2100. However, there are many recent reports of a much-increased rate of glacier and ice cap melting (e.g. Rahmstorf 2010), which can increase these estimates to 1-2 meters in Tanzania. In a modeling study, Brown *et al.* (2010) caution that even though other areas of the world such as SE Asia face greater SLR threats on account of extensive low-lying coastal areas, most African countries including Tanzania can be highly vulnerable to SLR given the large and growing coastal population and low adaptive capacity. The intrusion of seawater into water wells along the coast of the Bagamoyo town and the inundation of the Maziwe Island in the Pangani District are evidence of a rise in sea level compounded with decrease in freshwater inflows to the coast.

2.3.3. Climate projections for the Wami/Ruvu Basin

Temperature

Temperature trend: All sixteen GCM predict a definite warming trend over the present century, with a rise in annual temperature averaged over the basin from the current 24°C to 27°C by the 2090s.

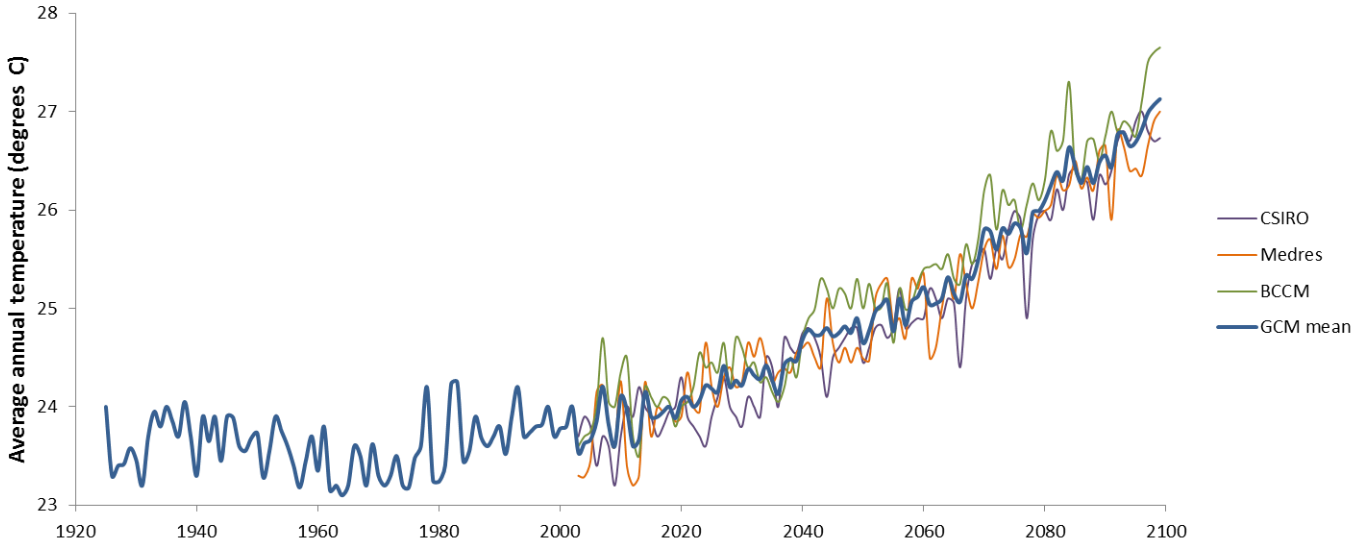


Figure 2-21: Average annual temperature over the Wami/Ruvu Basin (1925 – 2002) and (2003 - 2099): historical temperature (1925-2002) in blue, and predictions from 2003-2099 by 3 GCMs (CSIRO, Medres and BCCM) at the SRES A2 scenario.

Figure 2-22 shows the mean of three randomly selected GCMs as well as the time series of the models themselves. The models differ in their yearly predictions, based upon the individual assumptions (processes modelled, parameters chosen), however, they all indicate an increasing trend in temperature over a decadal scale. It is to be noted that the annual average temperature is just the mean of daily or even hourly summer and winter temperatures over a year; thus, a rise even by a degree indicates a rise in hot days and a decrease in cool days.

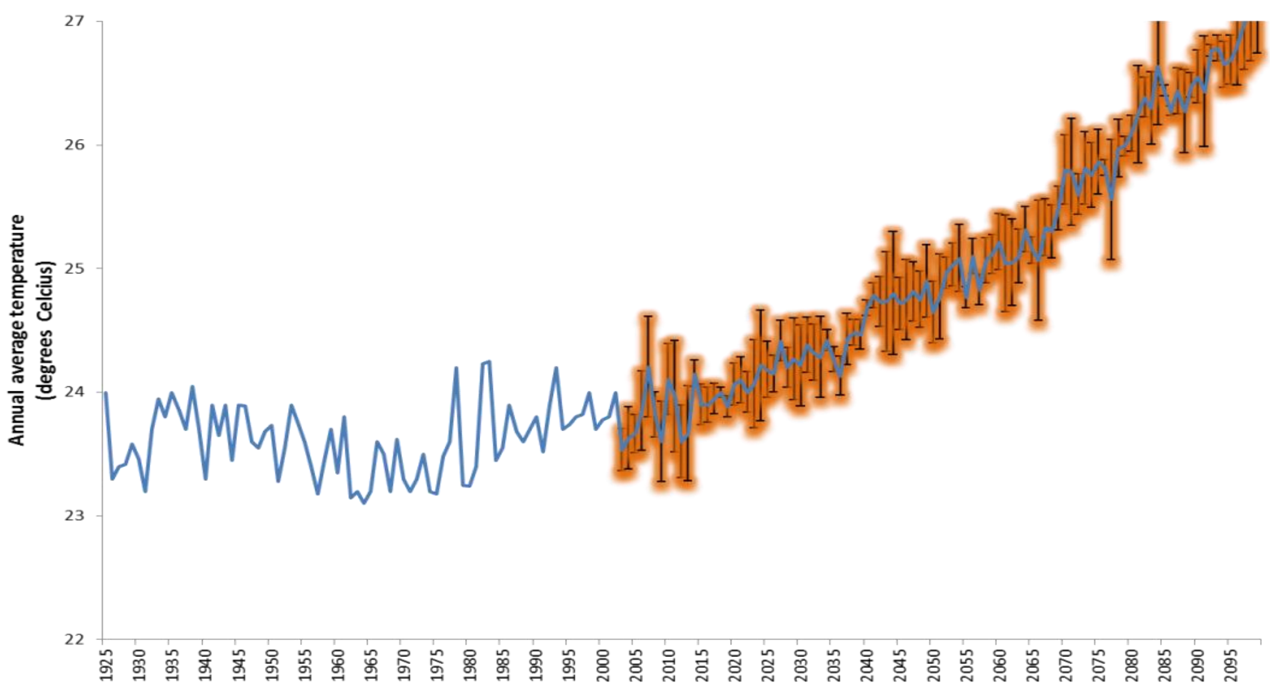


Figure 2-22: Average annual temperature over the Wami River Basin. Historical temperatures from 1925 to 2002 (blue) and predictions from 2003-2099 (orange) by an ensemble of 3 GCMs (CSIRO, Medres and BCCM - orange) at the SRES A2 emission scenario. Error bars signify one standard deviation from the mean predicted value of three models. [Data Source: ClimateWizard]

Spatial

Within the Wami/Ruvu Basin, there are spatial differences in predicted temperature, with the coast having higher annual temperatures than the interior highland plateau and the EAM blocks (Figure 2-23). Part of this spatial difference is accounted for the colder winter temperatures experienced in the interior, due to their location away from the temperate influence of the ocean and the higher altitude (300-1200 m).

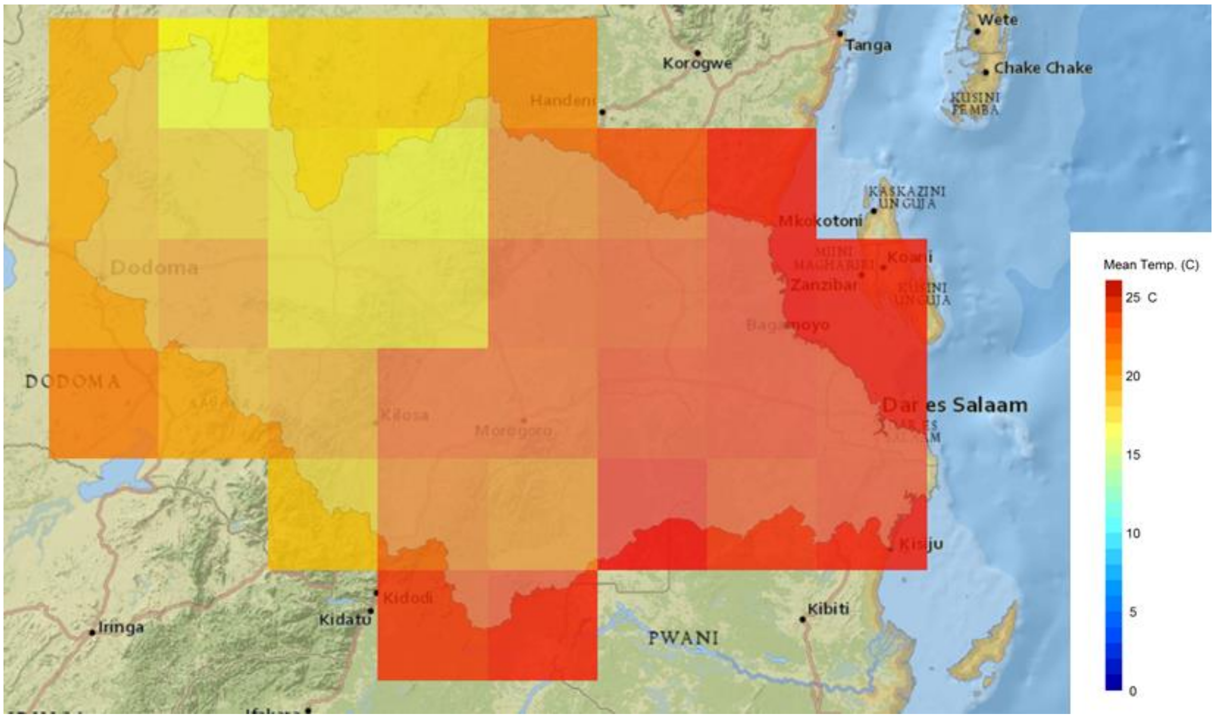


Figure 2-23: Average projected annual mean temperature in the Wami/Ruvu Basin (2014-2050). [Data Source: ClimateWizard]

Figure 2-24 shows predictions over three time periods: 2014-2040, 2041-2070 and 2071-2099, with every part of the Wami/Ruvu Basin seeing a progressive increase in annual temperature. Note that these figures show a uniform temperature over a 50 km*50 km area. Because of the influence of the EAM, parts of the basin will have larger differences in temperature; such fine scale heterogeneity is beyond the scope of this report.

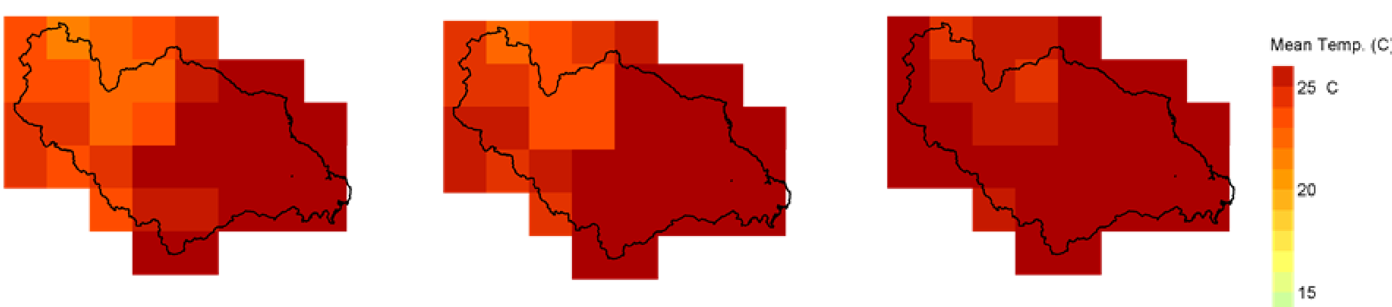


Figure 2-24: Annual mean temperature projections averaged over the Wami/Ruvu Basin (left 2014-2040; middle 2041-2070, right 2071-2099) by an ensemble of 16 GCMs at the A2 scenario. Dark red squares correspond to a temperature 26°C and higher. [Data Source: ClimateWizard]

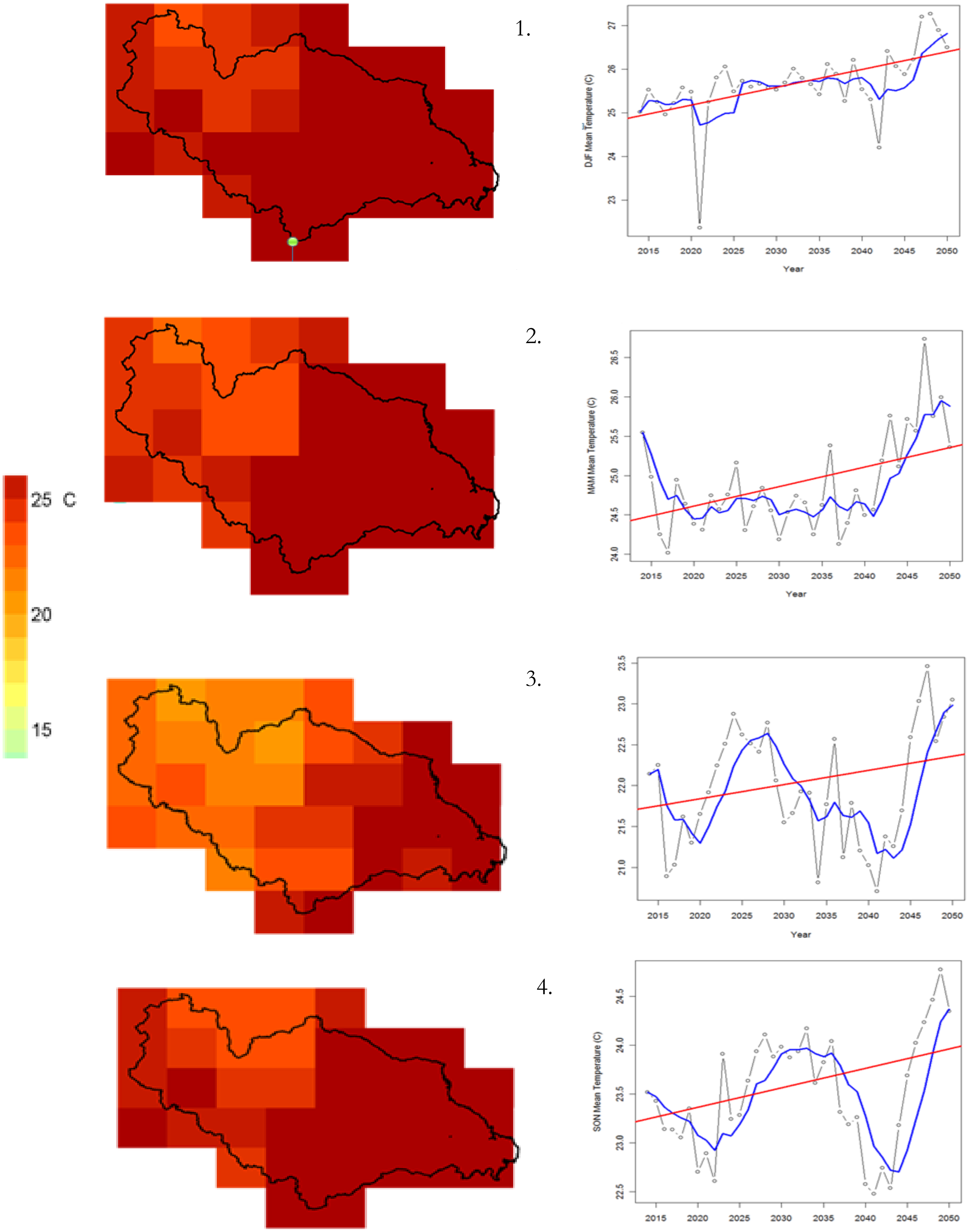


Figure 2-25: Seasonal average mean temperature predictions (2014 – 2050) by UKMO-had3 GCM. Left maps show predictions for the basin at a 50 km grid and right plots show the predictions by year. (1) December –February (2) March – May (3) June-August (4) September – November [Data Source: ClimateWizard]

Seasonal

Figure 2-25 depict seasonal (quarterly) temperature predictions that reflect current patterns. The winter (June-August) sees considerably cooler temperatures in the interior western and northwestern parts of the Wami/Ruvu Basin (the Dodoma region) as compared to the coast. The bottom panel shows interannual differences in the seasonal basin-wide temperature as predicted by the UKMO-had3 model, with an upward trend over decades similar to the annual temperature. Other models predict a similar trend over the century and are not shown here for the lack of space. Annex 1 explains how to run these models.

So far we have looked at the average value of the predictions by 16 models. To get a visual idea of the range of predictions by the 16 models, Figure 0-4 (Annex 2) has the lowest, middle and highest predictions of the yearly change in mean annual temperature averaged over the period 2014-2040, shown as the difference from the baseline mean over the period 1961-1990. Similarly Figure 0-5 (Annex 2) shows the same for the second half of the century (2051-2099).

Temperature departure or anomalies

Another way to visualize temperature projections is to consider the change in annual temperature for a future time period from the present or recent past. Figure 2-26 shows temperature departures over three periods over this century (2014-2040, 2041-2070, and 2071-2099) from the baseline mean of 1961-1990. Temperature is predicted to rise by almost 4°C by the last quarter of the century; this is the average of predictions by 16 GCMs. The western region of the Basin is also expected to see a larger change in temperature as compared with the coast, as seen in Figure 2-26, due to the proximity to the Indian Ocean that regulates temperatures on the coast.

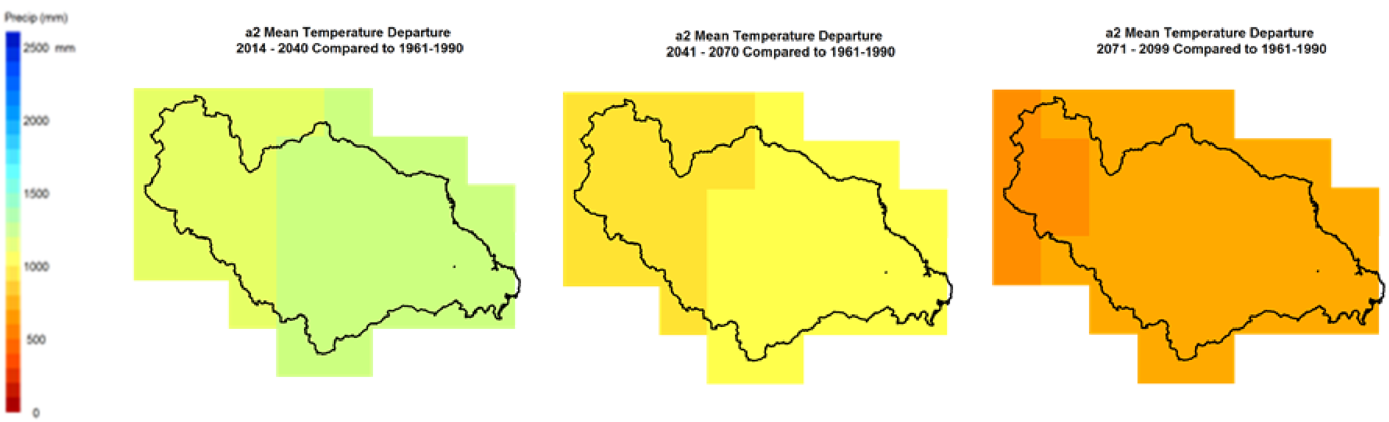


Figure 2-26: Predictions of change in projected annual mean temperature at a 50 km grid scale in the Wami/Ruvu Basin over three time periods: 2014-2040 (left), 2041-2070 (middle) and 2071-2099 (right) by an ensemble of 16 GCMs at the A2 scenario. [Data Source: ClimateWizard]

To visualize the change in predicted temperature, or how the temperature is likely to vary in the future with respect to the past, yearly predicted temperature departures from the baseline temperature are plotted (Figure 2-27). Like other plots, the baseline temperature is obtained by averaging the annual temperature value over the period 1961-1990 for the Wami/Ruvu Basin. Predictions plots from three models have been included in Figure 2-27.

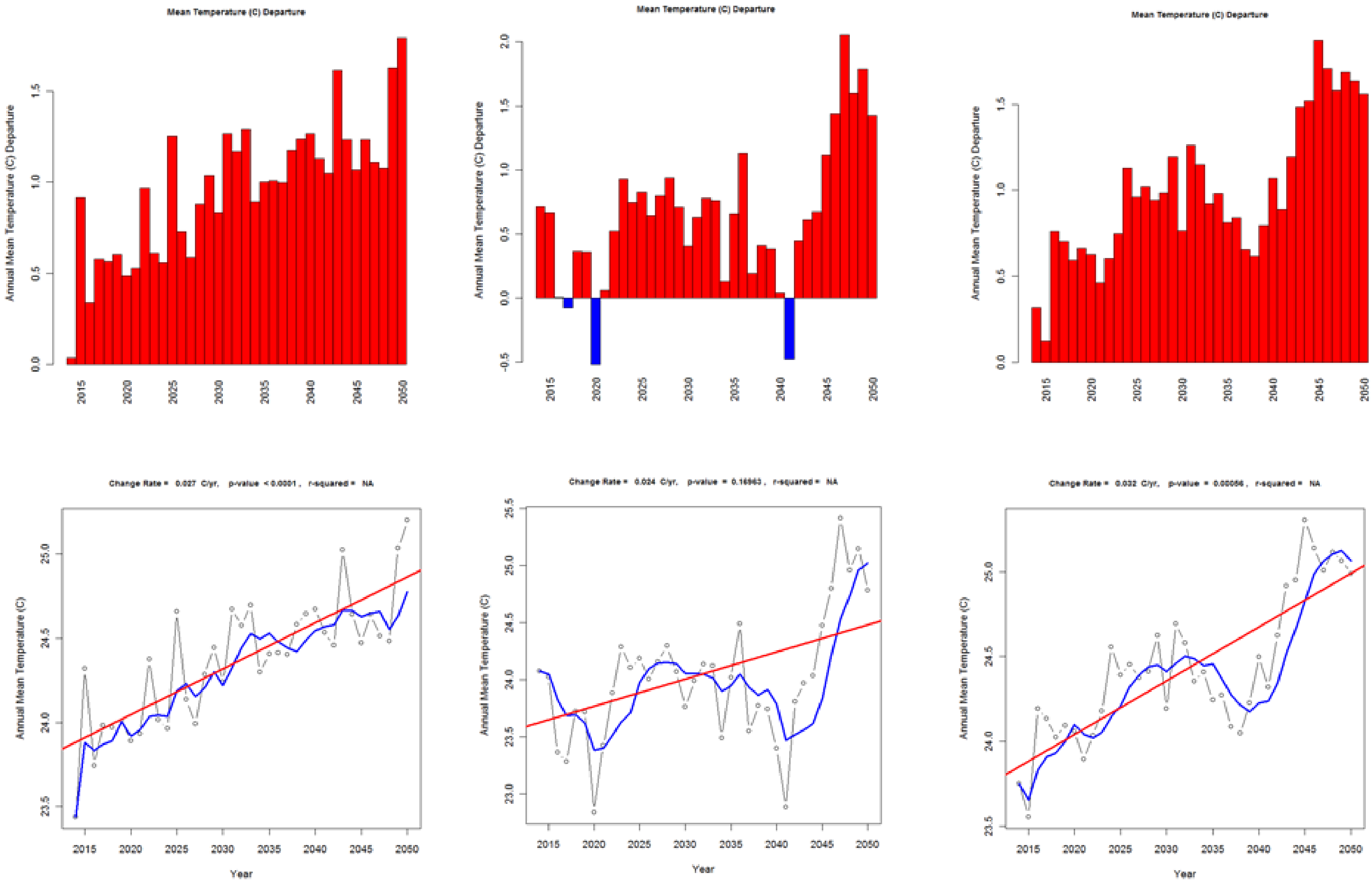


Figure 2-27: (Upper panel) Yearly mean temperature (2014-2050) deviations from the 1961-1990 mean by MIROC3.2 (left), CSIRO-Mk3.0 (middle) and UKMO_had3.1 (right) models under A2 emission scenario. Bars in red indicate an increase in annual mean temperature while blue bars indicate a decrease. (Lower panel) Yearly mean temperature predictions by the three models. [Data Source: ClimateWizard]

Apart from annual temperature predictions, it is also useful to look at seasonal predictions given the relevance of seasonality in agriculture and water resources management (for example, reservoir management). Seasonal predictions of the difference in average annual mean temperature of a period from the baseline mean of 1961-1990 are shown in Figure 0-6 (Annex 2). Overall, temperatures are predicted to increase over the century across all seasons, as seen from left (2014-2040) to right (2071-2099). The predictions range from < 1 °C increase averaged over 2014-2040 (left column) to almost 3 °C (right column) from the 1961-1990 baseline mean. Looking at Figure 0-6 from top to bottom (quarterly periods), summer (top two rows: December-May) is predicted to have a greater temperature increase than winter months (the bottom two rows: June-November). Spatially, the western region of the basin has predicted higher temperature increase; this could reflect temperatures on the coast as being modulated to some extent by the proximity to the Indian Ocean.

Precipitation

Unlike temperature, where all GCMs suggest warmer predictions for the 21st century, precipitation forecasts have less agreement. This disagreement reflects the tremendous complexity in forecasting precipitation, owing to the intricate interactions between net solar radiation, atmospheric, soil and water heat storage, topography, land cover, and vegetation type. The forecasts do preserve the spatial rainfall distribution patterns that are currently prevalent across the basin, with greater rainfall forecast for the EAM as compared to the surrounding lowlands (Figure 2-28). Precipitation is also seen to decrease westwards until the semi-arid zones around Dodoma for which the lowest rainfall in the basin is forecast.

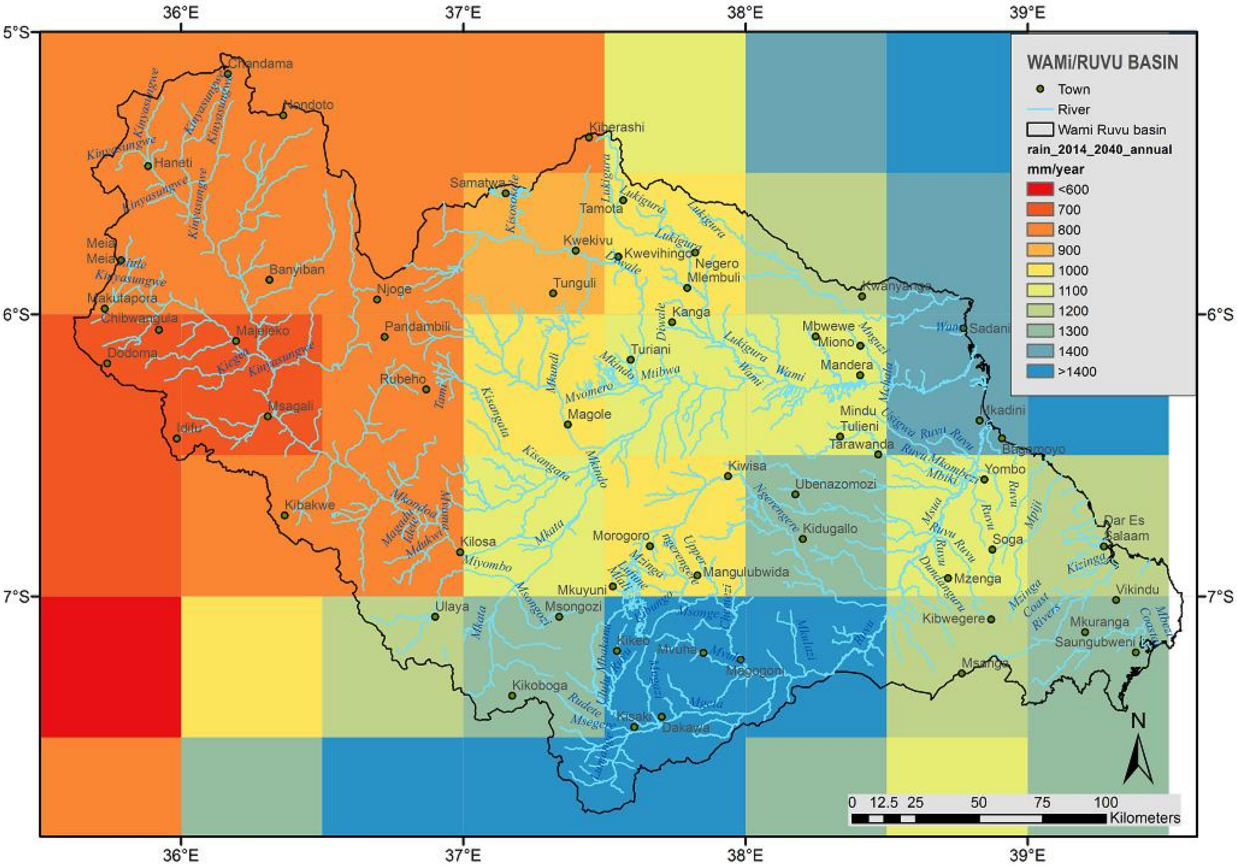


Figure 2-28: Predicted average annual precipitation (2014-2040) by an ensemble of 16 GCMs at A2 emission scenario for the Wami/Ruvu Basin. [Data Source: ClimateWizard]

The top panel in Figure 2-29 shows annual rainfall forecasts over the near future, middle, and end periods of the present century. It appears to be a very slight increase in precipitation basin-wide that can be observed by examining changes in each 50 km grid cell over the three time periods; this is more noticeable in Figure 2-29 bottom panel where rainfall anomalies, or the departure from the 20th century baseline, increase towards the end of the 21st century. The largest departure from the recent past is shown for the western semi-arid parts of the basin by most of the models. This may reflect the relative absence of modulating factors in the western semi-arid region as compared to the coastal regions that are buffered against large changes in temperature and precipitation to some extent by the moderating influence of the Indian Ocean.

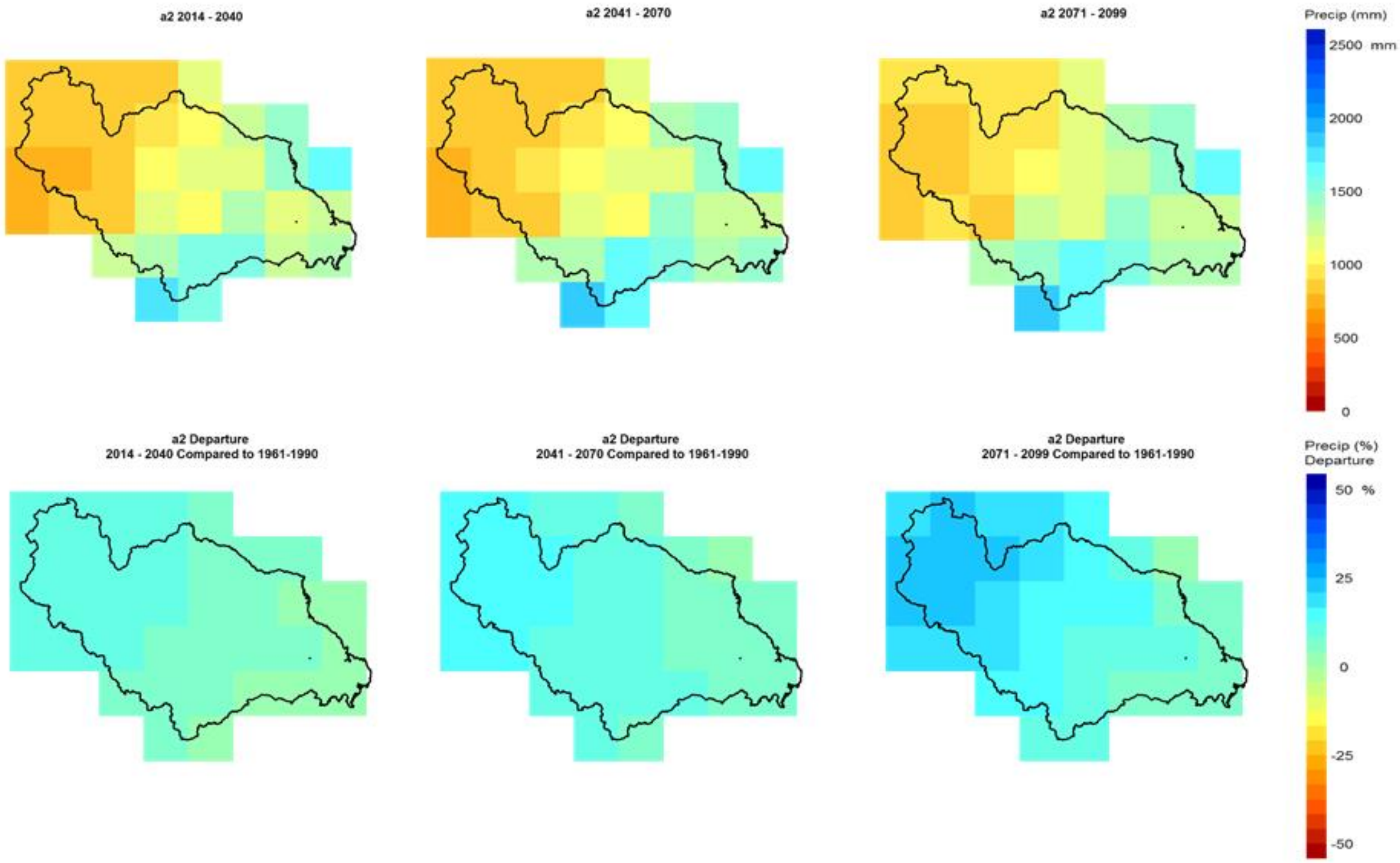


Figure 2-29: (Top) Low, middle and high predictions of the ensemble of 16 GCMs. (Bottom) Rainfall anomalies from 1961-1990 baseline for three periods in this century. [Data Source: ClimateWizard]

Seasonality

The GCM ensemble rainfall predictions suggest that the existing seasonality in the Wami/Ruvu Basin will be preserved under future climate scenarios over the next quarter century (Figure 2-30). The semi-arid Dodoma region is shown to receive the lowest rainfall in the basin, except in the months of January and February, when it actually receives higher rainfall than other regions (with the exception of the EAM). Rainfall in other regions is expected to increase around March-end to April, especially in the EAM, the Wami Dakawa region, and on the coast. Rains are predicted to cease in the Dodoma region in April while in the rest of the Basin, except in the Bagamoyo coast area, rains cease by May. The dry season (June – October) is expected to have very low rainfall basin-wide, with rain starting again in November/December. Note that the orographic condensation of easterly trade winds from the Indian Ocean (that results in the highest rainfall in the Basin falling on the EAM) is expected to continue as long as these winds occur. The scale of the model output (50km grid) does not reflect the rainfall differences between the EAM and the surrounding areas.

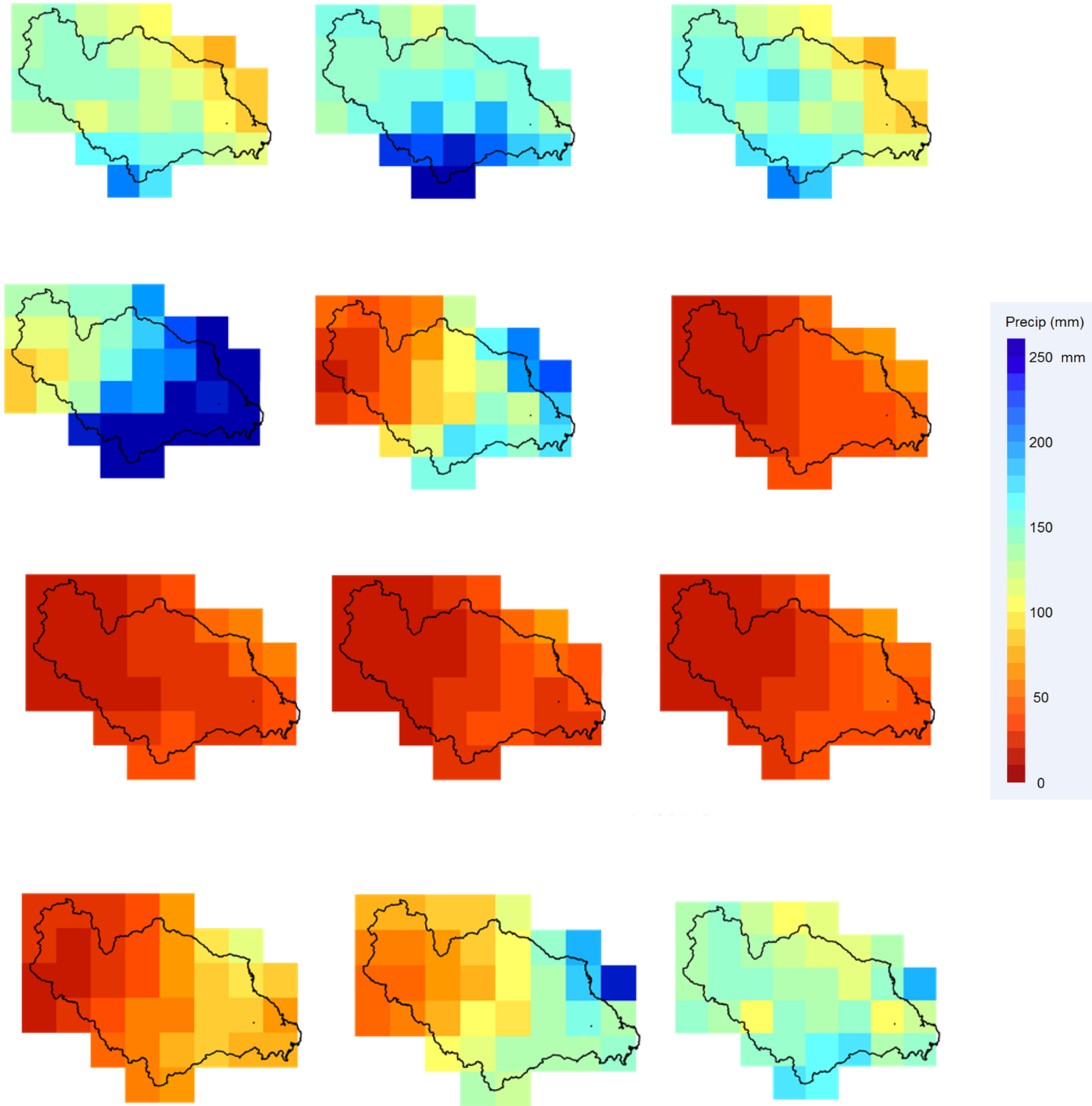


Figure 2-30: Monthly rainfall over 2014-2040 predicted by an ensemble of 16 GCMs at the A2 scenario. Left to right, starting from top: January to December (bottom right). [Data Source: ClimateWizard]

Uncertainty in precipitation projections

The uncertainty inherent in precipitation projections gives rise to large variability within model predictions as illustrated in the Figure 2-31. In this figure, the lowest, middle and highest projected rainfall annual trends (for the period 2030-2049) are seen to range from -1% to > +2% per year. Figure 0-2 (Annex 2) also illustrates this complexity by showing time series of rainfall projections by 12 individual models. Apart from the high inter-annual variations in rainfall present in each time series, there is no other common feature or trend between model forecasts. Neither there are any consistent inter-decadal patterns exhibited by the models. The range of predictions of different GCMs reflects the difference in model assumptions and parameterization, an indicator of the complexity of rainfall prediction. This uncertainty needs to be taken into consideration while looking at long-term precipitation projections. The inherent complexity in rainfall projections can also be visualized in the form of departures or rainfall anomalies (Figure 2-32), where different models predict different annual precipitation amounts. The models are seen to vary from Medres on the left that predicts predominantly higher rainfall as compared to the 1961-1990 baseline, to UKMO_HadCm 3.1 that predicts a larger variability of rainfall.

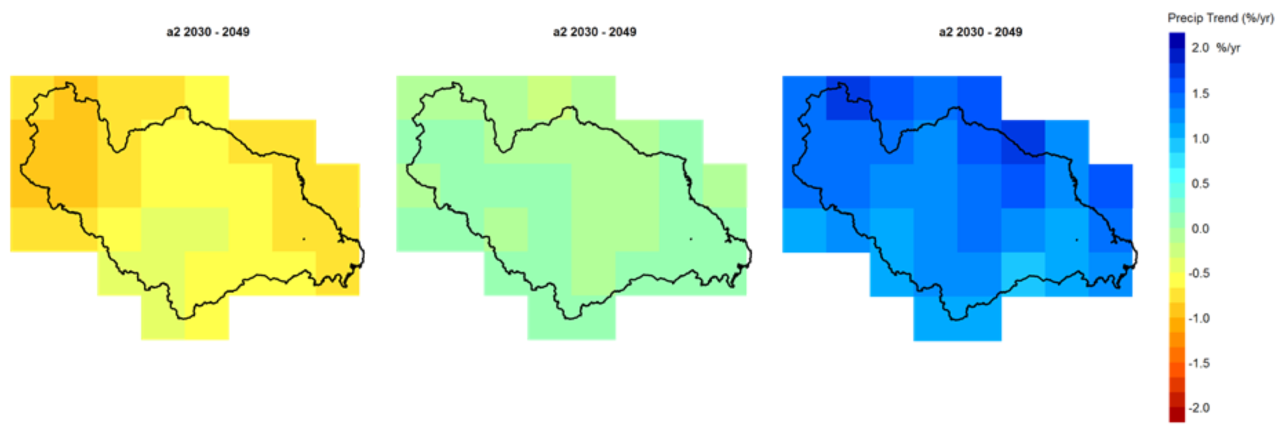


Figure 2-31: (From left to right) Low, medium and high values of projected annual precipitation (averaged over 2030-2049) trends by 16 GCMs at the A2 scenario. [Data Source: ClimateWizard]

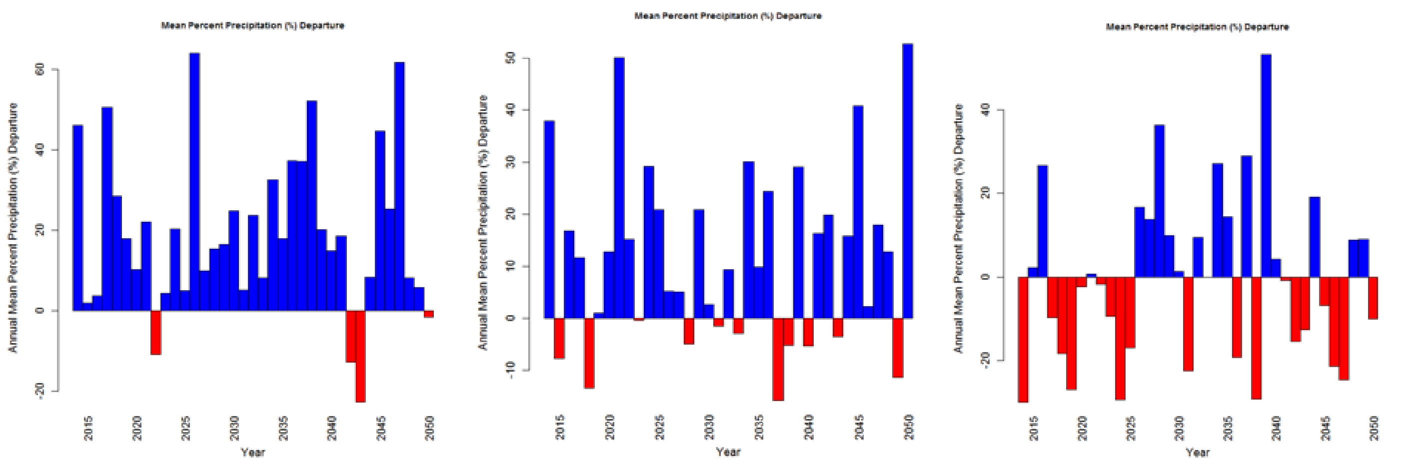


Figure 2-32: Yearly rainfall anomalies predicted by the Medres_1 (left), CSIRO_Mk3 (middle) and UKMO_HADcm3.1 (right) models with departure from the 1961-1990 baseline. [Data Source: ClimateWizard]

Running the models under three different greenhouse gas emission scenarios results in slightly different levels of rainfall projections as illustrated in Figure 2-32; however, the spatial pattern of rainfall is preserved under all three scenarios.

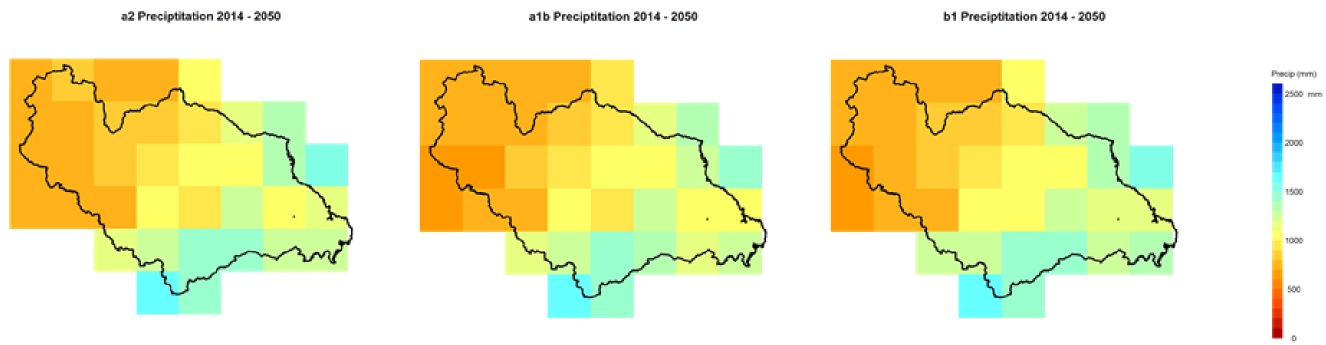


Figure 2-33: Annual trend in precipitation change under A1B, A2 and B1 emission scenarios by an ensemble of 16 GCMs forecast over 2014-2050. [Data Source: ClimateWizard]

Evapotranspiration

Evapotranspiration (ET) is a function of radiant solar energy (temperature) and water availability (precipitation). Higher radiant energy drives higher evaporation as well as transpiration. Plants photosynthesize more on sunny days, but also the loss of water through stomata serves to cool leaf surfaces on very hot sunny days. However, transpiration is limited by soil moisture, which varies seasonally and regionally. This is why in most cases actual evapotranspiration (AET) is less than potential evapotranspiration (PET). For this study, Hamon's equation (Hamon 1960, Lu *et al.* 2005) is used to estimate PET at a 50 km spatial scale, as it relies upon temperature alone and does not need other meteorological data, typically unavailable at the requisite spatial density in most parts of the world, including the Wami/Ruvu Basin.

Potential evapotranspiration (PET)

Following the temperature predictions (increasing trend over this century) by all 16 GCMs, similar predictions arise for PET (Figure 2-34). PET predictions go from 1250 mm/year currently to 1450-1500 mm/year by the end of the century. This is expected because PET is primarily a function of temperature as modelled. An increase in temperature provides more energy for evaporation of water from water bodies and the soil surface, as well as higher transpiration by plants in farms, wetlands, and woodlands. Note that these estimates are lower than the MODIS Global ET dataset estimates that are between 2000 – 2400 mm/year (Figure 2-14).

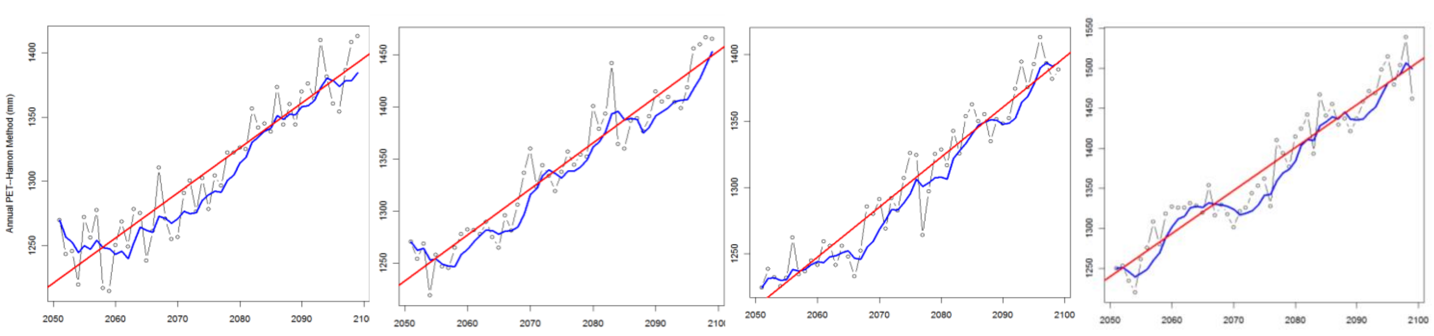


Figure 2-34: PET over 2051-2099 by 4 GCMs (2051-2099) accompanying a rise in temperature. From left to right the models are CSIRO_Mk3_0.1, MIROC_MEDRES_1, UKMO_HADCM3.1, and BCCR_BCM2_0.1. [Data Source: Climate Wizard]

Actual Evapotranspiration (AET)

As explained in Chapter 2, the ratio of AET to PET indicates water availability in the soil for evaporation and transpiration. Figure 2-35 shows the predicted value of this ratio, averaged over the period 2014-2050 at a 50 km grid scale. The closer the ratio is to unity, the lower is the water limitation. The semi-arid areas around Dodoma are shown with a relatively low AET/PET value, approximately 0.4, indicating that AET is about 40% PET. Another way of reading this is that severe water limitation, or very low soil moisture, constrains evapotranspiration to 40% of what could leave the earth's surface if there was no water shortage. Similarly, the cells with the Ulugurus and Ngurus mountains are seen to be around 0.6 while other areas are around 0.5. The higher values closer to the mountains reflect higher water availability, a consequence of the high rainfall and cloud condensation that the mountains receive. Again, note that these are averages over a 2500 sq km area, but areas within the EAM could have a ratio of 1.

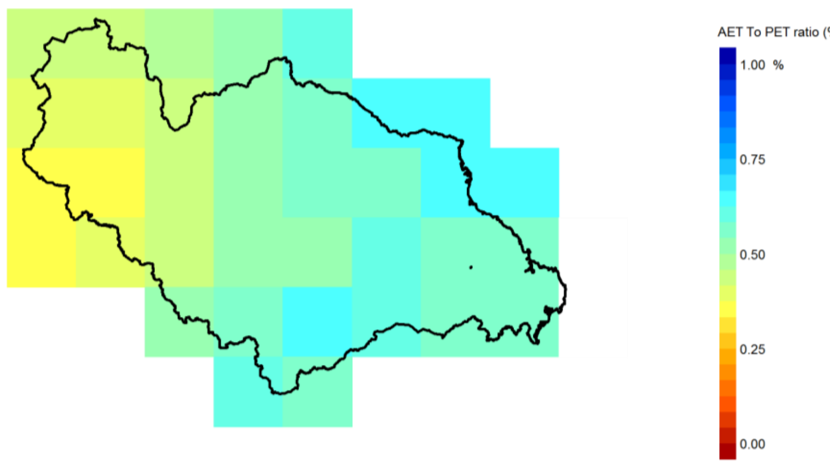


Figure 2-35: AET/PET estimates for the Wami/Ruvu Basin (2014-2050) at a 50 km grid scale. [Data Source: ClimateWizard]

The plots in Figure 2-36 indicates the annual predictions of AET/PET by three models; the ratio predicted varies between 0.45 and 0.6 over the next eight decades with considerably high interannual variation forecast by all three models shown here. Similar variability is obtained by all the other models (not shown here). It is to be remembered, that predictions of AET take precipitation projections into account, which are very complex and have a lot of uncertainty.

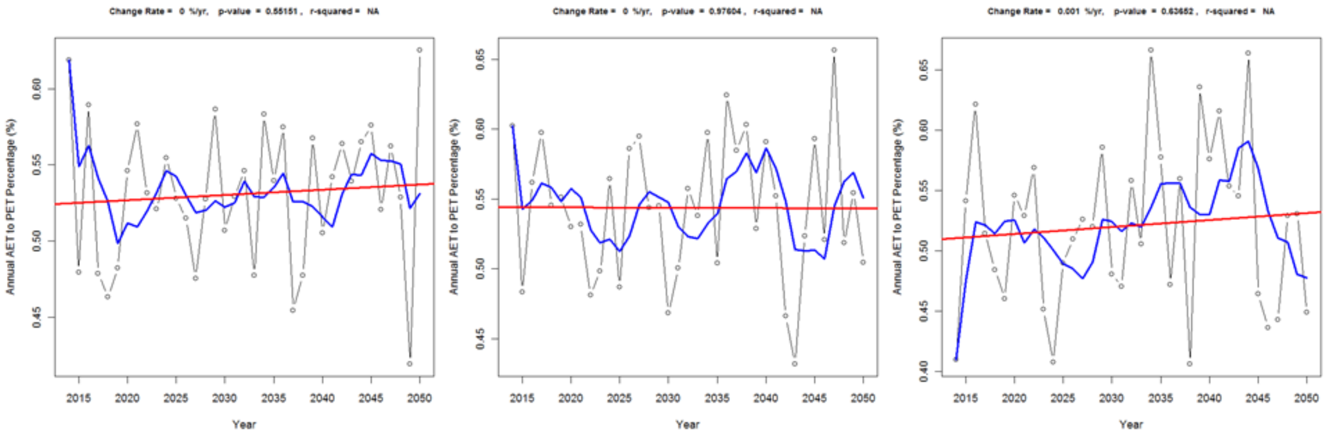


Figure 2-36: AET/PET projections obtained by CSIRO_Mk3, Medres_1 and UKMO_Hadcm3.1 models. [Data Source: ClimateWizard]

Figure 2-37 shows seasonal predictions of AET/PET. There is a basin-wide increase predicted for AET/PET in the rainy season (January-May), reflecting higher water availability that drives up AET. Drier parts of the year (July-September) see lower AET that drives down the AET/PET ratio while the ratio begins to increase again with the light rains of November and December. The semi-arid regions in the west show lower AET/PET than other parts of the basin, as expected, except in January-March when it is higher. This reflects the higher rainfall predictions by the GCMs for the region.

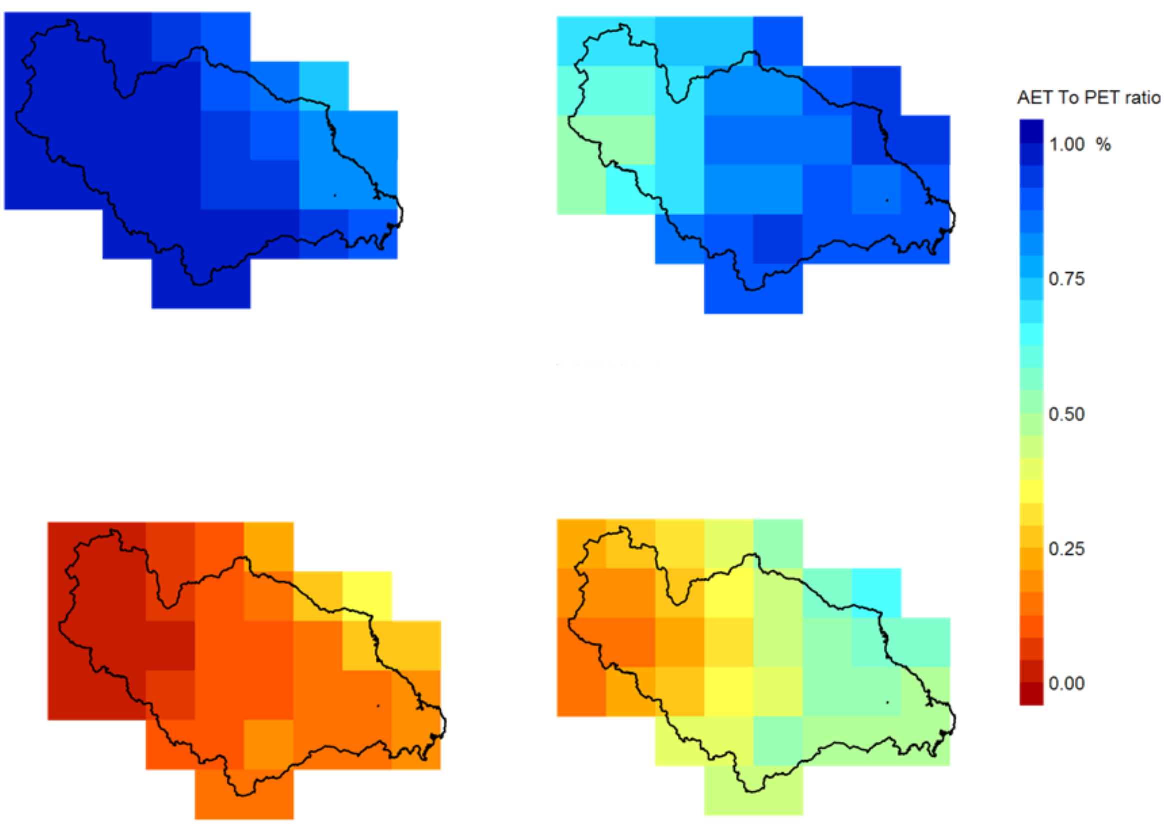


Figure 2-37: Seasonal AET/PET predictions expressed as a percentage by an ensemble of 16 GCMs (middle value) at a 50 km grid scale for the Wami/Ruvu Basin (top left: January-march; top right: April-June; bottom left: July-September; bottom right October-December. [Data Source: ClimateWizard]

Soil moisture deficit and surplus

Soil moisture is predicted to decrease over this century for almost every part of the Wami/Ruvu Basin, with greater deficits expected in the arid western region (Figure 2-38). This figure shows the soil moisture deficit; the greater the value, the lesser the soil moisture. This is a consequence of rising temperatures across the basin, with no clear indications of any long-term rainfall increase or decrease. Note that these predictions of soil moisture are solely based upon the predicted temperatures and precipitation and do not take into account projected changes in vegetation cover and land use, variables that also affect the amount of water taken up from the soil. However, given the strong causative relationship between temperature and soil moisture, these predictions give an idea of possible conditions in the future, with implications especially for the agriculture and livestock sectors. Soil moisture deficit averaged over the period 2014-2040 increased by 40-60 mm from the baseline value over the period 1961-1990 (Figure 2-38 right). It is further expected to increase over the second half of this century (Figure 2-39), as a consequence of rising temperatures and uncertainty in precipitation.

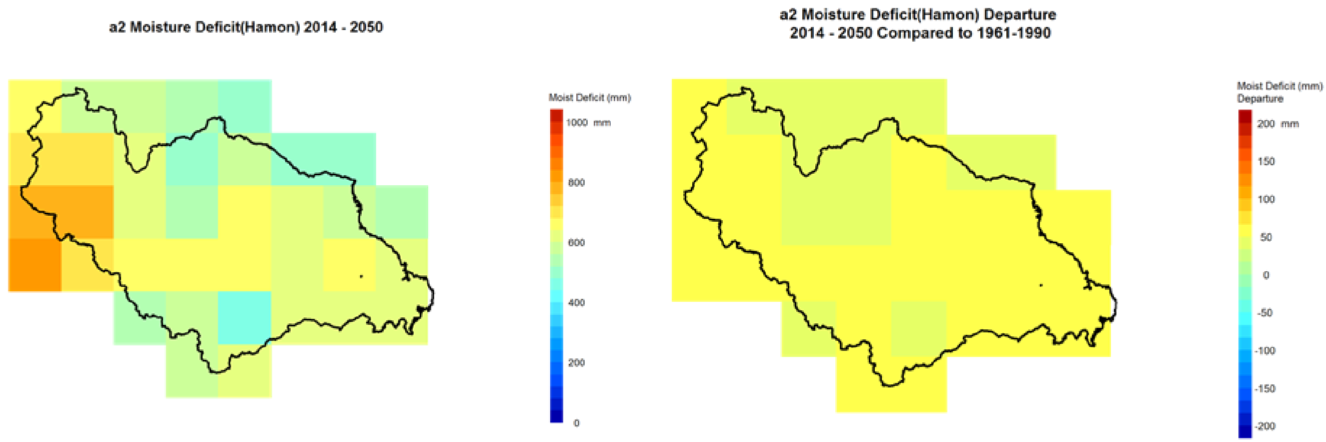


Figure 2-38: (Left) Soil moisture deficit predicted by an ensemble of 16 GCMs at A2 scenario as an average over 2014-2050. (Right) difference between predicted soil moisture deficit and the average soil moisture deficit prevailing over 1961-1990. [Data Source: ClimateWizard]

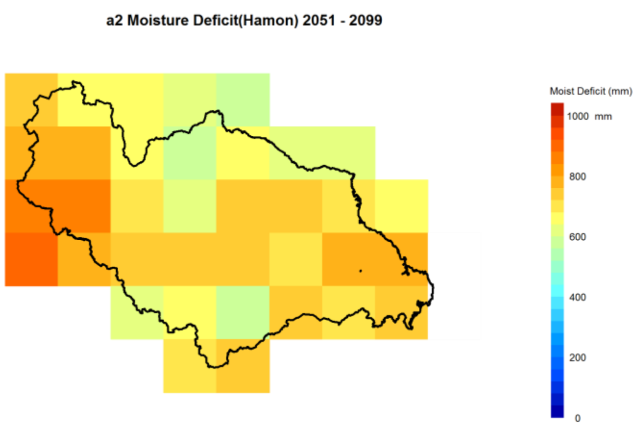


Figure 2-39: Soil moisture deficit forecast over 2051-2099 by an ensemble of 16 GCMs. [Data Source: ClimateWizard]

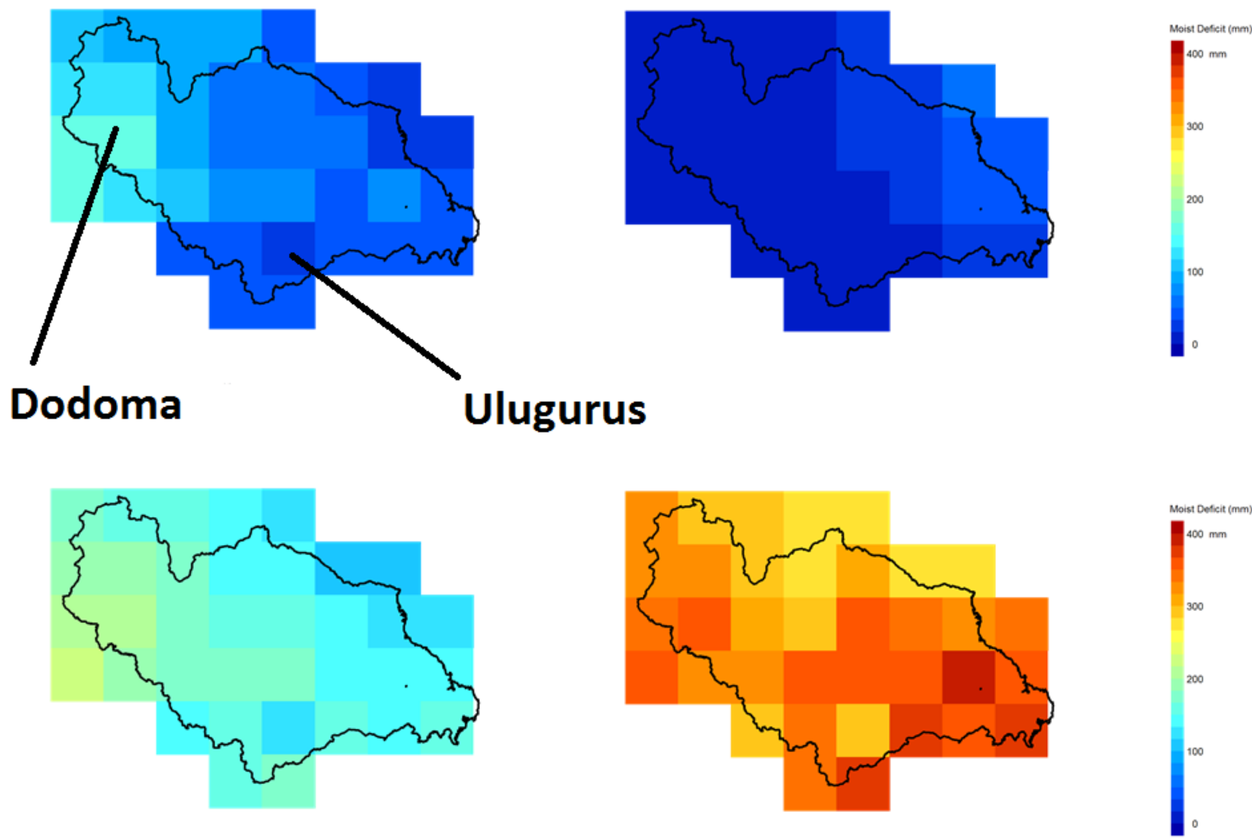


Figure 2-40: Seasonal predictions of soil moisture deficit by an ensemble of 16 GCMs. (top left: January-March; top right: April-June; bottom left: July-September; bottom right: October-December). [Data Source: ClimateWizard]

Seasonal and spatial aspects

The soil moisture deficit is low during the rainy season and increases over the dry season. Figure 2-40 indicates that the lowest soil moisture deficit is predicted to be during April-June and the highest deficit is during July-September. In general, the Dodoma region has the highest soil moisture deficit in comparison to other regions in the Basin except in the main rainy season (August-June). The Uluguru Mountains, as expected, are shown with the lowest soil moisture deficit in the basin; this is true for the higher reaches of all mountains, including the Ngurus that benefit from cloud condensation year-round.

Another way to depict soil moisture status is to display it as a surplus (Figure 2-41), typically a real time quantification of the soil moisture status after evapotranspiration. Spatially, much of the basin has an annual surplus of 300-500 mm with the western semi-arid zones having less and the EAM more, as seen by the prevalence of blue in the southern part of the Basin, where the Ulugurus are located, with adjoining Udzungwa Mountains further to the southwest.

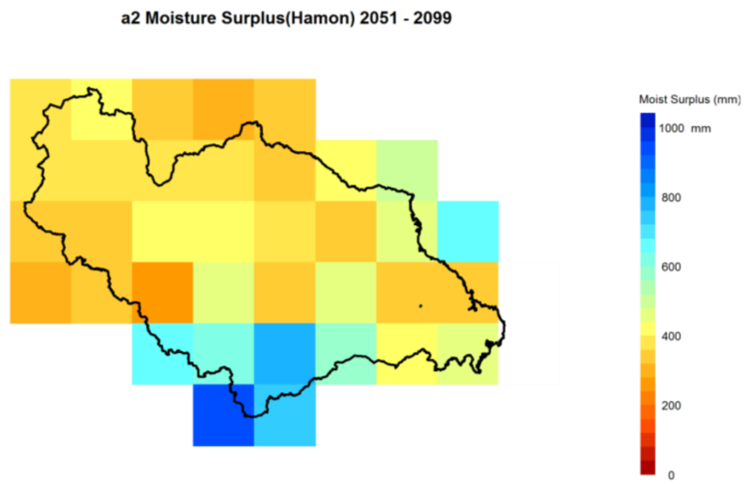


Figure 2-41: Moisture Surplus (Hamon) (2051 - 2099) as predicted by an ensemble of 16 GCMs at the A2 scenario. [Data Source: ClimateWizard]

2.4 Final remarks: implications of climate change for the vulnerability of water resources

Based on the literature review and model outputs in this study, the overall climate predictions over the 21st century for the Wami and Ruvu River Basins are:

- Rising temperatures across the seasons, with an increase in very hot days (> 32°C) and a decrease in cold days.
- Rising evapotranspiration demand and soil moisture deficits.
- Increasing uncertainty in the onset, regularity, and amount of rainfall. Occurrence of sizeable rain events in what has been usually considered dry season.
- Increasing frequency of extreme events – high rainfall events, floods, and long periods of scant or no rainfall that can potentially lead to a drought.
- Rising sea level that accelerates shoreline erosion, increases flooding episodes, and promotes saltwater intrusion into coastal wells; such negative effects can be intensified in areas near estuaries by decreases in freshwater river inflows.

Increased uncertainty in the onset of precipitation leads to increased susceptibility of rain-fed agriculture to either early or late planting. Uncertainty in precipitation in the form of departure from usual seasonal patterns can affect the growth, maturity, harvest, and post-harvest storage of crops. There is also the danger of pest outbreaks and diseases accompanying aseasonal extreme events such as droughts and floods. Other sectors such as livestock, beekeeping, fisheries and aquaculture also benefit from rainfall that is evenly distributed over a season; any uncertainty in onset or long rainless periods can affect their functioning. Water management for domestic and industrial sectors also has to account for increased uncertainty. Increasing uncertainty in surface water resources drives greater reliance on groundwater, which are considered more reliable in terms of year-round availability and quality. However, groundwater level monitoring is essential as a tool to detect high levels of extraction that can exceed natural groundwater recharge.

Extreme events may become more frequent under future climate scenarios. Patterns of rainfall distribution over a season are being seen to change towards events of high rainfall interspersed with long gaps of little or no rain. This possibility is suggested by rainfall records as well as observations collected from community elders in a recent survey conducted by the Tanzania iWASH Program in villages in the Mkindo River Catchment in the Nguru Mountains, Wami River Basin (Vogt and Shayo 2012). Very high rainfall events lasting a couple of days can lead to flooding, landslides, soil erosion, and other disasters.

A rise in the temperature regime represents a change in the overall energy balance in the region, thereby affecting every physical, ecological, economic, and social process. Water partitioning in a catchment is affected, since both evaporation and transpiration are affected by temperature, thereby decreasing stream runoff and groundwater recharge. Water requirements for agriculture can also increase on account of the increased evaporative and transpiration demands in farms. Cooling requirements and energy demand for domestic and industrial processes are also likely to increase. A rise in temperature can also be accompanied by changes in the geographical ranges of insects, with the chances of the spread of new agricultural and horticultural pests.

Sea level rise (SLR) may seem gradual on an annual scale, but it is likely to have sizeable influences on a decadal scale. One major issue is seawater intrusion into coastal aquifers that constitutes a serious challenge to the large coastal populations, including the cities of Dar es Salaam and Bagamoyo (Kebede *et al.* 2010). Another issue is accelerated beach erosion and damage to sea walls, already underway in coastal Pangani Basin. The effects of sea level rise in estuaries are compounded by the decrease in freshwater inflows (via rivers) that resist the advance of seawater upstream as well as regulate the salinity. Higher salinity leads to the retreat of seaward mangroves, exposing the shoreline to greater erosion from both ocean waves and storms, as well as negatively affecting seagrass beds and marine invertebrates that constitute nursery and food for marine fishes. This will in turn negatively affect marine fisheries that are already declining due to other reasons such as overfishing, by-catch, and coastal pollution.

3 Forest Loss in the Wami/Ruvu Basin

Climate change, associated with increasing irregularity of rainfall and changes in rainfall patterns, is affected by factors on a global scale, where changes in greenhouse gas concentrations that change the earth's energy balance, which in turn affects atmospheric pressure over the surface, and thus ocean and wind currents. Land cover change (such as deforestation) and its effects are more local in scope (i.e. catchment), while increasing human water demand/use are both local and regional in influence. The traditionally well-known role of forests and wetlands in moderating water availability and quality is reiterated as the most efficient and practical approach to buffer society and ecosystems from the uncertainty associated with climate change (e.g. Dudley and Stolton 2003, Nuñez *et al.* 2006, Biao *et al.* 2010).

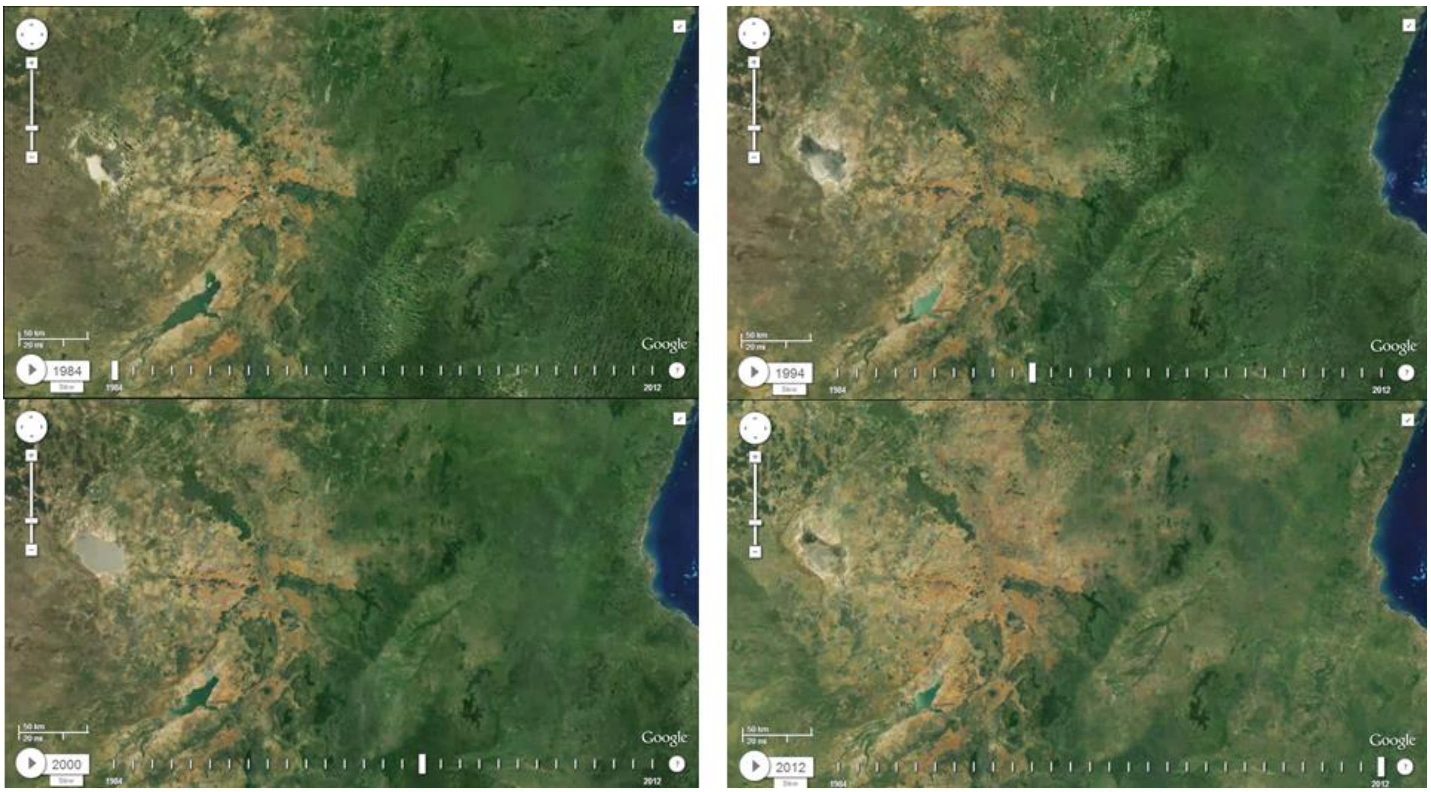


Figure 3-1: Satellite images (Landsat TM) of the Wami/Ruvu basin in 1984 (top left), 1994 (top right), 2000 (bottom left) and 2012 (bottom right).

The panel of images in Figure 3-1 depicts decreasing vegetation cover over the period 1984-2012 in the Wami/Ruvu Basin. Vegetation (tree cover) in these maps has been shown in green (true color rendition of satellite images). The decrease in vegetation cover over time, especially in the eastern part of Wami/Ruvu Basin, is evident as a decline of greenness of the images. The vegetation cover in 2012 (lower right) is much thinner than in 1984 (upper left), with the remaining thick cover restricted mainly to the tops of the Nguu, Nguru, Ukaguru, Uluguru and Rubeho blocks that comprise the Eastern Arc Mountains (EAM) within the Wami/Ruvu Basin. This chapter takes a closer look at the existing forest cover, and where forest cover has been lost over the past decade.

3.1 Background: hydrologic effects of changing forest landscapes

It is ancient knowledge that native forests play a significant role in regulating water quality, water availability and streamflow. In addition, the role of forests in facilitating convectional rainfall and the interception of moisture from clouds and fog is an active area of research in many parts of the world. Declining forest cover has been equivocally linked with an increase in flash floods, the earlier drying-up of springs and increased turbidity in rivers (e.g. Bruinjzeel 2004). While forest hydrology is a large area of research, a brief review of the links between forests and the hydrologic cycle are presented below, in order to clearly illuminate the instrumental role forests play in ensuring water quality and dry season flow (low flows).

Forest cover and hydrology

Rainfall in catchments is partitioned into surface runoff, infiltration to recharge groundwater, evaporation from all surfaces, and transpiration by plants. The presence of native forests increases rainfall interception by trees and the litter layer, which stores water and allows time for a greater degree of infiltration of rainwater into the ground. Some of this water is taken up by trees and transpired back into the atmosphere. In many tropical ecosystems, some of this transpired water forms clouds that locally rain once again. The groundwater thus recharged flows downhill and recharges springs and streams via baseflow; this is especially important in the dry season, being one of the very few remaining sources of water on the landscape.

The removal of native forest cover results in lower rates of infiltration and hence, greater runoff immediately following a rain event (e.g. Myers 1998, Calder 2007, Krishnaswamy *et al.* 2012). The lack of forest cover can accelerate soil erosion as well as flash floods following cloudbursts or periods of heavy rain. Additionally, the removal of cover leads to higher observed peak streamflows, therefore shortening the duration of the flow, with streams drying up earlier in periods with no rainfall. Furthermore, lower infiltration implies lower groundwater recharge, which then leads to springs and streams downhill drying up earlier.

At the same time, clearing forests and replacing with agriculture has been seen to increase the annual water yield by numerous studies, while reforesting cropland with plantations has been linked with lowered annual flows (e.g. Bosch and Hewlett 1982, Calder 2007). This is often a point of confusion as to the role forests have in catchments water resources management. A distinction must be made between total water yield which is an annual figure and the seasonal distribution of yield, which concerns the daily availability of water in streams (e.g. Bruijnzeel 2004).

Another item of confusion stems from the use of the term 'forests' – monoculture plantations of fast-growing trees such as *Eucalyptus* have a much greater water uptake than slower growing indigenous forests (Calder 2007), leading to lower baseflows in many cases (van Dijk *et al.* 2007). Monoculture plantations (typically *Grewellia, Casuarina* or *Eucalyptus* species) also have a more open canopy than native evergreen wet montane forests in the EAM. This can also lead to lesser rain/cloud interception and subsequently lesser infiltration than in native cloud forests. Yet the socioeconomic benefits arising from such plantations necessitates a mixed-land use approach of a mosaic of native forest lands, plantations and agroforestry (e.g. Jagger and Pender 2003, FAO 2011). Studies are needed in local catchments to see the ecohydrologic effects of the use of fast growing species for reforestation on the local water cycle, especially on downstream water bodies and spring flows. Preserving native forest cover in catchments remains by far the most economical approach towards ensuring year-round water availability and quality (e.g. Dudley and Stolton 2003, Nuñez *et al.* 2006, Biao *et al.* 2010).

Forest cover and water quality

The forest canopy shelters bare soil from being eroded and washed away by rains, as well as provides a leaf litter layer that develops over time. Hence streams in forested watersheds of the Eastern Arc Mountains are often clear-running, with stony bottoms whose crevices provide the only habitat for a community of aquatic macro-invertebrates that form the prey base for many fish species in these mountain streams. This is one of the reasons of stressing on the protection of natural vegetation along stream banks. It is worth noting though that, while the presence of forests, especially closed-canopy native forests are associated with resisting soil erosion, the underlying geology exerts a role in bigger landslides and rockslides (e.g. Sidle *et al.* 2006).

3.2 Forest cover change in the Wami/Ruvu Basin

Forest cover in the Wami/Ruvu basin consists of evergreen montane forests (cloud forests) on the higher reaches of the EAM, deciduous forests on the lower slopes of these mountains (below 600 m), gallery forests along river courses, *miombo* woodlands across lowlands east of the EAM, acacia thorn scrub forests in the arid regions around Dodoma, and mangrove forests along the coast and estuaries of the Wami and Ruvu Rivers.

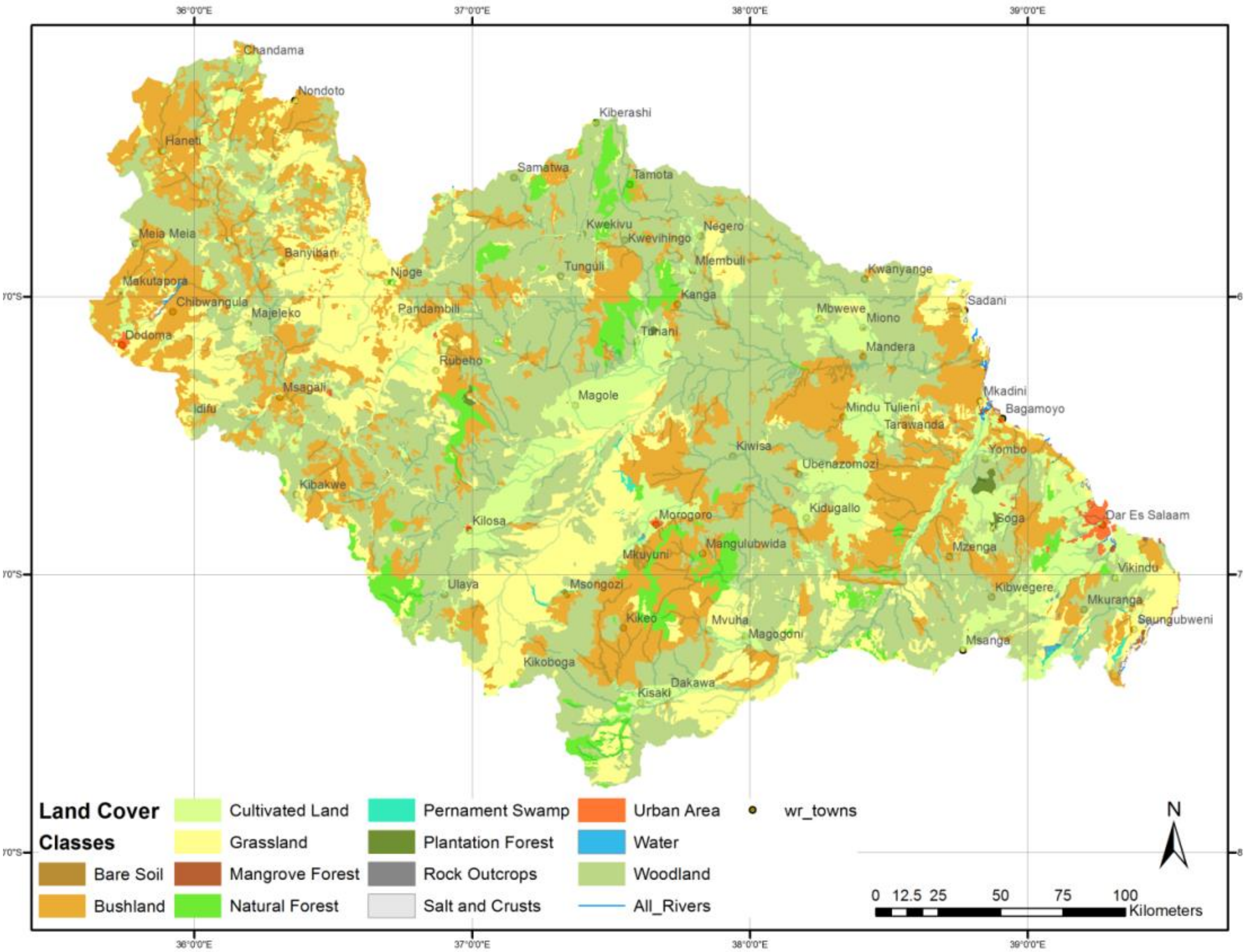


Figure 3-2: Land cover map of the Wami/Ruvu Basin, with land cover classification [Source: FAO-AFRICOVER, 2005]

Figure 3-2 indicates the evergreen forests as 'natural forests' in dark green; these are the forests in the headwater catchments of the Wami and Ruvu Rivers and their major tributaries and have reserved forest status (Figure 3-3). The lowland forests are shown in Figure 3-2 in a lighter shade of green and labeled 'woodland'. This includes a wide range of deciduous and thorn scrub forests. A view of the forest cover existing in the year 2000 is shown by the green areas in Figure 3-4 as classified from Landsat satellite imagery (30 m resolution, Hansen *et al.* 2013). The brightest green patches indicate dense forest canopy; these are mainly restricted to the reserve forests in the high reaches of the EAM.

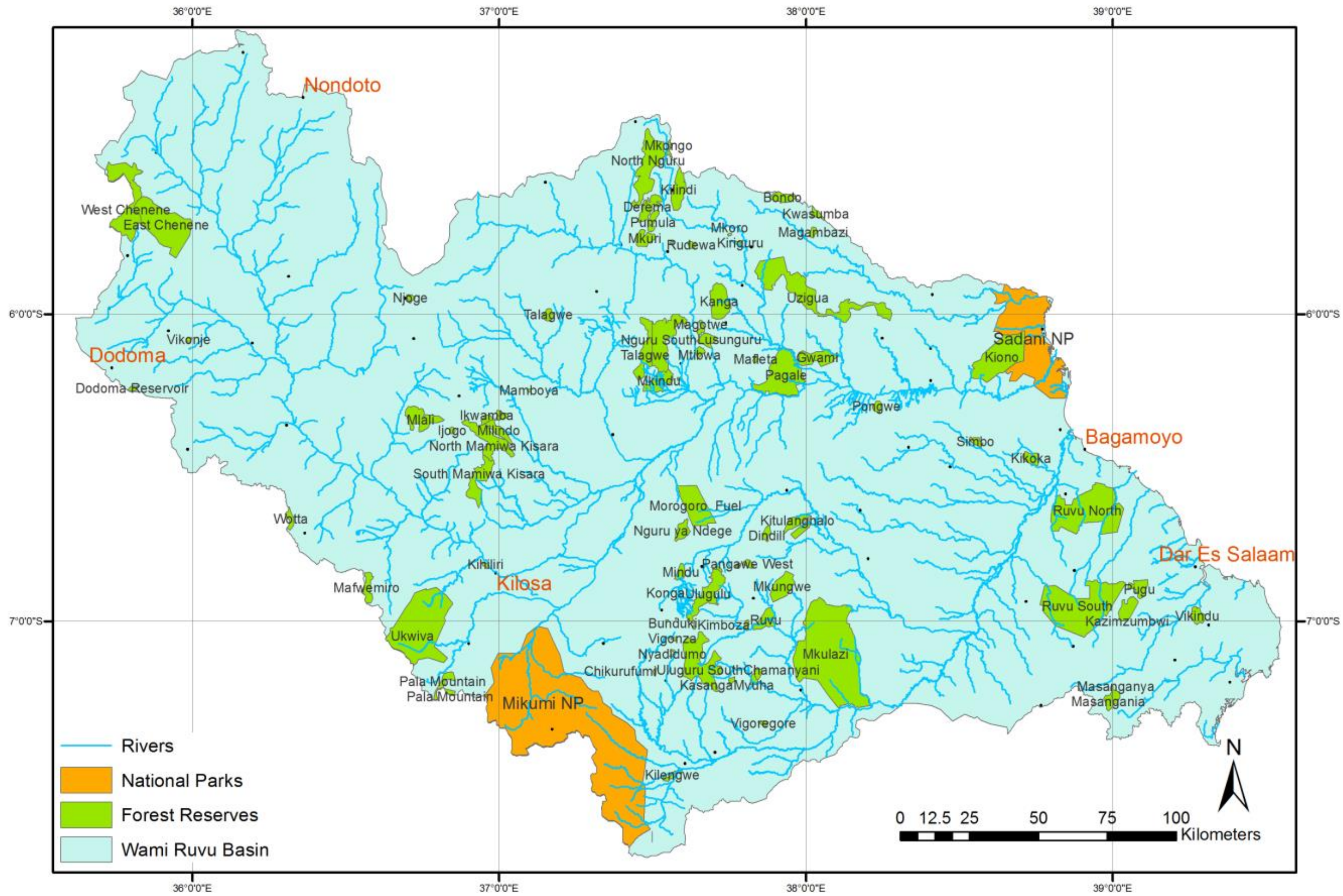


Figure 3-3: Map of forest reserves in the Wami/Ruvu Basin. Note that in addition to the reserves shown there are two national parks, Mikumi and Saadani (not shown), parts of which also fall in the Wami/Ruvu Basin [Source: FAO-AFRICOVER, 2005]

Lowland forests

The lowlands in the Wami/Ruvu Basin used to have extensive *miombo* woodlands amidst savanna grasslands, but has witnessed severe degradation – 43% woodland area decrease over 1970-1990s (Forestry and Beekeeping Division 2006) with that trend continuing over 2000-2012, mainly for charcoal and agriculture. In a study over 1991-2005, Ahrends *et al.* (2006) observed waves of deforestation spreading out from Dar es Salaam, with the inner deforestation wave being for charcoal (25 km from DSM), middle and outer waves for low-high value timber. Figure 3-4 shows an alarming amount of lowland deforestation (red spots) in the area between the EAM and the coast, between Morogoro and Dar es Salaam. Lowland deforestation thins out the canopy cover, with significant negative effects upon water and soil resources in the basin (e.g. Ahrends *et al.* 2012). A thinner canopy leads to faster drying out of the litter layer, allowing seasonal fires to penetrate the woodland and burn off this litter layer / soil organic horizon that has formed over centuries. Loss of this organic layer, as well as a thinner canopy, lessens the infiltration of rainwater underground, and almost all rain leaves as surface runoff, carrying along sediment.

Upland forests

A literature review by the Forestry and beekeeping Division report (2006) details the shrinking of Eastern Arc Mountain forests over the 20th century ranging from 60%-90% depending on the specific mountain block. The rate of loss has slowed down towards the end of the century. In comparison with lowland woodlands, the Eastern Arc Mountains have experienced lesser deforestation over 1970-1990 (6% - Forestry and Beekeeping Division 2006).

Much of the upland forest cover remains as seen over 2000-2012, primarily on account of the protection awarded by the status of reserve forests (Forestry and Beekeeping Division 2006, personal observation). Another reason for the lesser deforestation may be that the EAM are relatively far from the major Dar es Salaam metro region. However, deforestation still happens right up to the Reserve Forest boundaries; this is also seen in Figure 3-3 with the presence of red areas adjacent to the existing forest cover (green); especially evident in the Ukaguru and Rubeho Mountains west of Morogoro. The Forestry and Beekeeping report (2006) as well as Bracebridge (2006) indicate the occurrence of illegal logging inside reserve forests that is not detectable by remote sensing until a forest patch is significantly thinned out. Schaarsfma *et al.* (2012) found that charcoal manufacture in villages in the EAM accounted for around 11% of the charcoal demand in Dar and other cities, with an estimated annual value of USD 14 million.

Protecting forests in headwater catchments is critical; the continued existence of primary forests in the catchment areas of the Wami and Ruvu Rivers is testimony to the far-sightedness of the decision to award the protection of reserved forests to them.

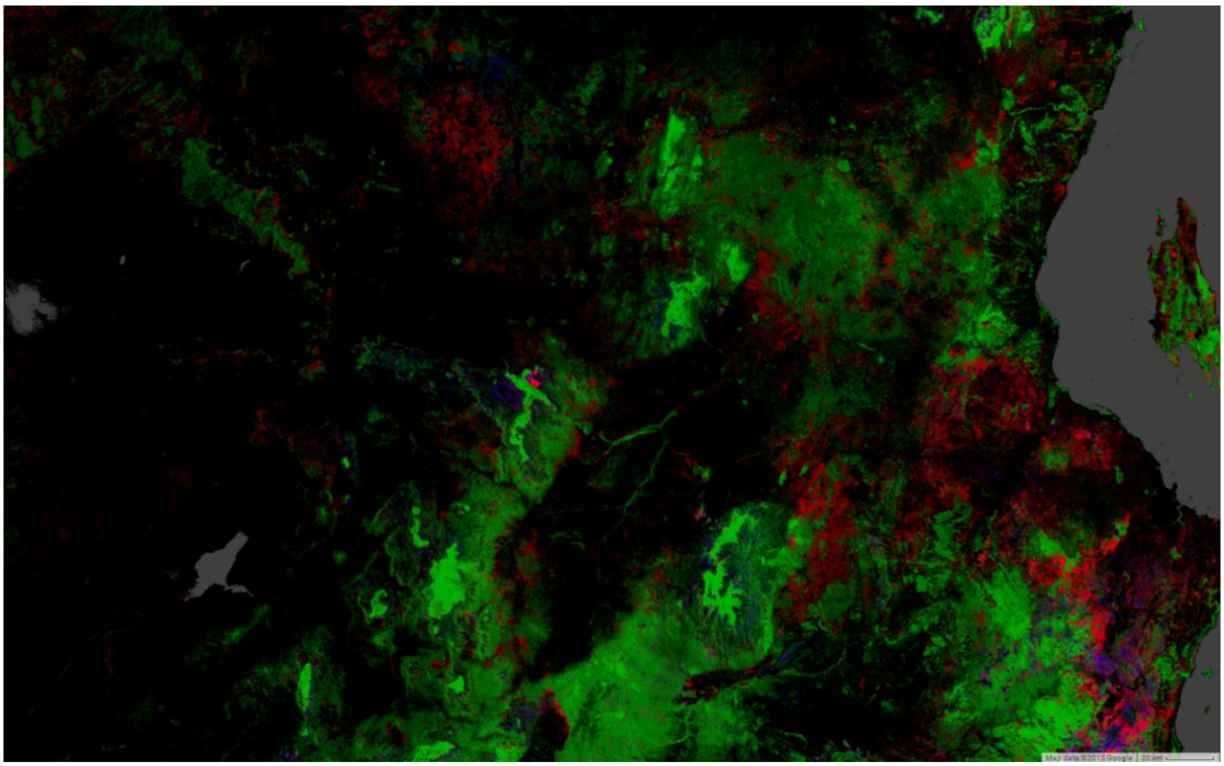


Figure 3-4: Forest cover in the Wami/Ruvu basin in the year 2000 shown in green. The colors red and blue represent areas with forest loss and gain respectively. Landsat imagery (30 m resolution) was used to classify forest cover. [Data Source: Hansen *et al.* 2013]

Figure 3-5 highlights the areas that have undergone deforestation over 2000-2012 in the Wami/Ruvu Basin, presented over a basemap of the area showing geographical details such as roads and towns. From the map it can be seen that most of the areas of forest loss has been in areas with no official protection in the form of reserved forests or national parks.

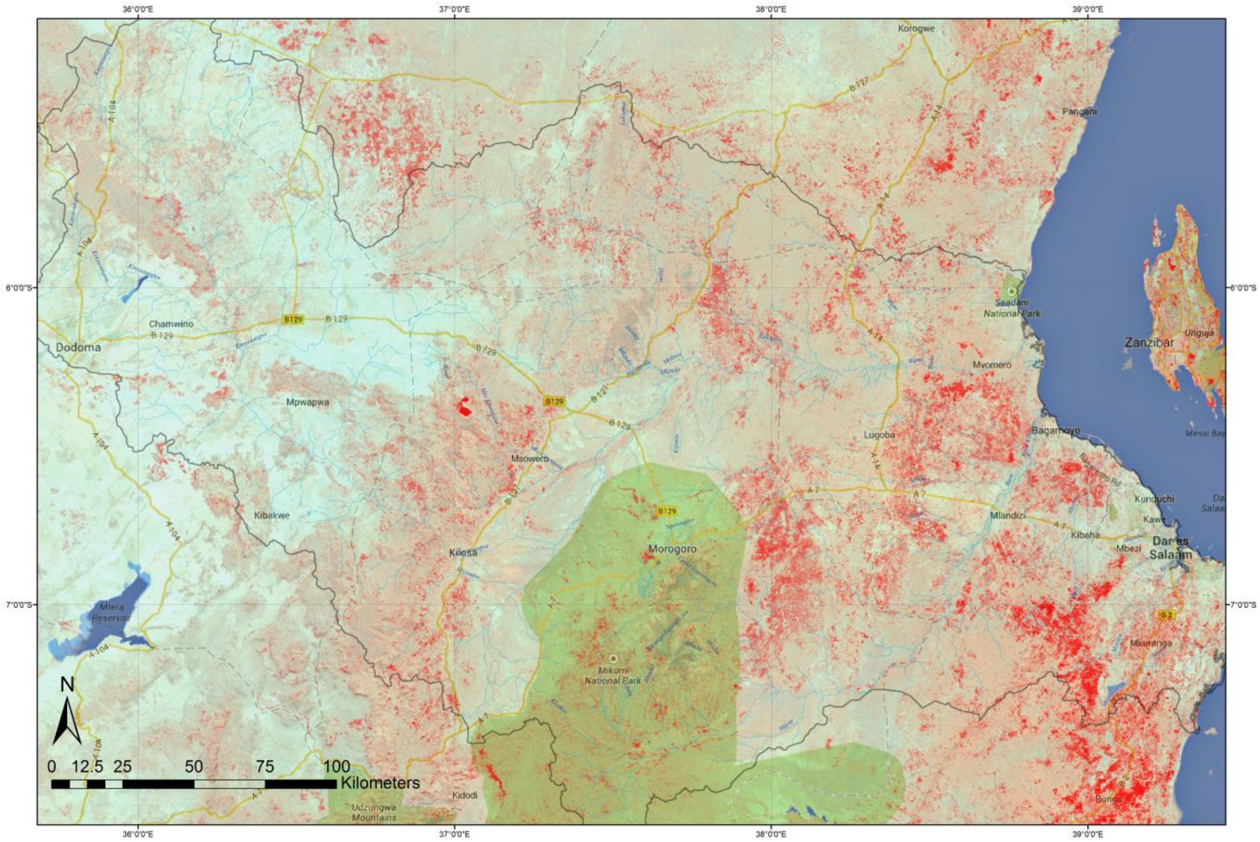


Figure 3-5: Forest cover loss over 2000-2012 (shown in red) in the Wami/Ruvu Basin. [Source: Hansen *et al.* 2013]

The protection of forests and restoration of forest cover requires the cooperation of the ministries of water, forests and wildlife, agriculture, rural development along with local communities and NGOs. These forests are also globally recognized as biodiversity hotspots. Already many sustainable tourism initiatives are beginning in other EAM (i.e. Usambaras, Udzungwa National Park). In this sense, the protection of forests can also provide opportunities for income generation in addition to the immense role forests play in facilitating water availability.

3.3 Wetlands in the Wami/Ruvu Basin

Wetlands and floodplains play a defining role in regulating hydrology by storing rainwater and surface runoff from hill streams during the wet season and discharging into rivers during the dry season. Sediment and other particles from upstream runoff have chance to settle in wetlands and wetland vegetation absorbs nutrients from the water. These storage and water quality improvement aspects of wetlands are only recently being appreciated by society, which has drained them for agriculture and hitherto considered marshes as wastelands. Apart from a defining role in regulating water flow and quality, wetlands also support large fisheries along with habitat for waterbirds and wildlife.

Figure 3-6 shows the locations of the major wetland complexes; they all lie along the Wami and Ruvu River floodplains. The major wetlands in the Wami drainage are the Tendigo swamps in the Mkata floodplain, followed downriver by the Wami Dakawa wetlands that also support large sugarcane farms such as Mtibwa. Major wetlands in the Ruvu system occur southeast of the Uluguru Mountains in the upper Ruvu catchment, followed by low-lying Ruvu floodplains in the lower Ruvu catchment. Smaller wetlands occur throughout the basin, including mountainous areas wherever topography and soil conditions allow the accumulation of water and impede drainage.

Agricultural practices in certain areas, land conversion, water abstraction, brick making and pollution are the main threats affecting wetlands of the Basin (Gritzner and Jemison 2009). A catchment-level water management perspective requires that plans for large-scale agricultural expansion involving wetland drainage consider the ecosystem services provided by wetlands and, furthermore, devise ways to minimize the loss of wetland area, connectivity and function. Increasing awareness generation amongst stakeholders active in wetland areas can facilitate the conservation and wise use of wetlands.

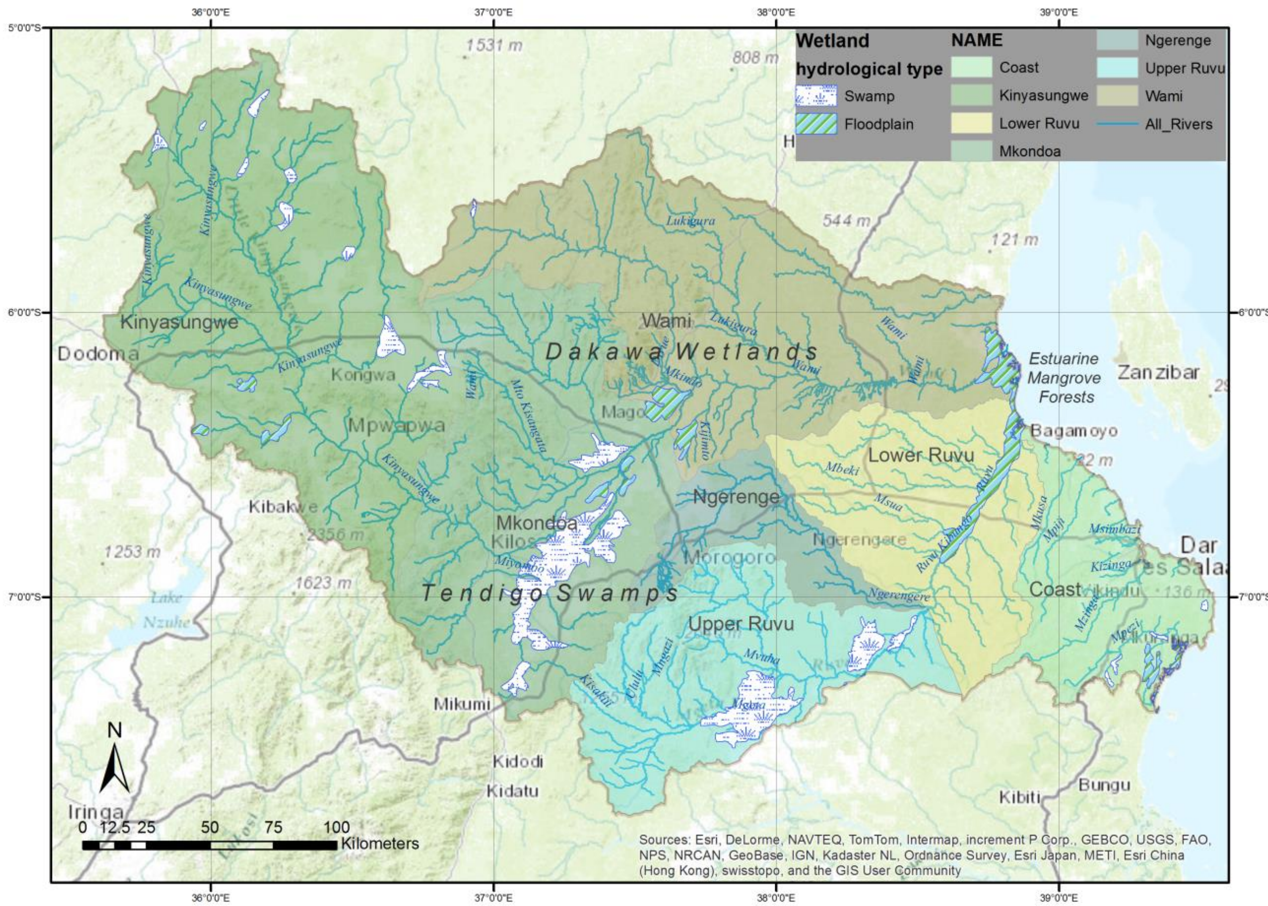


Figure 3-6: Large wetland areas in the Wami/Ruvu Basin (shown as swamps and floodplains) along with the river network. Subcatchments of the Wami, Ruvu and Coastal rivers are also shown. [Data Source: WRBWO]

3.4 Final remarks - the role of forests in buffering uncertainty in water supply

As described, forests partition incoming rainfall and increase the amount of infiltration and groundwater recharge and thereby extend stream flow later in the dry season. It is a very common sight to see streams running in forests while streams in the surrounding deforested areas are dry. Wetlands also store water during the rainy season that is then released to sustain downstream river flow in the dry season. This retention of water on the landscape, instead of losing all water to instantaneous runoff gets even more critical in years with below-average rainfall. Likewise, in years with very high intense rainfall events, forests and wetlands act as capacitors on the landscape and regulate the amount of downstream flow, thereby decreasing the intensity of flooding. Thus forests and wetlands play a very significant role in increasing water retention on the landscape. The protection of existing forests and wetlands and restoration of forest cover provide the most economical and effective approach to buffer a basin and livelihoods from the vagaries of rainfall and increased change of extreme events such as floods. This conclusion is by no means novel; however its importance needs to be repeatedly kept in mind, especially with the added uncertainty in rainfall caused by climate change.

However, as simple and well known this conclusion is, achieving forest and wetland protection is a complex endeavor owing to the need for coordination between multiple stakeholders. At the outset, conserving existing forests needs continued enforcement by the Ministry of Forests and National Park Authority along with the cooperation of village communities situated near forests who also depend upon forest produce for some of their needs as well as the active cooperation of the Ministry of Water, given the critical role catchment forests play in water availability. Steep deforested slopes need restoration via implementation of soil and water conservation measures. There are ongoing efforts in some areas, such as the Tanzania Agriculture Program, or by CARE. However, such efforts are necessary on a larger scale, which is possible with the involvement of government agencies as well.

4 Water Resources Vulnerabilities in the Wami/Ruvu Basin

According to the Water Resources Management Act (2009) of the Ministry of Water, Government of Tanzania, the formulation of water allocation and management plans are to be based upon understanding the balance between water resource availability and water demand. A detailed sector-wise assessment of water uses in the basin as well as projected water demands and potential water availability has been carried out by Water Resources Division, Japan International Cooperation Agency (JICA) in cooperation with the WRBWO (JICA 2013). The assessment is based upon water use permit information for major users such as water supply facilities, large irrigated agricultural operations and industries, as well as from estimates of water use for rural domestic (unimproved sources) and livestock. That information is summarized in this chapter to indicate the present water use and projected water demands by sector and sub-catchment, to examine the relative elasticity of sectors to climate change-based uncertainty as well as identify sources of vulnerability in each sub-catchment.

4.1 Water users and uses in the Wami/Ruvu Basin

4.1.1. Water users in the basin – by sector

Figure 4-1 indicates the locations and types of water use permit holders as of 2012. Table 4-2 has the water use in 2011 of different sectors along with the projected demand in 2015, 2025 and 2035. The table also indicates the percentage of each water use supplied by surface water and groundwater in the basin. Irrigation and domestic use are the dominant water uses by volume in the basin, as seen in Figure 4-2.

Domestic use

This sector is comprised of water required for drinking, cooking, washing, bathing, cleaning, and kitchen gardens. Piped water schemes managed by Urban Water and Sanitation Authorities (UWSA) supply many urban communities, while rural communities primarily use shallow wells, borewells, water points, and springs (Water Point Mapping Project, MoW 2014) as well as surface water from rivers and lakes. Urban water supply schemes mainly rely upon groundwater on account of being bacteriologically safer; furthermore, wells can be close to urban regions, thereby avoiding the need for costly pipelines or evaporation/seepage losses in canals. Residents in poorer neighborhoods not served by piped water, use unimproved sources such as local rivers or shallow wells. Domestic use per capita is set at 50 liters/day in urban areas and 25 liters/day in rural areas (MoW 2009). However, actual per capita consumption is higher in cities, as seen from metered connections: 95, 114, and 206 liters/day in Dodoma, Morogoro, and Dar es Salaam respectively (JICA 2013). The JICA study has estimated that basinwide about 127 million cubic meters of domestic water use in 2011 came from surface water, while 165 million cubic meters came from groundwater (Figure 4-2 right and Table 4-1). Growing projected water demands have been modeled with expected rise in population as per The Tanzania National Bureau of Statistics.

Agriculture

Agriculture is the mainstay of the country, contributing 26% to GDP and employing 75% of the workforce, with women comprising about 75% (USAID 2014). In general, the majority of agriculture in the basin is rain-fed. Crops mainly grown are maize, legumes, vegetables, fruits and paddy; sisal plantations are also rain-fed. The Basin also has irrigated farms growing rice and sugarcane. The JICA (2013) study has estimated agriculture water use from irrigation water use only, given that rain-fed agriculture is supplied by rainfall, thus is included in the natural water balance, and is not water that has to be explicitly supplied by the user. Table 4-2 shows the irrigation water use in 2011 as well as the projected demand, assuming no improvements in the efficiency of irrigation. Irrigation is seen to primarily use surface water from rivers and is mainly located in floodplains and wetlands with a shallow water table and alluvial soil. It is also the largest water use in the basin, as seen in Table 4-2.

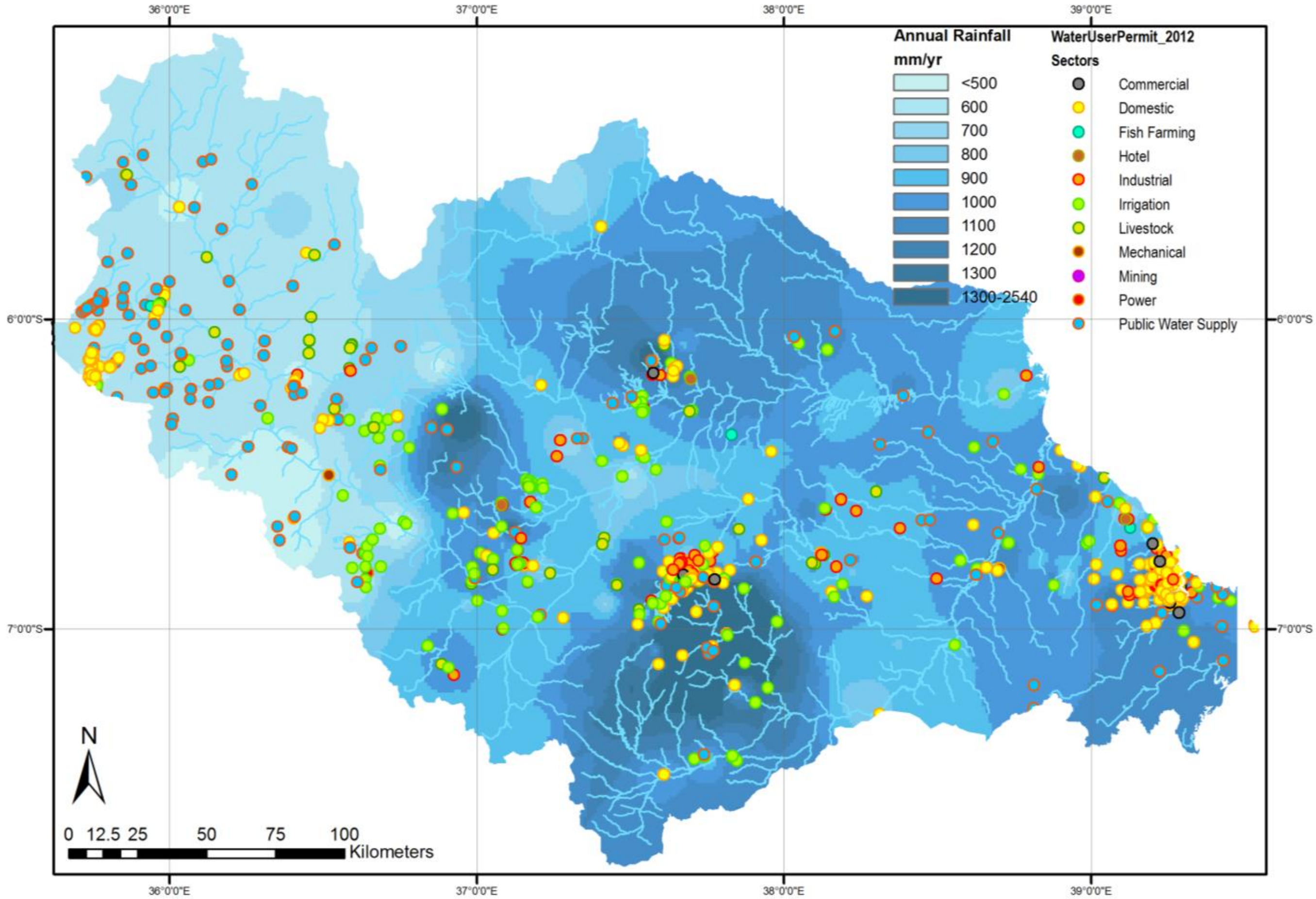
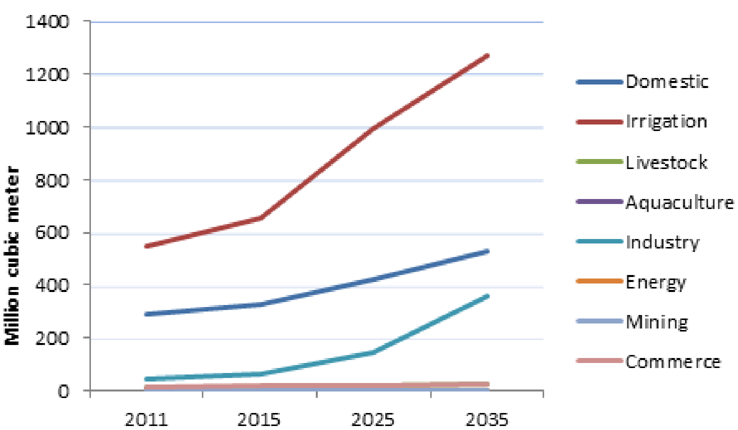


Figure 4-1: Locations of water user permit holders in the Wami/Ruvu Basin as of 2012 shown against a backdrop of average annual rainfall. [Source: WRWBO n.d.]



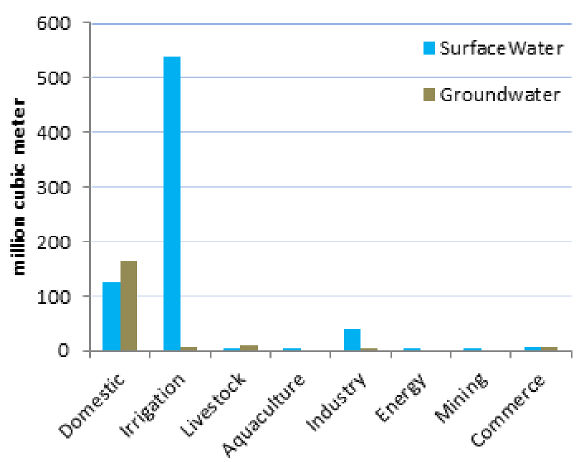


Figure 4-2: (Left) Sector-wise annual water use in 2011 and projected demand in 2015, 2025 and 2035 in the Wami/Ruvu Basin. (Right) Amount of surface water and groundwater used per sector in 2011. [Data Source: JICA 2013]

Table 4-1: Water use and projected demand in the Wami/Ruvu basin. Units are in million cubic meters of water; and surface and groundwater use for 2011 [Data Source: JICA 2103]

Sector	2011	2015	2025	2035	Surface water	Groundwater
Domestic	291	328	420	526	126.294	164.706
Irrigation	546	656	993	1268	538.356	7.644
Livestock	13	15	19	25	2.483	10.517
Aquaculture	0.12	0.13	0.15	0.18	0.12	0
Industry	44	61	142	355	41.58	2.42
Energy	0.04	0.09	0.09	0.09	0.04	0
Mining	0.01	0.01	0.01	0.01	0.01	0
Commerce	14	16	21	26	7.056	6.944

Livestock

Livestock herding is the mainstay of pastoral communities and forms an important sector in the nation's economy by the provision of meat, milk, hides and manure. The JICA (2013) study has estimated water use for livestock (cattle, goats and sheep) by considering the unit water consumption rate (MoW 2009) and population estimates from the National Sample Census of Agriculture. Demand projections are based upon population growth rate suggested by the Ministry of Agriculture and Food Security. Water sources for livestock are mainly from groundwater, although surface water features have been historically utilized when available. Note that while the total water consumption by the livestock sector in the Basin appears miniscule in comparison with irrigation, it is vitally important, and should be considered at the sub-basin level water management.

Fisheries/aquaculture

By being an important protein source and employing a large number of rural people, fisheries constitute an important socioeconomic sector. Most fish farming is carried out in excavated ponds in wetland areas that are rain-fed, but need replenishment from surface water for evaporation losses. Tilapia and other cichlid species, known for their hardiness and tolerance of low oxygen waters are the most commonly farmed fish.

Industry

The major industries are food-processing, textiles, chemicals, and printing. JICA estimates of water use are based upon the unit rate of production as determined by the Tanzania Department of Internal Development, report 2003 (referred to in JICA 2013) and the amount of production. Surface water is the dominant form of water used. Growth in the industrial sector is expected, and in turn, water demand.

Mining

Most of the organized sector mining in the Wami/Ruvu basin is for quarrying mineral aggregate, limestone, marble, and copper. JICA estimates of water use are based upon the unit water use rate per production and amount to < 10,000 million cubic meters of water, all from surface water.

Energy

Electricity in the basin is primarily generated in thermal power plants, where large quantities of water is used in cooling processes, with the exception the Songasu Plant that has an air cooling system. Electricity production and demand is reasonably assumed to increase. Water used is from surface water.

Commerce

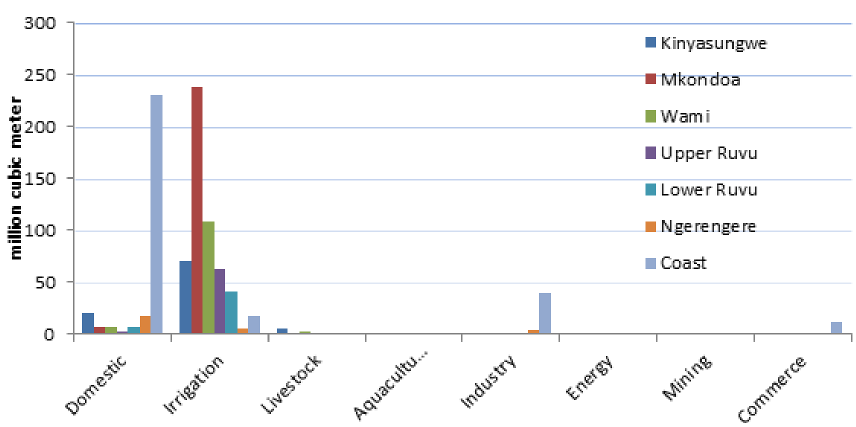
This sector includes markets, transportation, hospitality and tourism, education, and administration services, mainly concentrated in urban areas, and using surface water and groundwater in more or less equal proportions.

4.1.2. Spatial perspective - water use by sub-catchment

Water allocation and management plans are formulated at the sub-catchment level; the subcatchments are the watersheds of the major tributaries or sections of the Wami and Ruvu rivers. In addition, a third area comprising the catchments of the coastal rivers Mpiji, Mzimbazi, Mziinga, Kizinga, Mbezi, and Luhute is termed the Coast subcatchment.

Table 4-2: Sector-wise water use in 2011 per subcatchment of Wami/Ruvu Basin. Units are in millions of cubic meters. [Data Source: JICA 2013]

Subcatch	Dom.	Irrig.	Livest.	Aquac,	Ind.	Ener.	Mining	Comm	Total	SW	GW
Kinyasungwe	19.801	70.541	5.496	0.006	0	0	0	0.602	96.446	66	30
Mkondoa	7.367	238.36	1.579	0.025	0	0	.001	0.089	247.421	239.4	8
Wami	6.798	108.99	3.104	0.028	0.455	0	.002	0.171	119.548	111.3	8.2
Upper Ruvu	2.896	63.6	.804	0.024	0	0	0	0.012	67.336	65.3	2.1
Lower Ruvu	6.678	41.279	.787	0.0004	0	0	.003	0.211	48.9584	44.1	4.9
Ngerengere	17.318	5.758	.307	0.012	4.335	0	0	0.98	28.71	27.5	1.2
Coast	230.064	17.311	1.212	0.018	39.361	.042	.002	12.298	300.308	162.8	138



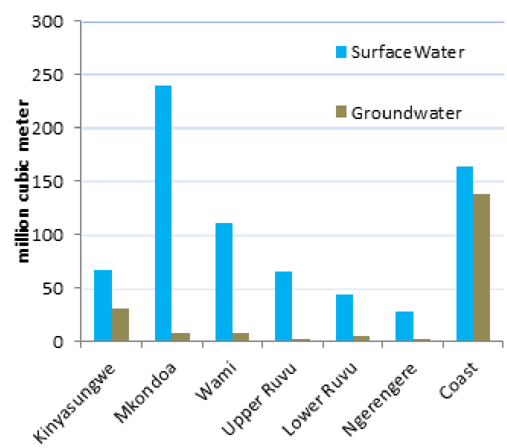


Figure 4-3: (Left) Sector-wise water use in subcatchments of Wami/Ruvu Basin in 2011. (Right) Surface water and groundwater use in subcatchments. [Data Source: JICA 2013]

Patterns of water use and the sources accessed differ regionally across the Wami/Ruvu Basin, as seen in Figure 4-3 and Table 4-2. By far the major domestic water demand as well as industrial water demand is in the Coast region on account of having the highest urban population. For irrigation, Mkondoa has the highest use, followed by the Wami subcatchment, then Kinyasungwe, and Lower Ruvu. The Kinyasungwe subcatchment has the largest livestock population in the basin. Other bulk water uses from sectors such as energy, mining, and aquaculture are very small when compared to domestic use and irrigation. Only the Coast and the Kinyasungwe regions utilize groundwater at comparable levels with surface water. The Coast relies heavily on groundwater on account of urban water supply requiring good water quality and proximity from a distribution perspective. Kinyasungwe relies upon groundwater on account of being an arid region with limited surface water resources.

4.2 Water resources vulnerability in the Wami/Ruvu Basin

4.2.1. Assessing water demand in relation to water availability

In the Wami/Ruvu basin it has been estimated that only 15-20% of annual discharge can be utilized to meet anthropogenic water demand (JICA 2013), because a large fraction of the annual discharge flow off as floods in the rainy season. However, the annual discharge is considered to be surface water potential from the perspective of development of reservoir capacity or storage capacity, as it is a measure of the total water that is potentially available part of which can be stored in reservoirs. JICA compared the present water use (2011) and future demands (2015, 2025 and 2035) in three scenarios (current use, industrial growth, and more efficient irrigation) against potentially available water (the surface water potential in normal and dry years, together with groundwater development potential)[5], in order to calculate the water deficit expected (Figure 4-4). The water deficit is then used to decide upon water storage augmentation and groundwater development to meet water demand.

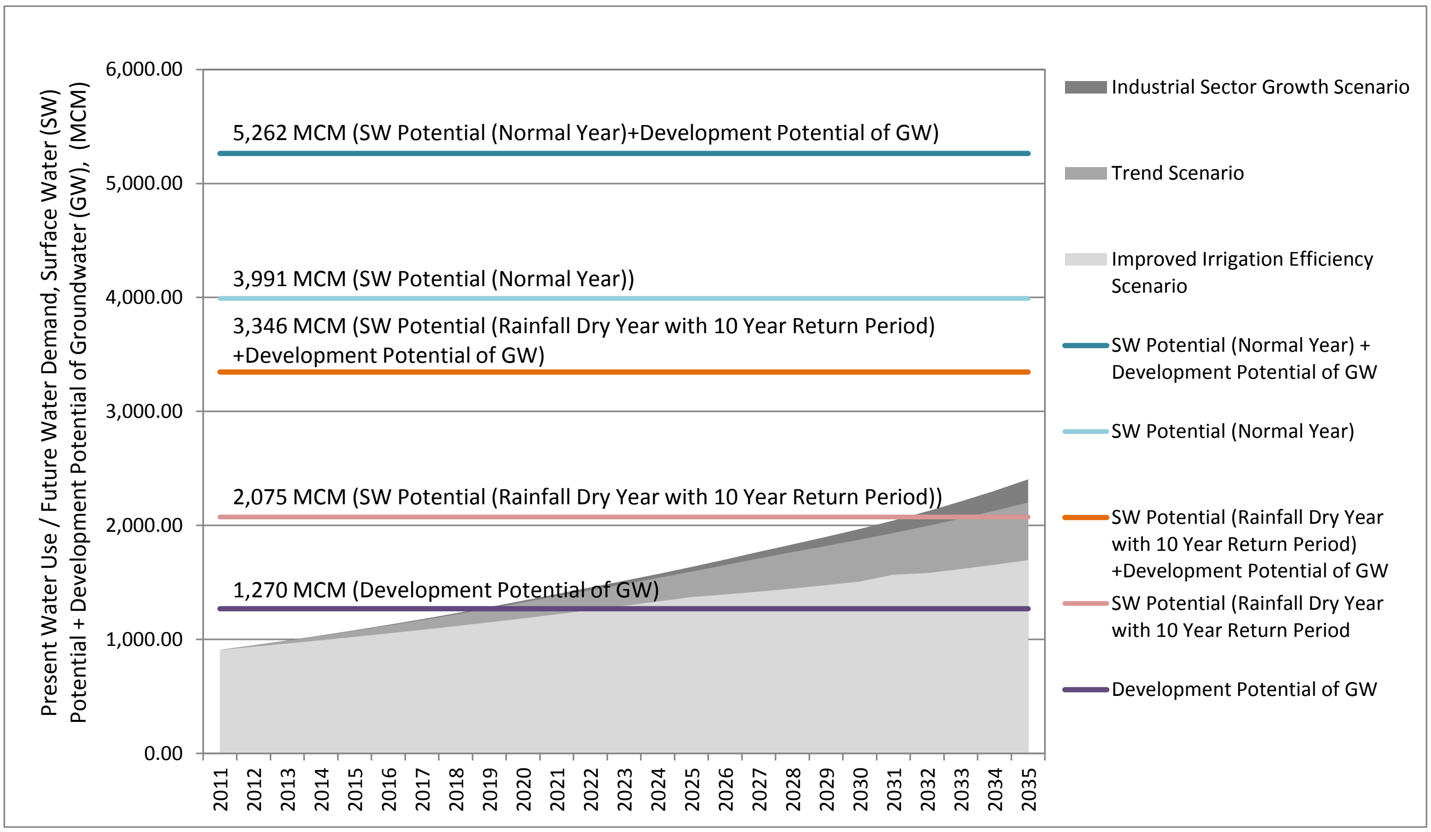


Figure 4-4: Water demand of three scenarios (trend, improved irrigation, and industrial growth) and water resources availability (surface water potential and development potential of groundwater) in the Wami/Ruvu Basin. [Source: JICA 2013]

[5] In this study, the surface water potential was obtained by a numerical model that calculates discharge in a catchment assuming no water withdrawals.

4.2.2. Variability in water sources – increasing uncertainty

Considering that rainfall is the main input of water into the basin, inter-annual variability in rainfall results in inter-annual variability in surface water potential. This is illustrated in Figure 4-4 by surface water potential under two rainfall scenarios: a normal rainfall year (equal to long-term average annual rainfall in basin) and a 'dry' rainfall year (low annual rainfall that re-occurs every 10 years). Surface water potential in a 'dry' year has been estimated as being almost half that of a normal year: 2000 million cubic meters in a dry year as compared to 4000 million cubic meters in a normal year. The surface water potential would be lower in a year with lesser rainfall, such as with a 20 year return period.

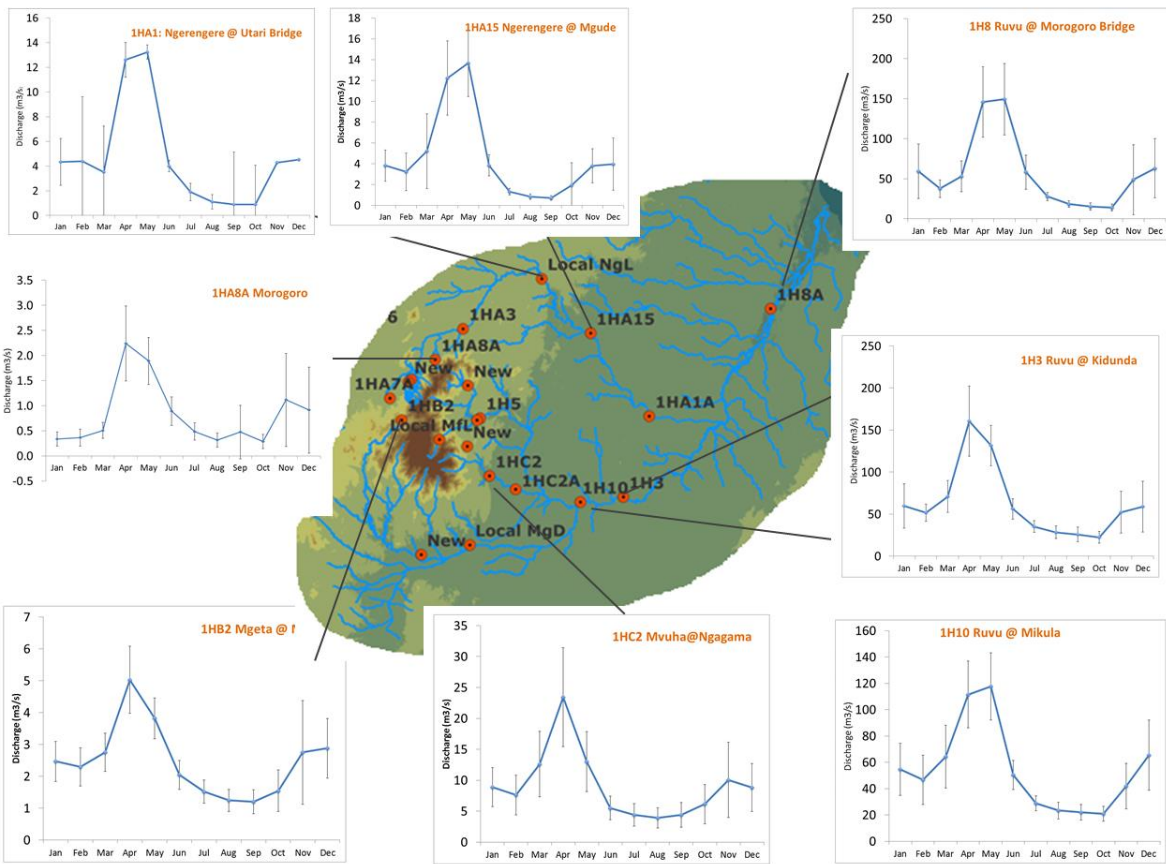


Figure 4-5: Monthly discharge (1952-2010) in the Ruvu Basin. Error bars represent standard deviation for each month, portrayed as half above and half below the mean for display purposes. [Data Source: WRBWO]

The challenge in predicting the occurrence of normal and dry rainfall years is further complicated by climate change. As seen in Chapter 2, most climate models predict an increased variability and uncertainty in the onset/ distribution of rainfall events for this century as well as changes in regional climate teleconnection patterns that affect rainfall. Anecdotal evidence from older residents in local communities suggests that there has been a change in rainfall occurrence in the past couple decades in comparison with further back. They mentioned that rainfall is now less evenly distributed, with high intensity rainfall events separated by dry or low rainfall periods (Vogt and Sheya 2012). This high level of uncertainty accompanies forecasts of increased or decreased streamflows in different basins (Agarwala *et al.* 2003). For instance, a 10% decrease in streamflow projected for the Ruvu Basin, or a 10% increase for the Rufiji Basin, is within the range of uncertainty in rainfall projections, especially evident when comparing multiple models.

While annual statistics of rainfall and surface water potential are convenient for planning storage and other strategies at the basin scale, the availability of water in rivers at a daily or weekly scale is useful for planning in most water use, such as domestic, agricultural, and industrial. Figure 4-5 and Figure 4-6 depict the variability in the long-term average monthly flows in different tributaries and parts of the Wami and Ruvu Rivers. Error bars signify one standard deviation in magnitude, which has been displayed on the map with half standard deviation above and half below, purely for ease of display purposes. High variability is evident in months with greater discharges in the rainy season, indicating flashiness resulting from variability in rainfall. Removal of forest cover and wetlands reduces infiltration/storage and increases the fraction of instantaneous runoff.

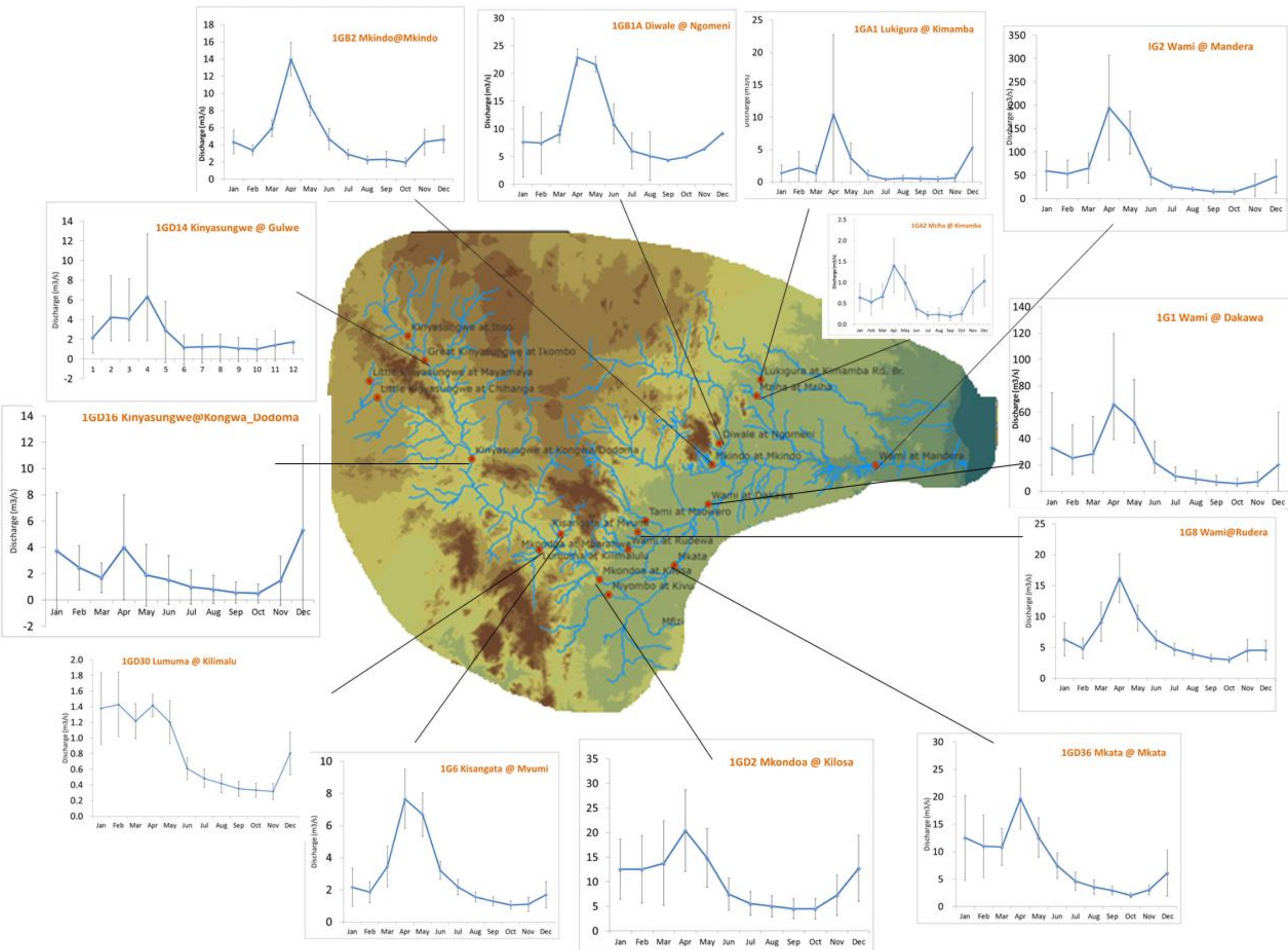


Figure 4-6: Monthly discharge (1952-2010) in the Wami Basin. Error bars represent standard deviation for each month, portrayed as half above and half below the mean for display purposes. [Data Source: WRBWO]

4.3 Final remarks - Exposure of water resources to vulnerability

Knowing the proportion of surface water and groundwater that is utilized by individual sectors in different regions of the basin enables assessment of the exposure of those sectors to vulnerability associated with water resources. In addition, growing population and industrialization will increase water demands in almost all sectors; surface water usage is expected to go up 2.6 times basinwide (from 716.3 million cubic meters in 2011 to a projected use of 1829 million cubic meters in 2035 – JICA 2013). Similarly groundwater usage is projected to increase 1.9 times, from 193 million cubic meters to 373 million cubic meters.

Irrigation with surface water is the largest water use in the basin. This dependence on surface water makes users susceptible to uncertainty in precipitation amounts as well as the distribution of rainfall events over the season. Higher temperatures predicted unanimously by models will lead to larger evaporative losses from surface water bodies, including reservoirs. Furthermore, the ongoing deforestation throughout much of the basin, especially in lowland savannas, significantly decreases water retention on the landscape leading to lower dry season flows in rivers.

The Mkondoa, Wami, and Upper Ruvu subcatchments have the largest amount of renewable surface water resources, due to the presence of EAM and extensive wetlands areas. These are also the areas with the largest surface water use, mainly for irrigated agriculture. The Coast region has the highest demand for both surface water and groundwater, on account of the large urban population and industry.

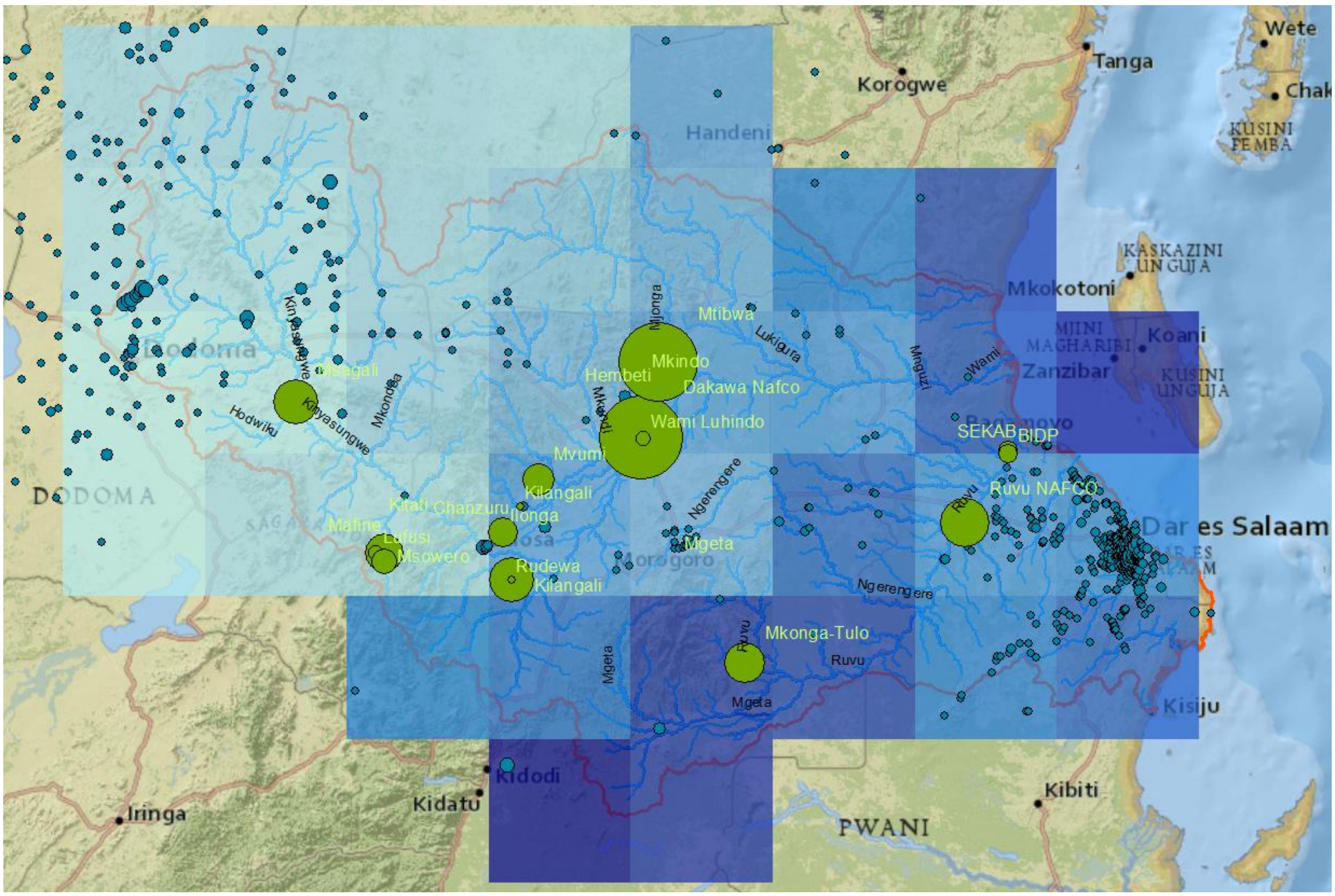


Figure 4-7: Location of borewells (blue circles) and irrigation projects (green circles) in the Wami/Ruvu Basin (orange boundary) overlaid over the mean Annual Precipitation (mm) at a 50 km gridscale. Circle size reflects relative amount of groundwater extraction for borewells and surface water use for irrigation. [Data Source: ClimateWizard and WRBWO]

Groundwater resources are indirectly vulnerable to climate change. An analysis of 55 years of water level data from the Makutapora wellfield in Dodoma region showed that the highly episodic occurrence of recharge coincided with intense anomalous seasonal rainfall associated with ENSO warm phase and IOD positive phase (Taylor *et al.* 2013). Else in most years the high evaporative demand results in very little of the scanty rainfall recharging the aquifer.

However, as discussed before, the high uncertainty on projected behavior of these two climate teleconnections makes groundwater recharge frequency unpredictable.

Recharge is also affected by the removal of forest cover and wetlands as discussed before. The share of groundwater in water demands goes up in drier years. Furthermore, groundwater use is expected to increase along with increase in population growth (domestic supply), livestock, and irrigation. There are plans already for large irrigation projects based on groundwater. There is a danger of falling water tables driven by extraction exceeding natural recharge. Figure 4-7 shows a high concentration of borewells in the semi-arid Dodoma region where current as well as future projected rainfall is low, implying low rates of groundwater recharge from rainfall. Dodoma has a growing urban region on account of being the capital of Tanzania. The other region that has a dense concentration of borewells is the coastal region around Dar es Salaam. While the rainfall in the coastal zone is not as low as Dodoma, sea water intrusion into the aquifer may be accelerated due to high rates of groundwater extraction.

Table 4-3 profiles the main water uses, water sources, exposure to vulnerability, and the directions for adaptive strategies for the subcatchments of the Wami/Ruvu basin. The following paragraphs further discuss the table.

Kinyasungwe: as per the JICA analysis, projected water demand at current consumption patterns is not likely to be satisfied by surface water resources alone even after increasing storage capacity through the rehabilitation of existing reservoirs (Dabalo, Hombolo, Buigili and Ikowa), constructing new reservoirs (Msagali, Ngipa) and transferring water from Farkwa Dam in the Internal Drainage basin outside the Wami/Ruvu basin. Hence more efficient irrigation (including drip irrigation) and higher water-use-efficiency crops are suggested. Development of groundwater extraction systems would also be needed on a larger scale to help meet the demand. Based upon existing hydrogeological investigations, groundwater resources are not known to be as plentiful as in floodplain areas of the Wami/Ruvu Basin, despite the presence of a fault network that holds water. Hence an increase in groundwater level monitoring program is necessary to avoid over-extraction. Livestock and urban areas of Dodoma depend primarily on groundwater in this semi-arid region.

Mkondoa: Surface water irrigation is the main water use in this subcatchment; a lot of the surface water comes from headwater catchments in the Ukaguru Mountains. Projected demands necessitate the construction of reservoirs (Ilonga, Eami, Kisangata and Tami), implementation of efficient irrigation methods and also develop groundwater resources. JICA (2013) describes the quantified analysis of demands and breakdown of each water source for meeting projected demand.

Wami: Like Mkondoa, irrigation is the major water user, using surface water. The Nguru and Nhuu mountains have headwater catchment for several Wami tributaries as well as hydrate the extensive Wami Dakawa wetlands that include Tanzania's largest sugarcane farm and food processing industry – Mtibwa Sugar. Water harvesting, via maintaining existing forest cover and wetlands, will ensure a high annual surface water potential. However, projected demands will require additional storage (Mvomelo and Dihinda) as well as groundwater development and more efficient irrigation.

Upper Ruvu: Irrigation using surface water is the largest water use. The Uluguru Mountains' water harvesting ensures a high annual surface water potential. However, like Wami subcatchment, additional storage development is recommended by the JICA (2013) report (Mgeta, Mungazi), transfer of water from Ruvu Kibungo reservoir and groundwater development.

Ngerengere: Morogoro city and suburbs drive water use in this catchment, with domestic and industrial sectors leading water use. The Mindu Dam and reservoir along with the Ngerengere River arising in the Ulugurus form the major surface water resources. Groundwater resources are relatively low as compared to other areas in the basin. While transfer of water from Ruvu Kibungo is a possibility, improving industrial water use efficiency can also aid water management in the future.

Lower Ruvu: Surface water irrigation is the major water use. The Kidunda Dam that is planned to be constructed in 2015 is intended to stabilize flow in the Ruvu River as well as provide urban water supply for both Lower Ruvu and Coast subcatchments.

Coast sub-catchment: this is the only region in the basin where both surface water and groundwater are used in similar proportions, driven by domestic and industrial demand. The large urban population (almost 4 million), projected to double by 2035, together with the high extent of industrialization represents challenges for water supply and water quality. The coastal location poses an added vulnerability to seawater intrusion to Kimbiji Aquifer that can be accelerated by groundwater extraction close to the coast. Surface water transfer from Kidunda Reservoir, groundwater supply from Kimbiji Aquifer and improved water use efficiency in different industries are ways to meet projected demand.

Table 4-3: Water use, exposure to vulnerability and directions for adaptive strategies in the subcatchments of the Wami/Ruvu Basin. [Data Source: JICA 2013]

Sub-catchment	Features	Main water use sector (%)	Sources (%)	Present & 2035 projected water demand x10^6 m^3 (increase)	Vulnerability	Adaptation
Kinyasungwe	Semi-arid; Dodoma urban	Irrigation (73) Domestic (21) Livestock (6)	SW (68) GW (32)	97 – 280 (2.9 times)	SW: uncertainty, droughts. GW: over-extraction	Catchment protection for GW recharge; SW and GW monitoring; storage
Mkondoa	Mkata plain agriculture	Irrigation (96)	SW (97) GW (3)	247 – 502 (2 times)	SW: uncertainty, droughts, CC.	Catchment protection in Ukaguru and Tendigo wetlands; storage; monitoring
Wami	Wami Dakawa Agriculture	Irrigation (91) Domestic Livestock	SW (93) GW (7)	120-247 (2 times)	SW: uncertainty, droughts, CC. Seawater intrusion along coast and estuary. Deforestation	Catchment protection in Ngurus, Nguu and Dakawa wetlands; monitoring; storage
Upper Ruvu	Mgeta and Ruvu river agriculture	Irrigation (94) Domestic (5) Livestock (1)	SW (97) GW (3)	68-128 (1.9 times)	SW: uncertainty, droughts, CC	Catchment protection in Ulugurus; monitoring
Ngerengere	Morogoro Urban	Domestic (60) Irrigation (20) Industry (15) Commerce (3.4) Livestock (1)	SW (96) GW (4)	29-82 (2.8 times)	SW: uncertainty, droughts, CC. Industrial growth and water pollution.	Catchment protection in Ulugurus; storage; monitoring
Lower Ruvu	Ruvu river for irrigation; GW/SW for commerce & domestic	Irrigation (84) Domestic (13.6) Livestock (1.6)	SW (90) GW (10)	49-119 (2.4 times)	SW: uncertainty, droughts, CC. Deforestation. Seawater intrusion along coast and estuary.	Catchment protection in floodplain wetlands and lowland savanna forest; storage; monitoring
Coast	Dar es Salaam urban area	Domestic (77) Industry (13) Commerce (4) Irrigation (5.7)	SW (54) GW (46)	300-845 (2.8 times)	SW: uncertainty, pollution. GW: over extraction, seawater intrusion. Sea level rise. Deforestation	Catchment protection for coast rivers; storage; monitoring GW, SW and water quality; industrial pollution control

5 Water Resource Management in a Changing Environment in the Wami/Ruvu Basin

Having examined the links between climate, forest cover and water availability in Chapters 3 and 4, as well as the water uses and their exposure to vulnerability in Chapter 5, a set of focal areas for developing adaptation strategies is now laid out. Specifics of the various adaptation strategies and activities are to be drawn up with the participation of all stakeholders. It is important to recognize what set of actions or approaches may constitute successful adaptations, as opposed to just temporarily coping with change (Sreenivasan *et al.* 2013). The details of the process of vulnerability assessment are described in Appendix 2.

5.1 Focal areas of adaptation

The focal areas for adaptation to climate change in the Wami/Ruvu Basin are:

1. Hydrological and water quality monitoring, data management and analysis, technical capacity-building.
2. Groundwater development – hydrogeological investigations and monitoring recharge rates to avoid overexploitation
3. Community awareness generation and community water monitoring programs.
4. Increase natural buffering capacity (water storage capacity) of watershed through forest and wetland protection; preserve water quality at source through soil/water conservation.
5. Maintain and develop basin water storage, supply, and control infrastructure.
6. Form sector-wise plans, e.g. agriculture, wastewater treatment, and natural disaster response management with other agencies and stakeholders.

The following paragraphs discuss some of these adaptations and management measures in the different dimensions of water resources, as well as sectors.

Hydrological and water quality monitoring, data management and analysis

Climate and land cover change in the Wami/Ruvu Basin is associated with higher uncertainty in water resources availability in time and spatial scale. Planned adaptation to climate change requires decision-makers to understand the degree to which a system is susceptible to and able to cope with adverse effects of climate change, and better manage the uncertainty associated with these changes. Water monitoring programs can gather the information needed to plan for and assess possible adaptations to a changing climate, including the understanding of water resources vulnerability (such as predictive modeling, risk assessment, early warning to protect against possible hydrologic events and trend assessment), the development of management tools (such as EFA for issuing water permits), and to better understand the impact of adaptation strategies that are implemented.

During this study and other studies done in the basin (eg. Gomani *et al.*, 2010), some of the water resources monitoring needs that have been identified, or should be strengthened, are river discharge and water quality monitoring. Low cost technology and simple methodologies can be used in order to deal with the limited amount of resources available.

Groundwater monitoring and recharge

Groundwater is thought to be an easily available source that could be utilized more in the coming decades for municipal supply, industries, and irrigated agriculture in the Basin (eg Kashaigili 2010). However, if annual extraction of groundwater exceeds the annual recharge, this would lead to falling water tables, necessitating deeper wells, which are very expensive to drill (6000-12,000 USD – Kashaigili 2010) and unaffordable by small users. Excessive groundwater extraction has been also associated with mobilizing salts underground into the pumped water, which then renders farms saline over time. Hence it is critical to install monitoring wells for groundwater along with a monitoring program to closely monitor the water table along with other water budget parameters such as rainfall. In addition to monitoring, strategies to recharge groundwater should be explored and formulated. Maintaining tree cover on catchments is one method, although fast-growing exotic species such as eucalyptus should not be utilized, as they have a water demand much higher than native tree species adapted to the region's water and nutrient availability.

The concentration of groundwater extracting borewells, and the growth of more such groundwater-based projects strongly necessitates developing a program to monitor groundwater in the Dodoma region. The other steps would be to take steps to promote and enhance recharge (although there is only a limited amount of rainfall in the first place) such as by check dams that retain water against running off. Conservation and reuse of water are other needed approaches. In a 2010 report for the status of groundwater resources in Tanzania, Kashaigili (2010) details steps necessary for the sustainable development of groundwater resources.

Basin water storage

Given the increasing uncertainty in the onset, frequency, and distribution of rainfall, a reasonable adaptive strategy is to enhance the storage capacity in the basin to meet water needs for various sectors. Figure 5-1 shows that most of the existing surface water reservoirs are located in the Wami and Lower Ruvu sub-basins, in addition to some larger reservoirs in the Kinyasungwe and Ngerengere sub-basins, the latter one includes the Mindu dam and reservoir that supplies water to the Morogoro City and rural areas. Existing reservoirs can have their capacity increased by raising the height of levees and spillways. The construction of a new reservoir requires capital and proper siting to minimize seepage losses and social/ecological destruction. Conserving existing wetlands is another way to retain water on the landscape. Degraded wetlands or floodplains can be artificially recreated and managed in a multiple-use scenario, such as fisheries.

Existing reservoirs and tanks require periodic de-silting and maintenance, which are quite expensive. In addition, the construction of overhead tanks in communities is an option to increase local storage in neighborhoods or zones. Treatment plants for large cities, such as the Chalinze treatment plant, would be required to formulate their own climate change adaptation plans, to cope with change in water availability. Infrastructure, such as pipelines, need to be monitored periodically to stop leaks, as water losses via leaky pipes are significant and often amount to 50% of the water supply.

Rural communities in the Wami/Ruvu Basin mainly depend upon springs, streams, rivers, and in a few cases, borewells for water. Increasing uncertainty in rainfall, along with deforestation that reduces infiltration leading to greater runoff following rainfall showers and lower baseflow in the dry season (Yanda and Munishi 2007), is a serious stressor to rural communities. Hence, it is imperative that rural communities supplement their water sources by adding storage (i.e. rainwater harvesting into tanks, digging ponds). Non-profit organizations have been involved in helping local communities build their own storage and water points; however, such activities need to be carried out throughout the Basin. In cases where communities rely upon groundwater via hand borewells, monitoring wells can be installed on those borewells, and with training provided to communities, such data can contribute to the Basin's groundwater monitoring datasets. High rainfall is continued to be forecast for the Easter Arc Mountains; this indicates the necessity to protect and maintain forested catchments to (i) increase infiltration into groundwater that maintains base flow in streams in the dry season, and (ii) to decrease soil erosion from heavy rainfall in deforested hill slopes, that apart from devastating the mountains, causes sedimentation problems in lowland rivers which in turn increases flood hazards, reduces channel storage, and irreversibly harms the aquatic ecosystem, including fisheries that local communities depend upon.

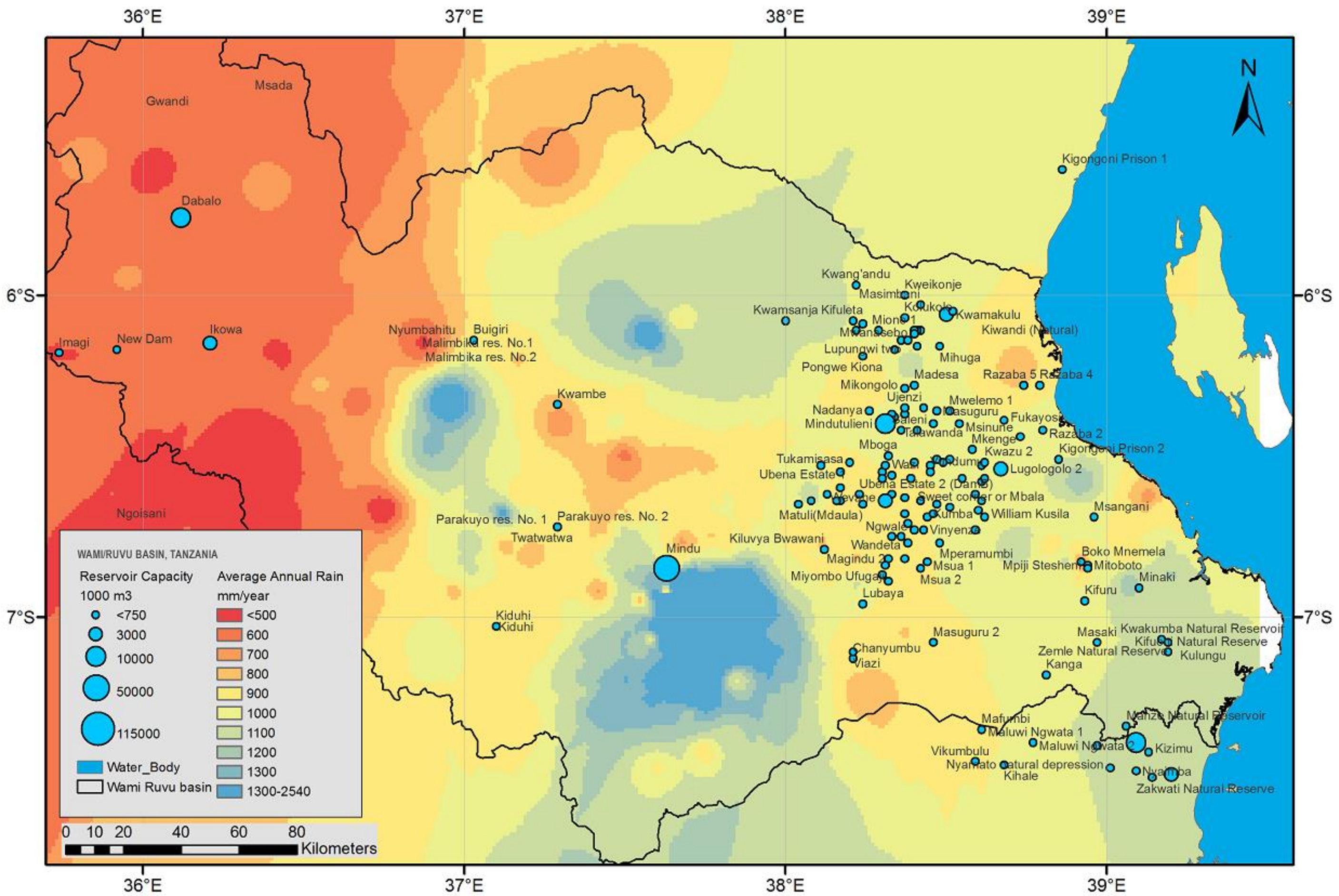


Figure 5-1: Surface water reservoirs existing in the Wami/Ruvu Basin over a backdrop of the average annual rainfall. [Data: WRWBO]

Extreme events and early warning systems

Deforestation in the mountains, sedimentation-induced reduction in channel depth, and predictions of more episodes of heavy rainfall increases the chances of flooding. For instance, frequent floods associated with high runoff and riverflow has been experienced in the Kilosa region in recent years. A network of early warning systems, if installed and maintained, can aid with decreasing losses in human life and some economic activity. Community monitoring programs create a mechanism whereby communities noticing high rainfall and water levels in their local vicinity report that to the other villages, specifically the downstream villages, the local Water Users Association and Basin Water Office. The use of mobile phones together with designated people in different communities to act as source persons in a network can comprise the signaling part of the early warning system. A system of reading water levels, whether staff gages or painted marks on a bridge pier / tree can add some quantitative objectivity to observing and reporting water levels.

The periodic maintenance of floodgates and other infrastructure in reservoirs such as the Mindu dam ensures that gates do not get jammed in the event of heavy rainfall and river flows. Sudden releases of vast amounts of water from a flooded reservoir due to breaking of in-operational gates create a catastrophic loss of life and property downstream. GIS-based floodplain and low elevation maps help in visualizing areas at risk to flooding, along with roads, schools and buildings that could serve as evacuation shelters to help with quick response to flood emergencies that usually do not leave much time for preparation.

Water quality and catchment protection

Water quality concerns get magnified under low-flow scenarios on account of water abstractions as well as low baseflows stemming from either land cover change or low rainfall. Sediment is the major non-point pollution source in the Basin (Yanda and Munishi 2007, Ngana *et al.* 2010), hence protection of water courses from sedimentation or excessive siltation is critical. Figure 5-2 shows maize cultivation without any soil conservation methods (such as terracing/contour bunds/mulching/contour trenching) on a steep hillside cleared of forest. Furrows are visible that will widen into gullies, at which point the task of regeneration of the slope gets very difficult on account of the lack of soil cover. There are some places in the Ulugurus where farmers have constructed terraces under the auspices of programs such as Tanzania Sustainable Agriculture. However, the on-going clearing of forests for cultivation without terracing is widespread (Figure 5-2), with serious consequences for water quality, reduction of river channel depth that exacerbates flooding, loss of habitat for aquatic macro-invertebrates and the consequent loss of instream diversity and water quality maintenance processes. The loss of soil itself is an irreplaceable loss for generations. Yanda and Munishi (2007) have described land cover change in the Ruvu river basin and accompanying reductions in flow and increase in sedimentation. Water resources and hence water quality is a common resource, and thereby a multi-stakeholder soil conservation program is essential for maintaining water quality.

The Eastern Arc Mountains (Nguu, Ngurus, Ukagurus and Ulugurus in the Wami/Ruvu basin) play a critical role by tapping moisture from the easterly trade winds in the form of rainfall and contain the headwater catchments of the Wami and Ruvu Rivers. While their elevation results in orographic precipitation from the trade winds, it is their forest cover at the higher altitudes that promotes interception and infiltration of rainwater, thereby reducing immediate runoff and sustaining baseflow over a longer period in the dry season. Forests also increase boundary layer resistance and are thought to contribute to retaining cloud cover which acts as another source of moisture (e.g. Bruinjzeel 2001). The importance of the EAM forest cover in hydrology is well known as evidenced by numerous reports and publications that recommend the controlling of deforestation (e.g. Yanda and Munishi 2007, Ngana *et al.* 2010, Nobert and Jeremiah 2012). Controlling deforestation and conserving headwater catchment forest cover is by and large the most important task facing the Wami/Ruvu Basin in relation to sustainable water resources management, and needs a multi-stakeholder multi-pronged approach.

Figure 5-2: View of secondary forest (left), corn farm (center) and soil erosion channels forming (right) on a hillside in the Nguru mountains, Mvomero district, Tanzania.

Sector-specific adaptation directions

Agriculture

Increased uncertainty in rainfall requires the diversification of crops with different tolerances to drought, pests, and floods. A long drought can trigger other plant stressors such as pests, e.g. locust invasions; observations of an apparent coincidence of stressors such as drought and pests are common across many ecosystems (Mattson and Haack 1987, Ayres and Lombardero 2000).

Drip irrigation methods require further popularization given that they use less water and thus avoid the salinization of soil that often accompanies irrigation with canal water or uplift of higher salt-content water from deeper layers. The Dodoma region has been identified as one of the most drought-stricken regions in Tanzania, with rainfall shortages causing crop failures (GOT 2007). Droughts have always been around; farming traditions in semi-arid areas have developed dryland agriculture techniques that are focused on conservation of water and nutrients. For instance, subsistence farmers in Burkina Faso dig small holes (zaï) on degraded land and fill them with leaves, twigs and animal waste, thereby adding nutrients to the soil where they sow their crops (Lee & Vischer 1990). They also construct contour bunds on their farmland to slow down water runoff, prevent erosion, and assist in groundwater recharging. Similar efforts have been underway by small farmers all across the world often in cooperation with NGOs, government agricultural extension units and networks such as Low External Input Sustainable Agriculture (http://www.agriculturesnetwork.org).

Flooding poses another set of challenges to agriculture. Osbahr *et al.* (2008) detail accounts from villages in Mozambique affected by a series of alternating droughts and floods, where drought resistant crops planted as an adaptation to an ongoing multi-year drought were destroyed by floods in the subsequent year. Farmers historically hedged their susceptibility to climate and environmental variability by planting a range of crops with a varied tolerance to floods, droughts and pests. The advent of the Green Revolution has led to the decreased planting and subsequent loss of many traditional cultivars in the pursuit of a fewer high-yielding varieties; such a traditional safeguard against changing environments needs to be restored and strengthened. In studies in the Gambia and India, Kerr (2012) mentions that the decrease in planting traditional foodcrops such as cereals, millets and groundnut and increases in rice planting has also led to a disproportionate increase in workload for women while decreasing nutrition intakes. Hence, social inequities and environmental concerns have to be considered in developing climate-smart agriculture strategies.

Livestock

Existing conflicts between pastoralists and agricultural communities in the Basin (Ngana *et al.* 2010) could be exacerbated by water scarcity and declining water quality. Livestock, especially cattle are very susceptible to droughts; the recent 2008-2009 drought in the Arusha and Manyara region killed more than 700,000 cattle and devastated the pastoralist communities (Arusha Times 2009, 2010). Upholding land tenure of livestock herders ensuring water access for livestock is a step towards conflict prevention and resolution. Moreover, the creation of additional livestock water points such as charco dams will lessen the needs for livestock herders to access the same water sources used for agriculture (De Bruin *et al.* 2102). Challenges remain in overcoming the historic universal animosity between settled and nomadic people; however a mutual understanding and cooperation on sharing water resources is a prerequisite to sustainable water management in the Basin.

Water supply and demand management

As review by this study, the availability of water resources in the Wami/Ruvu Basin are undergoing rapid and difficult to predict changes due to multitude of reasons, including change in the forest cover and climatic change. On the other hand, growing water demands in the Basin have been predicted following population growth and urbanization. Given this situation together with the limitations in the possibilities of developing new water resources in the country (WSP, 2011), it would be prudent to shift from the traditional 'supply based management' to a ‘demand management’ paradigm (Vairavamoorthy *et al*. 2008).

Demand management has been defined as “[t]he adaptation and implementation of a strategy (policies and initiatives) by a water institution to influence the water demand and usage, looking to shift from a reactive towards a proactive management of water resources. Among the measures to manage demand of water in order to meet any of the following objectives: economic efficiency, social development, social equity, environmental protection, sustainability of water supply and services, and political acceptability” (DWAF 2009). Demand management techniques to be explore for their implementation in the Basin include: intermittent water supply; water loss reduction (including leak detection and repair); comprehensive metering, changes in water pricing concepts, installation of water saving devices (retrofitting), wastewater reuse, institutional development, and public awareness and educational campaigns (Vairavamoorthy and Mansoor 2005).

Forests, biodiversity and tourism

The globally-renowned rich wildlife and natural heritage of Mikumi National Park and the Selous Ecosystem, the Eastern Arc Mountains and the coastal ecosystems of Saadani National Park are the major attractions for tourists to the Wami/Ruvu Basin. Maintaining the biodiversity, landscapes, and cultures of the region in a scenario of increasing uncertainty in water availability can benefit from ecohydrology studies that link wildlife and forest ecology to water quantity, quality and other ecosystem services. Cloud montane evergreen forests in the Ulugurus, Ngurus, and Ukagurus, apart from being the headwaters for the Wami and the Ruvu, have many endemic species and are very rich in biodiversity (Burgess *et al*. 2007).

Involving local communities in the management and protection of local forests (such as the Joint Forest Management and Community Forest Management) attempts to achieve a sustainable co-existence by meeting basic income, fuel and fodder needs of people who also are positioned to be sentinels. A multi-stakeholder effort is essential, despite the significant challenges involved. Bringing together organizations such as the Eastern Arcs Conservation Endowment Fund, NGOs like Tanzania Sustainable Agriculture, the WRWBO, ministries of forest resources and environment can catalyze the process of working with local communities to develop alternate income generating activities (to charcoal production), soil conservation on existing farms and the development of tourism, with hiking trails and the economic opportunities that responsible tourism can provide to local villages. The Ulugurus in particular can benefit from the proximity to Morogoro, Mikumi National Park, Selous, and Dar es Salaam.

A small fraction of lowland savannas and *miombo* woodlands are preserved in Mikumi and Selous. Rising temperatures and declining water availability across these areas will result in a general shift to drier vegetation regimes; from moist forests to dry forests, accompanied by greater chances of forest fires (Platt *et al*. 2013). Detailed studies on how the ecosystem structure and function is connected to water are required, that are then to be incorporated in efforts to shield the ecosystem from rapid unprecedented fluctuations in rainfall. The creation and careful siting of pools inside national parks is one way to ensure water availability for wildlife. Preservation of catchment forests provides a degree of buffering from water stress that is not possible in any other manner at the landscape scale.

On the coast, the Saadani National Park is the only park in East Africa that includes marine areas, along with coastal and estuarine areas. Healthy seagrass and mangrove ecosystems are essential to maintain coastal marine fisheries because they act as nurseries for fish and sustain marine aquatic communities. These ecosystems rely upon the quantity and quality of the freshwater inputs from upstream, dimensions that susceptible to climate change Environmental Flow Assessments used to ensure the amount of freshwater required to maintain healthy estuaries, as well as basin wide pollution control practices are required to keep these ecosystems healthy.

Energy sector

Given the increased uncertainty associated with the different climate change scenarios, the energy sector needs to consider the diversification of energy sources into renewable energy where possible. Furthermore, years with very high rainfall can necessitate water level management in reservoirs by operating floodgates to release some of the impounded water downstream. These gates should be maintained periodically so that they do not get jammed or not operational in times of crisis of extreme high water levels in reservoirs that can endanger the dam itself, or lead to pulsed flash floods downstream.

Coastal zone management

Coastal Wami/Ruvu basin supports a high human population and vigorous economic activities, including tourism, industry, shipping, subsistence agriculture and fisheries. Sea level rise is likely to have a considerable impact on Tanzania's coastal communities, their infrastructure and the ecosystems they depend on for their livelihoods (e.g. Tobey and Mwakifwanba 2009, Tobet *et al.* 2011, Brown *et al.* 2012, Yanda 2013).

High rates of groundwater extraction associated with the increasingly high concentration of borewells in and around growing coastal cities like Dar es Salaam and Bagamoyo has the danger of accelerating sea water intrusion into the coastal aquifers and subsequent salinization of water that would render borewells unusable (de Witte 2012).

Sea level rise will increase the risk of coastal flooding; for instance, around 10% of Dar es Salaam lies within 10 m elevation above sea level; exposure to flooding and related infrastructural problems is projected to affect 210,000 people and almost 10 billion USD worth of assets by 2070 under SLR caused by current rates of emissions (Kebede and Nicholls 2010).

Tobey and Mwakifwamba (2008) mention mangrove rehabilitation, formation of community mangrove management associations, relocation of wells from saline areas to upland areas, training of community workers in water conservation, management and recycling, construction/upgrading coastal sea walls, dikes and spillways in Rufiji, Pangani and Zanzibar as possible management strategies to address adaptation to climate change in productive zones in coastal Tanzania.

Public Health and Epidemiology

Increasing temperature regimes favor the risk of malaria, dengue fever, and encephalitis spreading to central highland areas as well as higher up the EAM (Siraj *et al.* 2104), as has been seen in highlands of Ethiopia and Colombia (University of Michigan 2014). Increases in heavy rainfall events can create pools of standing water that provide opportunities for mosquitoes to breed. The existence of stagnant water-filled pits in abandoned illegal goldmines in EAM combined with temperature increases can lead to malaria moving up the mountains.

Infectious diseases such as cholera, dysentery, and typhoid are rampant in the aftermath of floods, with clean drinking water and appropriate sanitation in short supply. As the risk of flooding increases under climate change, it is likely that so too will the risk of diseases outbreaks. Disaster management plans and programs need to acknowledge the possibility of a higher frequency of extreme events coinciding with a rise in urban populations.

5.2 Final remarks – managing water resources vulnerabilities in the Wami/Ruvu Basin

Climate predictions for the Wami/Ruvu Basin by this study suggest rising temperatures across the basin through this century. Rising temperatures have the potential to affect almost every economic sector as well as cause species and community shifts in ecosystems. Models have far less agreement on precipitation trends, given the complexity of climate systems influencing rainfall. However, the close connection between temperature increases and atmosphere-biosphere energy budget, evapotranspiration and pressure systems indicates possible changes in rainfall patterns – both the onset and the spatiotemporal distribution of precipitation. This connection can also result in a possible increase in extreme events such as floods, droughts and related problems like pest outbreaks and fires.

An increase in uncertainty of water availability is a key issue to be considered in natural resource management. Adapting to climate change provides opportunities to manage water resources and activities in ways that strive to ensure that water needs are met amidst this uncertainty in water availability. Lessening negative impacts on ecosystems is crucial, because it is the various ecosystems—from cloud forests in the mountains that trap rain and ensure streamflow through the year, to wetlands that acts as sinks, to mangroves that protect coastal shores from erosion and preserve fisheries and coastal livelihoods—that buffer human populations from the vagaries of extreme events, uncertain rainfall and high temperature.

Some of the activities (such as water demand analysis, water balance analysis and development of water resource monitoring programs) are wholly within the purview of the regional water authorities, such as the WRBWO. Local and international research institution networks can aid water authorities in integrating technical and scientific advances in fields related to water resource management, such as hydrological monitoring, climate and land cover analysis, data management and modeling. The use of open-source software is encouraged to decrease chances of data analysis and management applications being unusable on account of the quick obsolence of commercial applications that necessitate license renewals and upgrades.

Other activities such as catchment forest protection and wetland management require cooperation between government institutions, local communities, NGOs and research institutions. The need for community awareness of the very real possibilities of increasing water scarcity and deteriorating quality is going to be even more critical with rising urban populations and per capita resource demand. Conservation, wise use and storage of water at the consumer's end can help the quest for sustainable water demand management at all scales.

A multi-scale coordinated strategy spanning sectors and stakeholders is the framework required to achieve the balance between economic development/growth and sustainable water resource usage. As both water supply and demand are continually changing, this balance is also dynamic, and achieving the best combination of strategies to obtain this balance is dependent upon the lessons learned from implementation of management plans. Furthermore, plans developed and implemented by the WRBWO can be a source of information / guidance for the development of similar water resource management plans elsewhere in Tanzania and the Developing World.

References

Agrawala S, Moehner A, Hemp A, van Aalst M, Hitz S, Smith J, Meena H, Mwakifwamba SM, Hyera T, and Mwaipopo OU. 2003. Development and Climate Change in Tanzania: Focus on Mount Kilimanjaro Report. OECD, Paris, 72pp.

Ahrends A, Burgess ND, Milledge SAH, Bulling MT, Fisher B, Smart JC, Clarke GP, Mhoro BE and Lewis SL. 2010. Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. Proceedings of the National Academy of Sciences. 33, 14556-14561

Arusha Times. 2009. http://www.arushatimes.co.tz/2009/47/front_page_1.htm Accessed October 10, 2014

Arusha Times. 2010. Arusha Records 700,000 Livestock Deaths at End of Drought Spell, The Arusha Times, [internet] 29 May. http://allafrica.com/stories/201005311054.html Accessed October 10, 2014

Allen M and Ingram WJ. 2002. Constraints in future changes in climate and the hydrologic cycle. Nature. 419, 224-232.

Allen RG, Pereira L, Raes D, and Smith M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. http://www.fao.org/docrep/X0490E/X0490E00.htm accessed May 12, 2013.

Alusa AL and Ogallo LJ. 1992. Implications of Expected Climate Change in the Eastern African Coastal Region: an Overview. UNEP Regional Seas Reports and Studies No. 149, UNEP.

Arnell, NW (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change. 14, 31–52.

Ayres MP and Lombardero MJ. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci Total Environ. 262, 263–286.

Balica SF, Douben N, Wright NG. 2009. Flood vulnerability indices at varying spatial scales. Water Sciecne Technology. 60, 2571–2580.

Bernacsek. 1980. Freshwater fisheries and industry in the Rufiji River Basin, Tanzania: the prospects for coexistence (http://www.fao.org/docrep/008/ad793b/ad793b00.htm) accessed December 19, 2012.

Beyadi, A. 2010. Environmental Cost of Soil Erosion Amounts to One-Third of GDP, Tanzania Daily News, [internet] 24 May, Available at http://allafrica.com/stories/201005241545.html

Biao Z, Wenhua L, Gaodi X, Yu X. 2010. Water conservation of forest ecosystem in Beijing and its value, Ecological Economics. 69(7), 1416-1426.

Boening, C., J. K. Willis, F. W. Landerer, R. S. Nerem, and J. Fasullo (2012), The 2011 La Niña: So strong, the oceans fell, Geophys. Res. Lett., 39, L19602, doi:10.1029/2012GL053055.

Bosire, J. 2009. Kenya: Climate Change Favours Coffee Pest, The East African [internet] 10 August. Available at: http://allafrica.com/stories/200908101181.html

Bracebridge, C. 2006. Mkindo Forest Reserve: forest disturbance report. Report for Tanzania Forest

Conservation Group and Participatory Environmental Management Programme, Dar es Salaam, Tanzania.

Brown S, Kebede AS and Nichols RJ. Sea Level Rise and Impacts in Africa: 2000-2100. School of Civil Engineering and the Environment, University of Southampton, UK.

Bruijnzeel LA. 2001. Hydrology of tropical montane cloud forests: a reassessment. Land Use and Water Resources Research 1:1.1 – 1.18

Bruijnzeel, LA. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees?, Agriculture, Ecosystems and Environment. 104(1), 185-228.

Burgess ND, Butynski TM, Cordeiro NJ, Doggart NH, Fjeldsa J, Howell KM, Kilahama FB, Loader SP, Lovett JC, Mbilinyi B, Menegon M, Moyer DC, Nashanda E, Perkin A, Rovero F, Stanley WT, Stuart SN 2007. The biological importance of the Eastern Arc Mountains of Tanzania and Kenya. Biological Conservation. 34, 209-231.

Calder I. 2007. Forests and Water: ensuring forest benefits outweigh water costs. Forest Ecology and Management. 251(1-2), 110–120.

Chambwera M and MacGregor J. 2009. Cultivating success: the need to climate-proof Tanzanian agriculture, IIED, London,2pp. CRED. 2010. EM-DAT: Emergency Events Database. Available at http://www.emdat.be/

Church JA and White NJ. 2011. Sea level rise from the late 19th to the early 21st century. Survey Geophysics. 32, 585-602.

ClimateData EU. http://www.climatedata.eu/climate.php?loc=tzxx0002&lang=en Accessed October 9, 2014

De Bruin A, Cinderby S, Mbilinyi B, Mahoo H, Barron J. (2012) Watershed Level Baseline Assessment in the Mkindo Watershed, Wami Basin, Tanzania. Report for Agricultural Water Management (AWM) Solutions Project. Stockholm Environment Institute.

De Wit M and Stankiewicz J. 2006. Changes in Surface Water Supply Across Africa with Predicted Climate Change. Science. 311(5769), 1917-1921.

De Witte I. 2012. Characterization of the status of Dar es Salaam aquifer in view of salt-water intrusion and nitrate contamination.Master of Geology thesis, Universiteit Gent, The Netherlands. p.134.

Dudley N and Stolton S. 2003. Running Pure: The importance of forest protected areas to drinking water. A research report for the World Bank / WWF Alliance for Forest Conservation

DWAF. 1999. Water Conservation And Demand Management – National Strategy Framework, Department of Water Affairs and Forestry, South Africa.

Eggleston J and Pope J. 2013. Land subsidence and relative sea-level rise in the southern Chesapeake Bay region: U.S. Geological Survey Circular 1392, 30 p., http://dx.doi.org/10.3133/cir1392.

FAO. 2011. Eucalyptus in East Africa, Socio-economic and environmental issues, by Gessesse Dessie, Teklu Erkossa. Planted Forests and Trees Working Paper 46/E, Forest Management Team, Forest Management Division. FAO, Rome (unpublished).

Fields, S. 2005. Why Africa's climate change burden is greater. Environmental Health Perspectives. 113, A534–A537.

Forestry and Beekeeping Division. 2006. Forest Area Baseline for the Eastern Arc Mountains. Compiled by Mbilinyi, B.P., R.E. Malimbwi, D.T.K. Shemwetta, Songorwa, E. Zahabu, J.Z. Katani and J. Kashaigili for Conservation and Management of the Eastern Arc Mountain Forests, Forestry and Beekeeping Division, Dar es Salaam.

Gain A, Carlo G, and Renaud FG. 2012. Climate Change Adaptation and Vulnerability Assessment of Water Resources Systems in Developing Countries: A Generalized Framework and a Feasibility Study in Bangladesh. Water ISSN 2073-4441 www.mdpi.com/journal/water

Godwin O. 2005. The impacts of ENSO in Africa. In: Low P. S. (Ed). Climate change and Africa, Cambridge University Press, Cambridge, 369pp.

GoT - Government of the United Republic of Tanzania. 2003. Initial National Communication of Kenya to the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), United Republic of Tanzania Vice President's Office, Dar es Salaam, 143pp.

GoT - Government of the United Republic of Tanzania. 2007. National Adaptation Programme of Action, United Republic of Tanzania Vice President's Office, Dar es Salaam, 52pp. Retrieved from http://unfccc.int/resource/docs/napa/tza01.pdf

Gomani MC, Dietrich O, Lischeid G, Mahoo G, Mahay F, Mbilinyi B, Sarmett, J. 2010. Establishment of a hydrological monitoring network in a tropical African catchment: An integrated participatory approach. Physics and Chemistry of the Earth. 35, 648–656.

Gritzner J and Jemison R. 2009. Wami River Sub-Basin Wetland Assessment and Training. USDA Forest Service Technical Assistance Trip Report.

Hamlington, B. D., R. R. Leben, M. W. Strassburg, R. S. Nerem, and K.-Y. Kim (2013), Contribution of the Pacific Decadal Oscillation to global mean sea level trends, Geophys. Res. Lett., 40, 5171–5175, doi:10.1002/grl.50950.

Hamon RH. 1960. Estimating Potential Evapotranspiration. Massachusetts Institute of Technology, Department of Civil and Sanitary Engineering. 150 pp.

Hamouda MA, Nour El Din MM, and Moursy FI. 2009. Vulnerability assessment of eastern Nile basin. Journal of Water Resources Management. 23, 2697-2725.

Hansen J. 2007. Scientific reticence and sea level rise. Environmental Research Letters. 2, 024002

Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO, and Townshend JRG. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science 342: 850–53. Data available on-line from:http://earthenginepartners.appspot.com/science-2013-global-forest.

Harteminke A and Wienk J. 1995. Sisal cultivation and soil fertility depletion in Tanzania. Outlook on Agriculture. 24(2), 91-96.

Hulme M, Doherty R, Ngara T, New M and Lister D. 2001. African Climate Change: 1900-2100. Climate

Research. 17(2), 145-158.

Indeje M, Semazzi FHM and Ogallo LJ. 2000. ENSO signals in East African rainfall seasons. International journal of climatology. 20, 19–46.

IPCC. 2000. Emission Scenarios – Summary for Policymakers. Special Report of the IPCC Working Group III.UNEP 2000. http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf

IPCC. 2007. Climate Change 2007. Synthesis Report. An Assessment of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf Accessed September 26, 2014.

Jack C. 2010. Climate projections for the United Republic of Tanzania. Climate Systems Analysis Group, University of Cape Town, South Africa.

Jagger P and Pender J. 2003. The role of trees for sustainable management of less-favored lands: the case of eucalyptus in Ethiopia. Forest Policy and Economics. 5(1), 83–95.

JICA. 2013. The Study On Water Resources Management And Development In Wami/Ruvu Basin In The United Republic Of Tanzania. A Report by Japan International Cooperation Agency (Water Resources Division) and the Ministry of Water, Tanzania.

Kashaigili, J. 2010. Assessment of groundwater availability and its current and potential use and impacts in Tanzania. Report for International Water Management Institute. p.67

Kalugendo PP. 2008. Impacts of climate variability on ground water in Dar es Salaam, Tanzania. In: Proceedings of the International Conference Groundwater and Climate in Africa, Kampala, Uganda, p. 52.

Kebede AS and Nicholls RJ .2010. Population and Assets Exposure to Coastal Flooding in Dar es Salaam (Tanzania): Vulnerability to Climate Extremes. Report for Global Climate Adaptation Partnership.

Kebede AS, Brown S and Nicholls RJ. 2010. Synthesis Report: The Implications of Climate Change and Sea-Level Rise in Tanzania – The Coastal Zones http://www.trust.org/item/?map=rising-tides-threaten-tanzanias-coastal-towns.

Kerr RB. 2012. Lessons from the old Green Revolution for the new: Social, environmental and nutritional issues for agricultural change in Africa. Progress in Development Studies. 12(1-3), 213–229.

Kijazi, AL and Reason CJC. 2005. Relationships between intraseasonal rainfall variability of coastal Tanzania and ENSO. Theoretical and Applied Climatology. 82, 153–176.

Kilembe C, Thomas TS, Waithaka M, Kyotalimye M, Tumbo S. 2012. East African Agriculture and Climate Change, A comprehensive analysis for Tanzania. CGIAR/International Food Policy Research institute, December 2012. http://www.ifpri.org/sites/default/files/publications/aacccs_tanzania_note.pdf (accessed December 2012).

Krishnaswamy J, Bonell M, Ventatesh B, Purandara BK, Lele S, Kiran MC, Reddy V,Badiger S, Rakesh KN. 2012. The rain-runoff response of tropical humid forest ecosystems to use and reforestation in the Western Ghats of India. Journal of Hydrology. 472-473, 216-237.

Lambeck K, Esat TM abd Potter E. 2002. Links between climate and sea levels for the past three million years. Nature. 419: 199-206.

Lee, M.D. and J.T. Visscher 1990. *Water harvesting in Five African Countries*. IRC Occasional Paper No. 14, 108 p.

Liu G, Obura D, Richmond M, Souter D, Eakin M. 2011. Climate and Regional Phenomena in A Field Guide to the Seashores of Eastern Africa and the Western Indian Ocean, Richmond, MD (ed). Sida/WIOMSA464 pp, ISBN 9987-8977-9-7.

Lu S, McNalty C, and Amatya D. 2005. A comparison of six potential evaportranspiration methods for regional use in the southeastern United States. Journal of the American Water Resources Association. 41, 621-633.

Madulu, NF. Changing Water Needs and Uses in Rural Communities of Mwanza Region, Tanzania.

Matayo I, Semazzi F and Ogall LJ. 2000. Enso Signals in East African Rainfall Seasons. International Journal of Climateology. 20, 19 – 46.

Mattson WJ, Haack RA. 1987. The role of drought in outbreaks of plant-eating insects. Bioscience. 37, 110–118.

McSweeney, M, New, M. and G. Lizcano. 2008. UNDP Climate Change Country Profiles : http://country-profiles.geog.ox.ac.uk/

McSweeney C, Lizcano G, New M, and Lu X. 2010. The UNDP Climate Change Country Profiles: Improving the accessibility of observed and projected climate information for studies of climate change in developing countries, Bulletin of the American Meteorological Society. 91(2), 157-166.

MOD16 Global Terrestrial Evapotranspiration Data Set. 2014. Numerical Terradynamic Simulation Group, University of Montana. http://www.ntsg.umt.edu/project/mod16 Accessed October 7, 2014.

Mora C, Frazier AG, Longman RJ, Dacks RS, Walton MM, Tong EJ, Sanchez JJ, Kaiser LR, Stender YO, Anderson JM, Ambrosino, CM, Fernandez-Silva I, Giuseffi LM, Giambelluca, TW. 2013. The projected timing of climate departure from recent variability. Nature. 502(7470),183-187.

MoW. 2009. Design Manual for Water Supply and Wastewater Disposal. Ministry of Water , Government of Tanzania. http://maji.go.tz

MoW. 2014. Water point mapping project. http://maji.go.tz/userfiles/wpmproject(1).pdf

Muhammed et al. 2004. Water Resources in South Asia: Asia-Pacific Network for Global Change Research.

Mwandosya, MJ, Nyenzi BS, and Luhanga ML. 1998. The Assessment of Vulnerability and Adaptation to Climate Change Impacts in Tanzania. Centre for Energy, Environment, Science and Technology (CEEST), Dar es Salaam, Tanzania. pp. 256 pp. CEEST Book Series No. 11 ISBN 9987-612-11-3.

Myers N. 1998. Tropical forests – much more than stocks of wood. Journal of Tropical Ecology. 4(2), 209-221.

NASA 2013. http://climate.nasa.gov/400ppmquotes/

Nobert, J and Jeremiah, J. 2012. Hydrological Response of Watershed Systems to Land Use/Cover Change. A Case of Wami River Basin. The Open Hydrology Journal. 6, 78-87.

Ngana J, Mahay F and Cross K. 2010. Wami Basin A situation Analysis. Report for the Wami/Ruvu basin Water Office. IUCN Eastern and Southern Africa Programme. Xviii + 92 pp.

Noel S. 2010. The economics of climate change in Tanzania Water resources. Stockholm Environment Institute.

Núñez D, Nahuelhual L, Oyarzún C. 2006. Forests and water: The value of native temperate forests in supplying water for human consumption. Ecological Economics. 58(3), 606-616.

Osbahr H, Twyman C, Adger WN and Thomas DSG. 2008. Effective livelihood adaptation to climate change disturbance: Scale dimensions of practice in Mozambique. Geoforum. 39, 1951–1964.

Paavola, J. 2004. Livelihoods, Vulnerability and Adaptation to Climate Change in the Morogoro Region, Tanzania. CSERGE Working Paper EDM 04-12, December 2004, 19 pp.

Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss. 2012. Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1. 37 pp.

Patz JA , Campbell-Lendrum D, Holloway T, Foley JA. 2005. Impact of regional climate change on human health. Nature. 438, 310–317.

Platts PJ, Gereau RE, Burgess ND and Marchant, R. 2013. Spatial heterogeneity of climate change in an Afromontane centre of endemism. Ecography. 36, 518–530.

Platts PJ, Omeny PA and Marchant R. 2014. AFRICLIM: high resolution climate projections for ecological applications in Africa. African Journal of Ecology doi:10.1111/aje.12180

Poff NL, Allan DJ, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE and Stromberg JC.(1997). The Natural Flow Regime. Bioscience. 47(11): 769-784.

Potsdam Institute. 2013. Turn down the Heat: why a 4 degree world must be avoided. A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics. November 2012.

Rahmstorf S. 2010. A new view on sea level rise. Nature Reports Climate Change. doi:10.1038/climate.2010.29

Ropelewski, A.1999. Consequences. 5(2), 17-25. Available at http://www.gcrio.org/CONSEQUENCES/vol5no2/article_2.html

Saha AK, Moses C, Price R, Engel V, Smith TJ, Anderson, G. (2012). A hydrological budget (2002-2008) for a large subtropical wetland indicates seawater intrusion accompanies diminished freshwater flow. Journal of Estuaries and Coasts. 35(2), 459.

Sanchez and Pfeifer. 2012. SERVIR Africa Biodiversity Project: Assessing the Vulnerability of Biodiversity to Climate Change Report on Assessing Impacts of Future Climate Change on VEGETATION in East Africa and Kenya-Tanzania Borderlands. Expanding Datasets and Model Refinement. University of York partnership with NOAA, Missouri Botanic Garden, National association of museums in Kenya and UKAID.

Schaafsma M, Morse-Jones S, Posen P, Swetnam RD, Balmford A, Bateman IJ, Burgess ND, Chamshama SAO, Fisher B, Green RE, Hepelwa AS, Hernández-Sirvent A, Kajembe GC, Kulindwa K, Lund JF, Mbwambo L, Meilby H, Ngaga YM, Theilade I, Treue T, Vyamana VG, Turner RK. 2012. Towards transferable functions for extraction of Non-timber Forest Products: A case study on charcoal production in Tanzania. Ecological Economics

Shemsanga C, Omambia AN, and Gu Y. 2010. The Cost of Climate Change in Tanzania: Impacts and Adaptations Journal of American Science 6(3),182-196.

Siraj AS, Santos_Vega M, Bouma MJ, Yadeta D, Ruiz Carrascal D, Pascual M. 2014. Altitudinal Changes in Malaria Incidence in Highlands of Ethiopia and Colombia. Science. 343, 1154-1158.

Sreenivasan V, Thomas B, Jamwal P and Lele, S. 2013. Climate vulnerability and adaptation of water provisioning in developing countries: approaches to disciplinary and research-practice integration. Current Opinion in Environmental Sustainability. 5, 1-6.

Sullivan CA 2011. Quantifying water vulnerability: A multi-dimensional approach. Stochastic. Environmental. Research Risk Assessment. 25, 627–640.

Taylor RG, Todd MC, Longola L, Maurice L, Nahozya E, Sanga H and MacDonald A. 2013. Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. Nature Climate Change. 3, 374-378.

The Economist Print Edition. May 10, 2007. Global Warming in Africa: Drying Up and Flooding Out. http://www.economist.com/world/africa/PrinterFriendly.cfm?story_id=9163426, Accessed on Sept. 23, 2014.

Thornton PK, Jones PG, Owiyo T, Kruska RL, Herrero M, Kristjanson P, Notenbaert A, Bekele N, Omolo N. 2006. Mapping Climate Vulnerability and Poverty in Africa. Report to the Department for International Development, ILRI, Nairobi, Kenya.

Tobey J and Mwakifwamba. 2008. Developing Core Capacity to Address Adaptation to Climate Change in Productive Coastal Zones of Tanzania. LDCF-funded Project (UNEP).

Tobey J, Meena H, Lugenja M, Mahenge J, Mkama W. Robadue D. 2011. Village Vulnerability Assessment and Adaptation Planning: Mlingotini and Kitonga, Bagamoyo District, Tanzania, Coastal Resources Center, University of Rhode Island, Narragansett, RI, 20 pp.

UKCIP. 2003. Climate adaptation: Risk, uncertainty, and decision making – UKCIP technical report http://www.ukcip.org.uk/wordpress/wp-content/PDFs/Risk.pdf (Accessed online November 6, 2012).

UNDP Climate Change Country Profiles: http://country-profiles.geog.ox.ac.uk/

United Nations Economic Commission for Africa (UNECA). 1999. Global Environment Outlook 2000. UNEP. Earthscan, London, 1999.

UNFCCC http://unfccc.int/national_reports/napa/items/2719.php

University of Michigan. 2014. Warmer temperatures push malaria to higher elevations. ScienceDaily, 6 March 2014. <www.sciencedaily.com/releases/2014/03/140306142545.htm>. Accessed October 2, 2014.

USAID. 2007. Adapting to Climate Variability and Change. A guidance manual for development planning. http://pdf.usaid.gov/pdf_docs/PNADJ990.pdf Accessed September 13, 2013.

USAID. 2008. Profile of the Wami River Sub basin. http://pdf.usaid.gov/pdf_docs/PNADN794.pdf

USAID. 2014. Tanzania: Economic Growth and Trade. http://www.usaid.gov/tanzania/economic-growth-and-trade.

Vairavamoorthy K, Mansoor MAM. 2005. Demand management in developing countries. In: Butler, D and Memon F (Ed). Water Demand Management, IWA, ISBN: 1843390787.

Vairavamoorthy K, Gorantiwar, SD, Pathirana A. 2008. Managing urban water supplies in developing countries – Climate change and water scarcity scenarios. Physics and Chemistry of the Earth, Parts A/B/C, 33(5), 330-339.

Valimba, P. 2004. Rainfall variability in southern Africa, its influences on streamflow variations and its relationships with climatic variations, PhD dissertation, Rhodes University, South Africa, 217 pp.

Valimba, P. 2007. Environmental Flow Assessment (EFA), Wami River Sub-Basin, Tanzania: The Wami Hydrology. Volume 1 – General Description. 2007. Wami-Ruvu Basin Water Office. 42p.

van Dijk AIJM, Keenan RJ. 2007. Planted forests and water in perspective. Forest Ecology and Management. 251(1-2), 1-9.

Vogt K and Sheya T. 2012. Interviews with village elders in the Nguru mountains. Report for the Tanzania IWASH program. Unpublished.

Water and Sanitation Program. 2011. Water Supply and Sanitation in Tanzania: Turning Finance into Services for 2015 and Beyond. An AMCOW Country Status overview.

Wilby and Miller. 2009. Climate Vulnerability Assessment. Technical Working Paper no 5, Water Research Foundation.

World Resources Institute, 2013. http://insights.Wami/Ruvui.org/news/2013/08/burkina-faso-farmers-lead-way-food-security-and-climate-change-resilience. Accessed on September 6th, 2013.

Yanda, PZ and Munishi, PKT. 2007. Hydrologic and land use/cover change analysis for the Ruvu river (Uluguru) and Sigi river (East Usambara) watersheds. Report for WWF/CARE Tanzania, Dar Es Salaam, 87 p.

Yin J, Griffies SM, and Stouffer RJ. 2010. Spatial Variability of Sea Level Rise in Twenty-First Century Projections. Journal of Climate. 23, 4585–4607.

Zemadim B, Mtalo F, Mkhandi S, Kachroo R and McCartney M. 2011. Evaporation Modelling in Data Scarce Tropical Region of the Eastern Arc Mountain Catchments of Tanzania. Nile Basin Water Science & Engineering Journal, 4(1).

Time series data for Tanzania- past observed precipitation:
http://www.geog.ox.ac.uk/research/climate/projects/undpcp/index.html?country=Tanzania&d1=Observed&d2=Mean&d3=Climatology
http://www.thegef.org/gef/sites/thegef.org/files/documents/document/Website_LDCF_Tanzania4141.pdf
http://www.economics-of-cc-in-tanzania.org/images/Water_resources_final_.pdf (accessed Dec 21, 2012)
http://www.cpc.ncep.noaa.gov/products/african_desk/cpc_intl/africa/africa.shtml - climate projections for Africa.

Annex 1: Resources for running climate models

A: Climate Wizard

Climate Wizard is a web-based tool developed by Chris Zganjar (The Nature Conservancy), Evan Girvetz (University of Washington) and George Raber (University of Southern Mississipphi); refer Girvetz *et al.* (2009) or www.climatewizard.org for further information.

www.climatewizard.org is a user-friendly website where the user can run past and future climate projections by an ensemble of 16 GCMs under three IPCC emission scenarios (A2, AIB, B2) at the country level, downscaled to a 50 km grid. In addition, a user can upload a shapefile of a desired area and have maps and graphs generated for any time period going back to 1925 till 2002 (for historical projections) and 2002-2099 for predictions either by individual models, or ensembles. The tool uses the gridded dataset CRU TS 2.0 developed by the Climatic Research Unit at the University of East Anglia, UK.

More information can be found in the documentation set available on http://www.climatewizard.org. In particular, an important article describes the assumptions and limitations of the historical data set as well as climate predictions, especially the dangers of using prediction data in regions that are data poor, ie have very few weather stations, and thereby interpolated data for these regions has a low level of rigour.

Climate Wizard (http://www.climatewizard.org) is a web-based analysis and mapping tool that uses state-of-the-art climate models and advanced statistical analysis to examine both the current and future climate conditions of any place on the earth. Pre-calculated map products are available through a free webpage where users can easily visualize and download data for both historic and future climate conditions. Future climate projections are based on General Circulation Models output produced under three different greenhouse gas emission scenarios for two future time periods; mid and end century. Additionally the user has the ability to examine the statistical variations of 16 different general circulation models used to generate these future climate projections by displaying individual model results or selected model combinations. Data Source: Global climate model output, from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl *et al.* 2007), were downscaled as described by Maurer *et al.* (2009) using the bias-correction/spatial downscaling method (Wood *et al.* 2004) to a 0.5 degree grid, based on the 1950-1999 gridded observations of Adam and Lettenmaier (2003).

B: Climate Portal of the World Bank

http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=TZA#
Both these online tools use data from the dataset
http://www.cru.uea.ac.uk/data
Climatic Research Unit Time Series ver2.10 Historical 50km Global dataset Average Monthly Temperature are monthly averages for the 1901-2009 time period. These data are proxies based on gridded climatologies from the Climate Research Unit. Modeling has been used to extrapolate estimates where instrumental (station) data were unavailable or unreliable, especially in the early 1900's. The station time series data used in this interface are from the Global Historical Climatology Network (GHCN) beta version 2 monthly station precipitation data set and the GHCN version 2 station monthly mean temperature data set. The gridded temperature and precipitation data are from the Hulme Global Gridded Precipitation Version 1.0 data set and the CRUTEM3v Variance-Adjusted Global (Land-Only) Gridded Air Temperature data set.
Catalog Source: World Bank Climate Change Knowledge Portal; Climate Research Unit, University of East Anglia.

C: Source Data Description and Citation

Historical Database CRU TS 2.1 publicly available from Climatic Research Unit and the Tyndall Centre, University of East Anglia, UK (http:/www.cru.uea.ac.uk/)

Resolution: 0.5° (WGS84) or 50 km
Spatial Extent: Global
Temporal Extent: 1901-2002 monthly time-series
Climate Variables: Precipitation
Average Temperature
Average Maximum Temperature
Average Minimum Temperature
For more information on development of this data set, refer to: Mitchell and Jones (2003)

D: References for GCM section appendix

Adam, J. C. and Lettenmaier, D. P. (2003): Adjustment of global gridded precipitation for systematic bias, J. Geophys. Res., 108, 1–14.

Girvetz EH, Zganjar C, Raber GT, Maurer EP, Kareiva P, Lawler JJ. 2009. Applied Climate-Change Analysis: The Climate Wizard Tool. PLoS ONE 4(12): e8320. doi:10.1371/journal.pone.0008320

http://www.cru.uea.ac.uk/cru/data/hrg/timm/grid/CRU_TS_2_1.html has discussion on the number of stations in each grid cell and the correlation decay distances for each variable.

Maurer, E.P., J.C. Adam, and A.W. Wood (2009): Climate Model based consensus on the hydrologic impacts of climate change to the Rio Lempa basin of Central America, Hydrology and Earth System Sciences 13, 183-194 (connect to online version).

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor (2007): The WCRP CMIP3 multi-model dataset: A new era in climate change research, Bulletin of the American Meteorological Society, 88, 1383-1394.

Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme, M., New, M. (2003): A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Journal of Climate: submitted.

New, M. G., M. Hulme, and P. D. Jones. (1999): Representing twentieth century space-time climate variability. Part I: Development of a 1961-1990 mean monthly terrestrial climatology. Journal of Climate 12:829-856.

New, M. G., Hulme, M., and Jones, P. D. (2000): Representing twentieth century space-time climate variability. Part II: Development of a 1901-1996 monthly terrestrial climate field. Journal of Climate 13:2217-2238.

Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor, 2007: Cilmate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wood, A. W., Leung, L. 5 R., Sridhar, V., and Lettenmaier, D. P (2004).: Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs, Climatic Change, 62, 189–216.

http://www.cru.uea.ac.uk/cru/data/hrg/cru_ts_2.10/data_dec/ has raw data files in ASCII form for climate at 0.5 degree grid for the world from 1901 to 2002.

Annex 2: Supplementary climate prediction maps

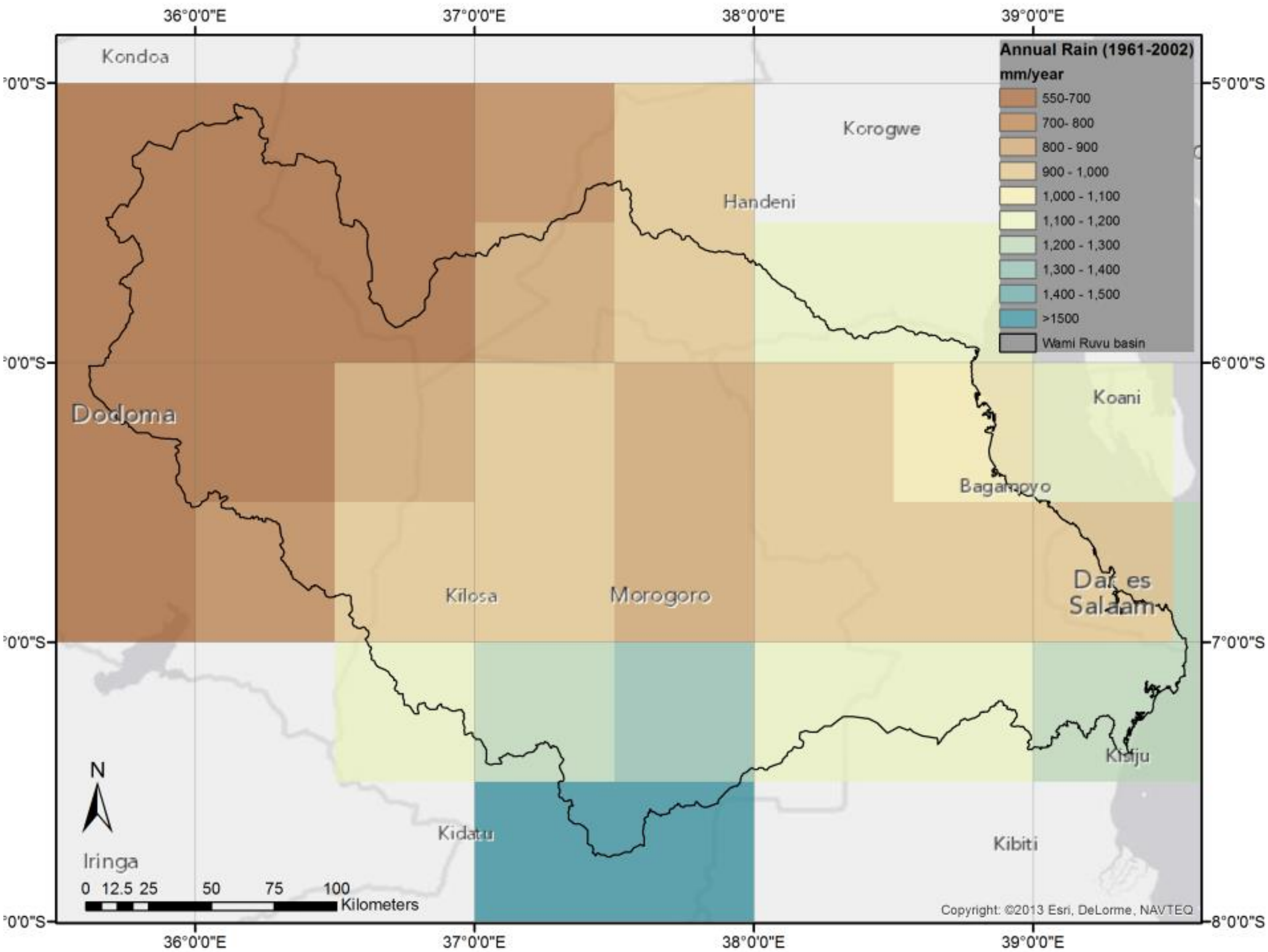


Figure 0-1: Historical projection of annual mean precipitation for the Wami/Ruvu Basin (black boundary) averaged over 1961-2002 at a 50 km grid scale. [Data Source: ClimateWizard and ESRI basemap]

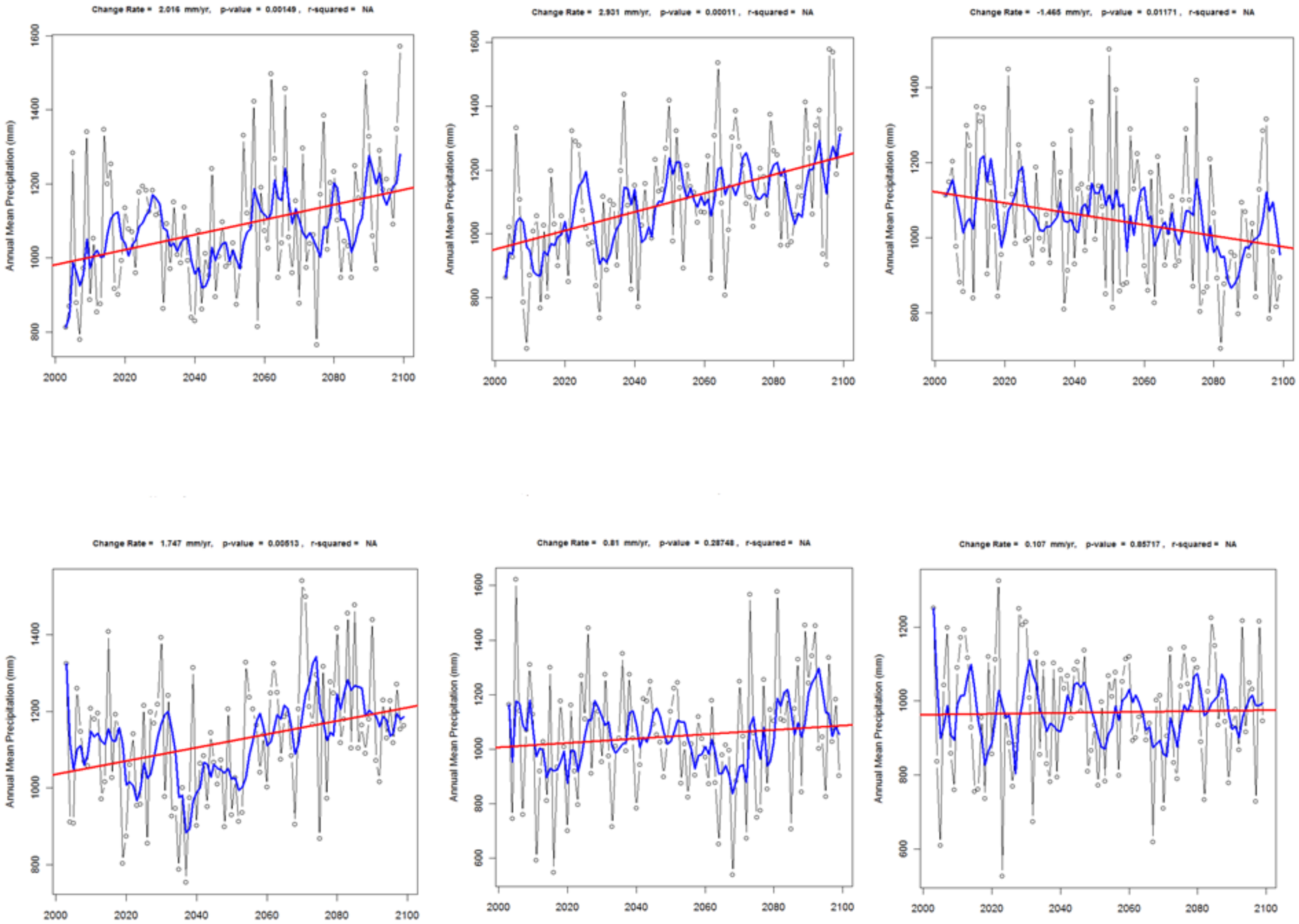


Figure 0-2: annual precipitation projections (2000-2099) by models bccr_bcm2.0, cnrm_cm3.1, csiro_mk3, cccma_cgcm3, gfdl_cm2_0.1, gfdl_cm2_1.1. [Data Source: ClimateWizard]

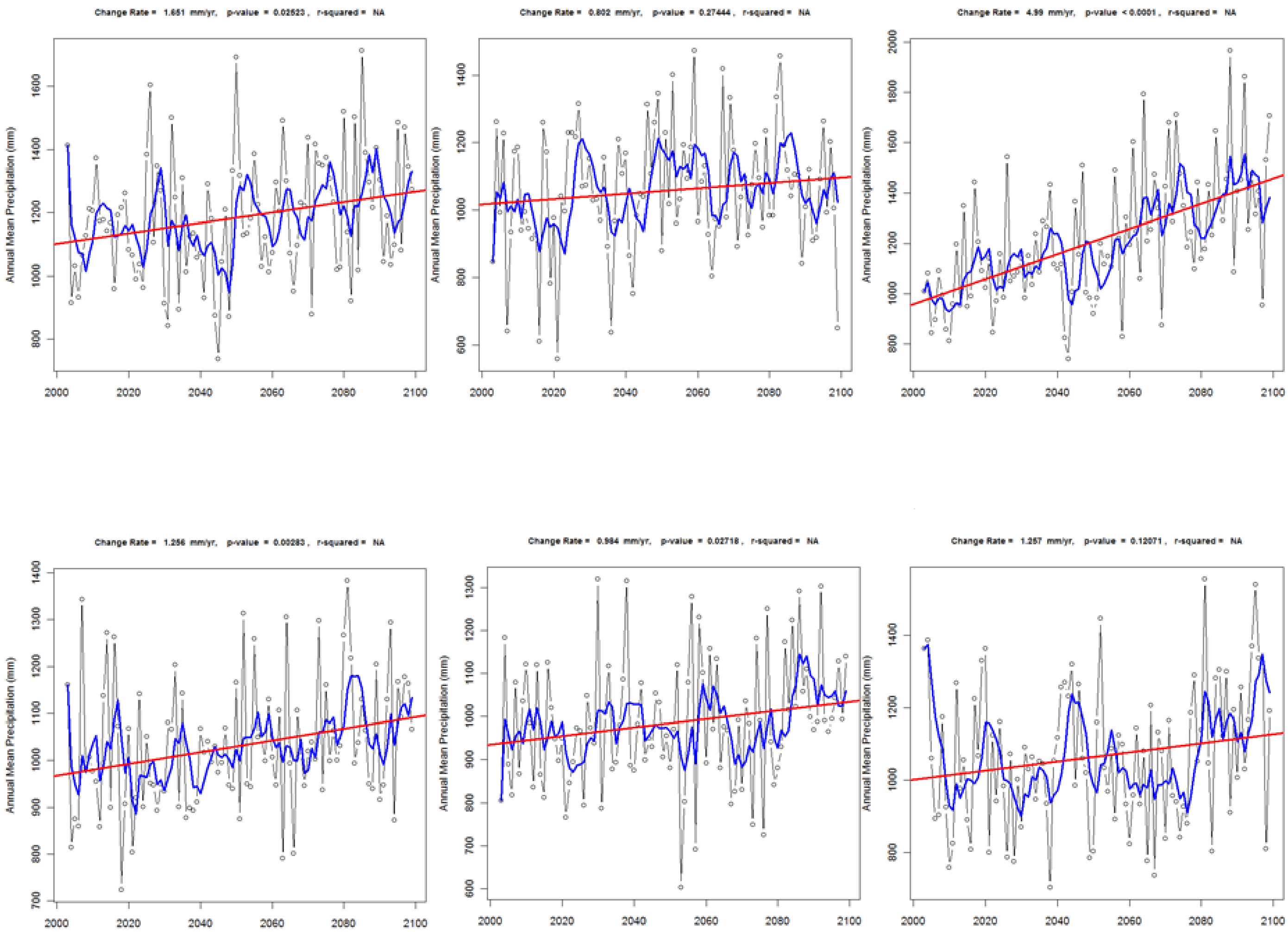


Figure 0-3: annual precipitation projections (2000-2099) by models inmcm3_0.1, giss_model_er.1, micro_3_2Medres, miub_echo_g.1, mpi_echam5.1 and ipsl_cm4.1. [Data Source: ClimateWizard]

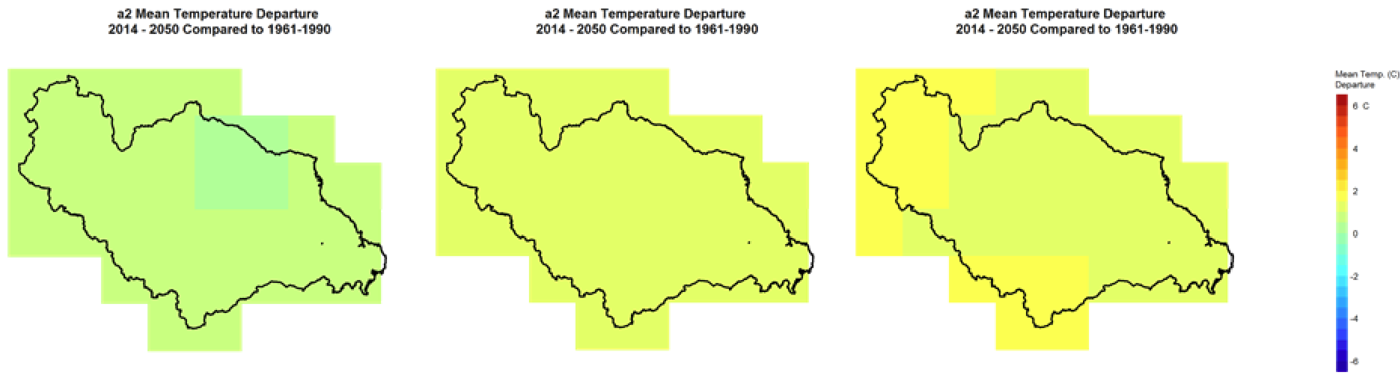


Figure 0-4: Temperature departure per year in °C averaged over 2014-2050 from the 1961-1990 baseline mean: low (left), ensemble mean (middle) and high (right) prediction values amongst 16 GCMs at A2 scenario. [Data Source: ClimateWizard]

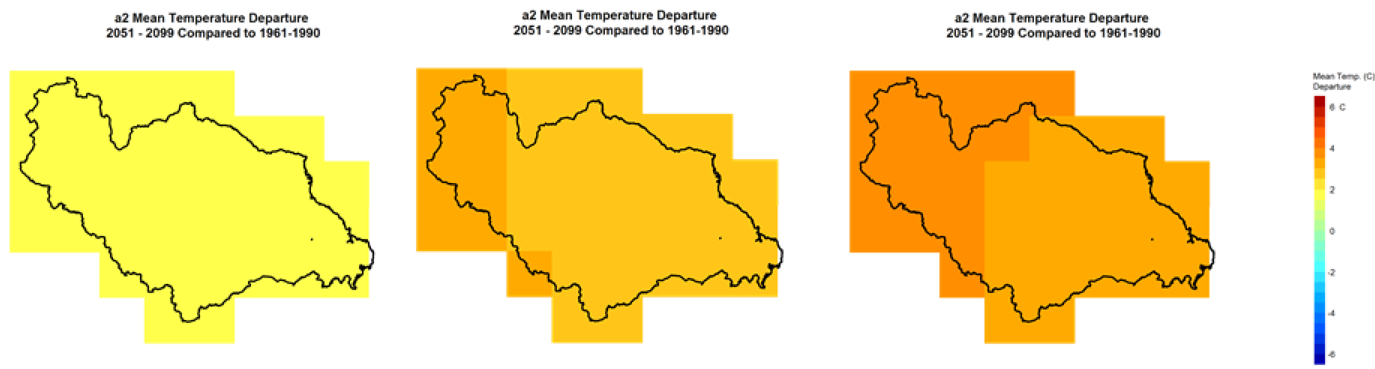


Figure 0-5: Mean temperature departure per year (°C) averaged over 2051-2099 from the 1961-1990 baseline, A2 scenario for low, middle and high estimates amongst 16 GCMs. [Data Source: ClimateWizard]

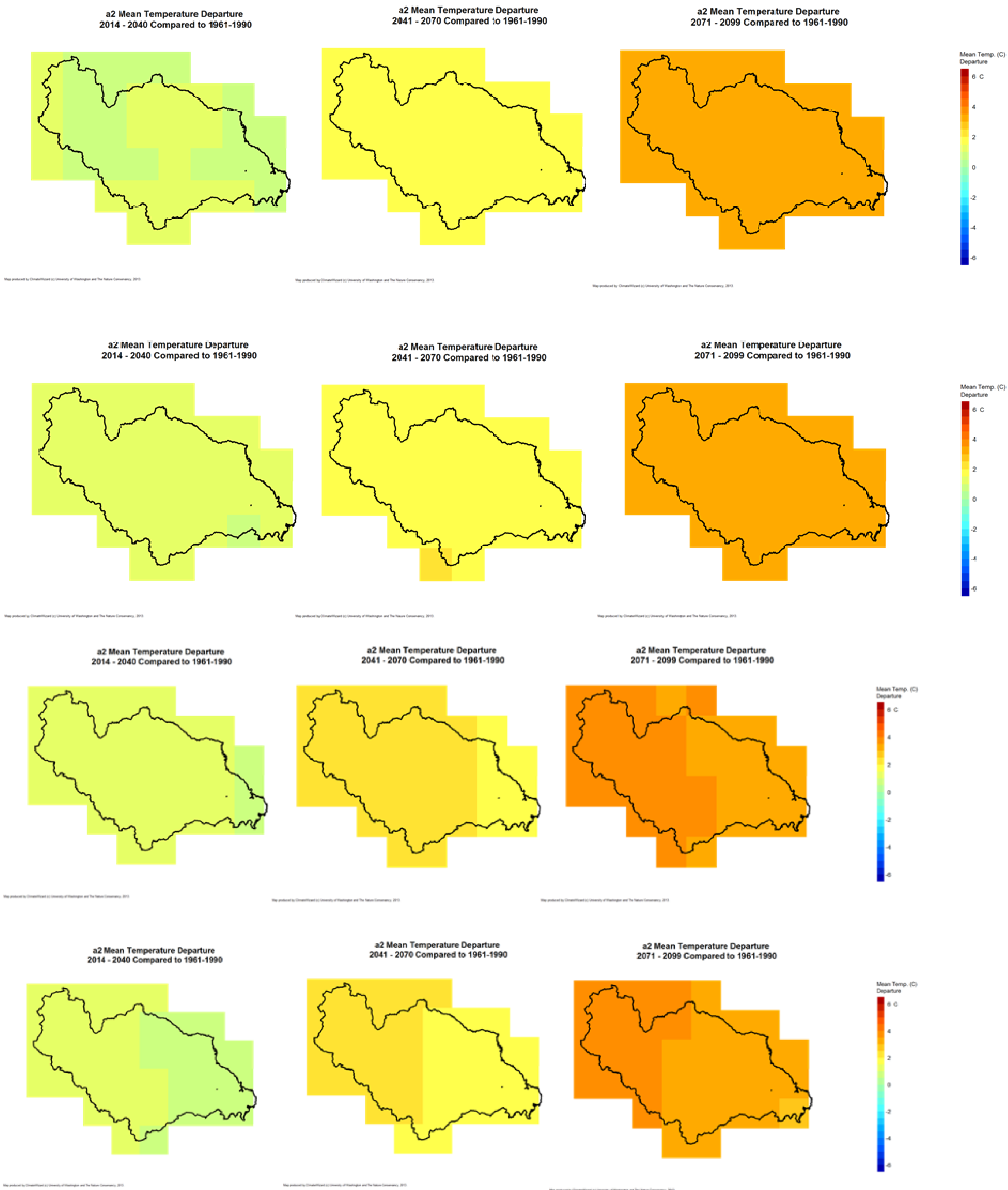
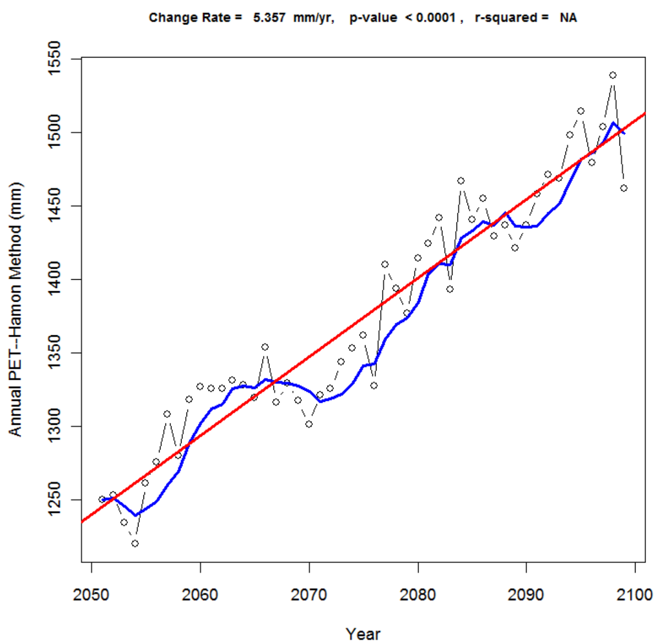


Figure 0-6: Seasonal temperature predictions shown as the difference in temperature over a time period (2014-2040, 2041-2070 and 2071-2099 from left to right) from the 1961-1990 baseline. Top row (average over December-February); second row from top

(average over March-May); third row from top (June-August) and bottom row (September-November). [Data Source: ClimateWizard]



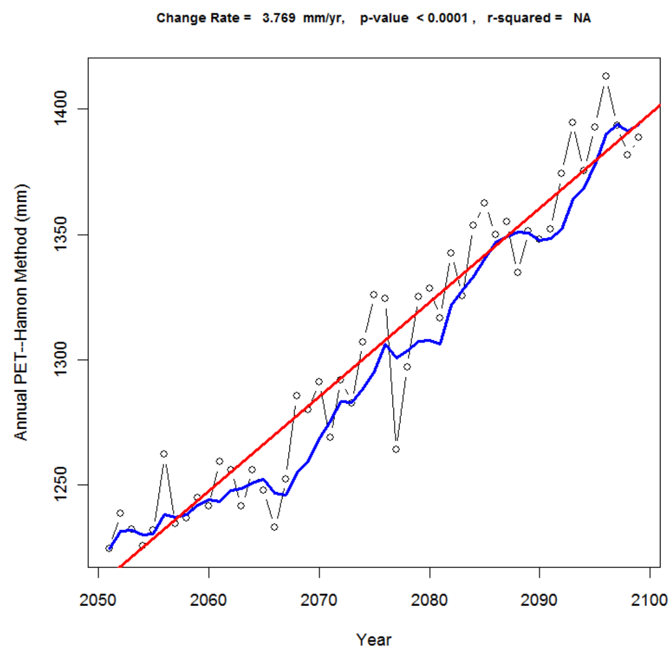


Figure 0-7: Predictions of Annual Potential Evapotranspiration over 2051-2099 by UKMO_HADCM3.1 (left) and BCCR_BCM2_0.1 (right) [Data Source: ClimateWizard]

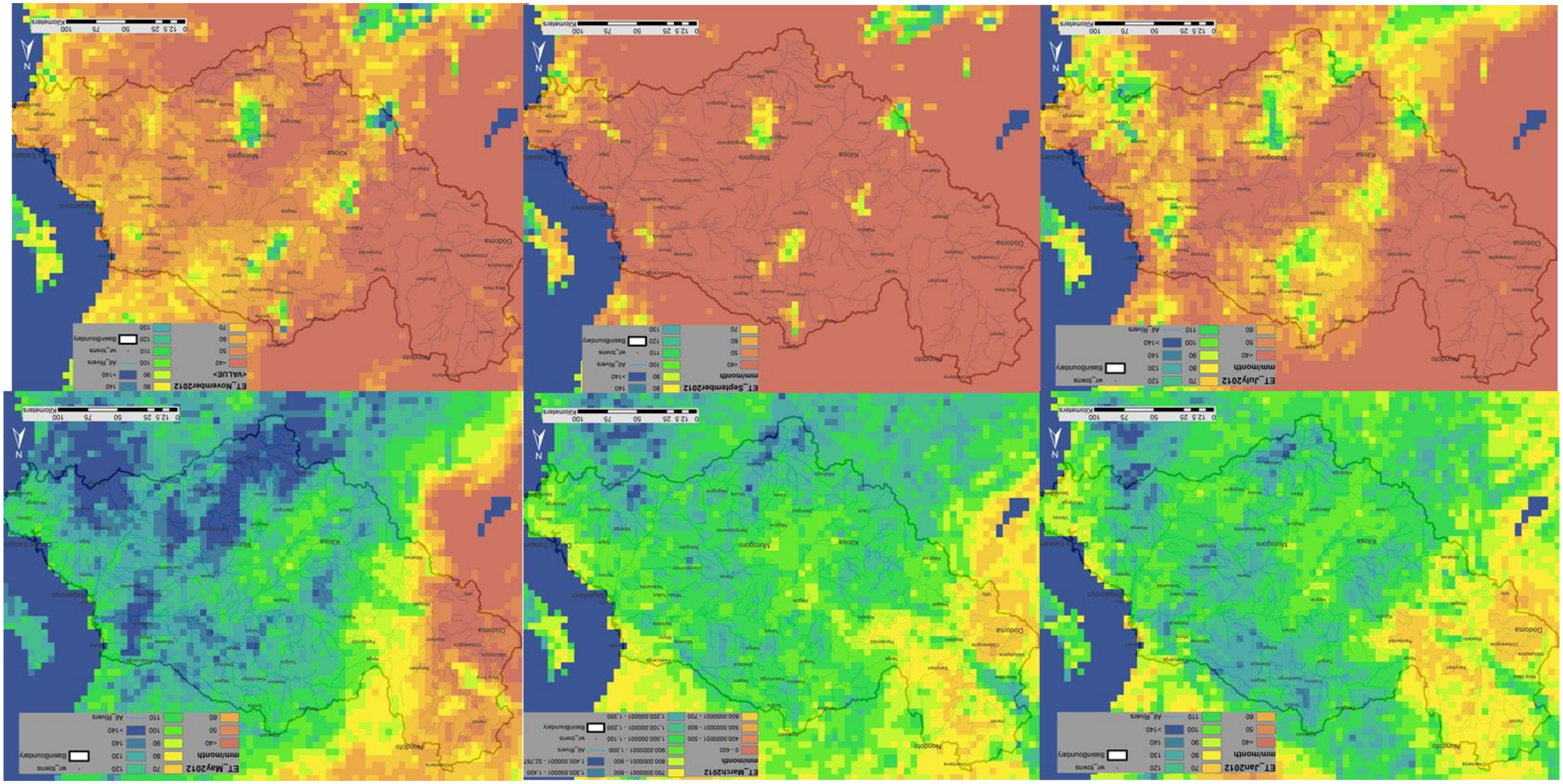
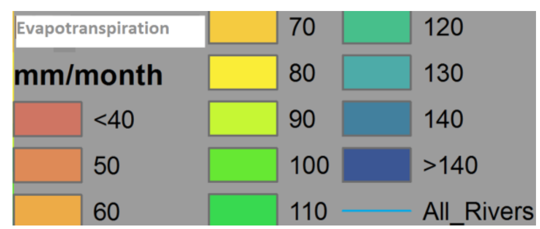


Figure 0-8: Monthly actual evapotranspiration at a 1 km scale for the Wami/Ruvu Basin for January, March, May, July, September and November (from top left to bottom right). [Data Source: MODIS]



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