DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL ENGINEERING

AHMADU BELLO UNIVERSITY, ZARIA, NIGERIA

ASSESSMENT OF THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES AVAILABILITY IN THE SOKOTO-RIMA RIVER BASIN

BY

ABDULLAHI SULE ARGUNGU

JUNE, 2015

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DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL ENGINEERING

FACULTY OF ENGINEERING

AHMADU BELLO UNIVERSITY, ZARIA, NIGERIA

JUNE, 2015

DECLARATION

I certify that the work in this thesis titled "**ASSESSMENT OF THE IMPACT IMPACT OF CLIMATE CHANGE ON WATER RESOURCES AVAILABILITY IN THE SOKOTO-RIMA RIVER BASIN"** is based on the results of research carried out by me, that it is my own composition, and that it has not previously been presented for another degree at any institution.

ABDULLAHI SULE ARGUNGU		25/07/2015
Name of Student	Signature	Date

CERTIFICATION

This thesis titled: " **ASSESSMENT OF THE IMPACT IMPACT OF CLIMATE CHANGE ON WATER RESOURCES AVAILABILITY IN THE SOKOTO-RIMA RIVER BASIN" by Abdullahi Sule Argungu** meets the regulations governing the award of the degree of Doctor of Philosophy, water resources and Environmental Engineering, Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

I dedicate this work to

Almighty ALLAH

Who gave me the wisdom to do it.

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I express my gratitude to Almighty ALLAH, for granting me the capacity and ability throughout the period of this research.

My sincere gratitude goes to my supervisors, Prof. A. Ismail, Dr. D. B. Adie and Prof. J. A. Otun of the Department of Water Resources and Environmental Engineering. I am grateful for their invaluable advice, useful suggestions and criticisms.

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ABSTRACT

This study reports impact of climate change on water resources availability in the Sokoto-Rima river basin (SRRB). SRRB is located in the North Western Nigeria and spread across four (4) States (i.e. Sokoto, Kebbi, Katsina and Zamfara) with ninety three (93) Local Government Areas, with a human population of more than 15million. The study uses Water Evaluation And Planning (WEAP) model to asses and evaluate the impact of climate change on surface water availability and investigate the sensitivity of SRRB to climate change. This model allows the simulation and analysis of various water allocations and scenarios. The available data was used to model the surface water resources situation, and then projected in to the present situation of the existing hydraulic condition of the basin. The hydrological processes that occur for the six major rivers within the basin during 1970 to 2013 was satisfactorily modelled and calibrated by visual observation and compared with the measured data. The calibration process of the model was done using the first twenty years climatological records (1970-1990) and validated with the remaining eighteen years data (1990-2008). Simulations were proposed for various climatic situations considering the global climatic models (GCM) predictions and linear trend of the data. Six (6) selected climate change scenarios of temperature increases (0, +0.5, +1 ^{o}C) coupled with decrease or increases in precipitation (0,-10%, +10%) were combined and applied for the study area in the WEAP model for simulation. The model was used to analyse the linkage between the water availability and the demand in some selected sections within the basin. Base on the human population, the hydraulic situation of the basin was projected to the future to analyse the water availability up to the year 2064. The runoff, evapotranspiration, and water demand series were obtained as output of the model. Results showed that climate change will reduce

the runoff, and increase evapotranspiration and water demand in the basin, more especially the demand for irrigation. Results also indicated an annual reduction in the total available water by about 1.70 billion cubic meter and a maximum monthly water demand of 17.11 billion cubic meter for the month of April (which is the driest month in the basin) for the selected sites, under 10% reduction in the actual rainfall within the basin and increase in evapotranspiration under $1^{o}C$ increase in temperature, this indicate reduction of the surface water in the future for the basin. In addition, the dependency of the basin on surface water sources make it imperative to apply some methods of efficient use of water resources, to ensure future sustainability.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Fresh water is crucial to human society, not just for drinking, but also for farming, washing and many other activities. It is expected to become increasingly scarce in the future, and this is partly due to climate change. The International Reports clearly stated the importance of freshwater to life support system and is widely recognised (Falkenmark, 1986; Dudgeon *et al.*, 2006). Fresh water is indispensable for all forms of life and is needed in large quantities, in almost all human activities.

Climate, freshwater, biophysical and socio-economic systems are interconnected in complex ways, so a change in any one of these induces a change in another. Anthropogenic climate change which refers to the production of greenhouse gases emitted by human activity adds a major pressure to nations that are already confronting the issue of sustainable freshwater use. The challenges related to freshwater are: having too much water, having too little water, and having too much polluted water. Each of these problems may be exacerbated by climate change. Freshwater-related issues play a pivotal role among the key regional and sectoral vulnerabilities. Therefore, the relationship between climate change and freshwater resources is of primary concern and interest (Bates *et al.*, 2008).

As climatic variability intensifies, changes in atmospheric conditions altered water resources, their distribution in space and time, the hydrological cycle of water bodies, and water quantity. The water cycle is altered by climate change, but because of the complexity of the hydrosphere in the Earth system, it is difficult to predict how precipitation patterns might

change. Changes expected include the timing, amount, and location of precipitation and runoff. Such changes are major drivers of vulnerability and will alter the patterns of water availability in many regions, more especially the Sahel and Sudano-Sahelian belt that are areas with higher temperatures, low precipitation and most affected by droughts.

The large portion of Sokoto-Rima River basin (SRRB) is Sahel eco-climatic zone and Sudano-Sahelian belt in the south, which is characterised by strong climatic variations and an irregular rainfall. It is located in the North Western Nigeria and spread across four (4) States (i.e. Sokoto, Kebbi, Katsina and Zamfara) that have ninety-three (93) local government areas. The states rely heavily on its water resources for their socio-economic sustenance. The people living in those States consider rivers and streams within the basin as very important source of surface water for their municipal and agricultural demands. Therefore, even a small decrease in runoff within the basin could have dramatic effects on the welfare of the region.

In view of the above, this study focused on evaluating the impact of climate change on available water resources in the six major rivers (i.e. Bunsuru, Gagere, Rima, Sokoto, Zamfara and Ka) of the SRRB using a decision support system known as the Water Evaluation and Planning (WEAP) Model. WEAP is an analytical framework developed for the evaluation of climate change and other drivers that water managers commonly confront (Yates *et al*., 2006). WEAP model is one of the useful tools for integrated water resources management and it can be used as a database for forecasting and as a policy analysis tool, depending on the focus of the study. In this regard, the applicability of WEAP in assessing the impact of climate change as well as its main function as a sophisticated water allocation model was utilized in this study.

1.2 Justification of the study

The assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC) and direct observations on the surrounding environment are increasingly providing evidence that climate change is actually happening much faster than initially assessed by the scientist. While the exact nature of the changes in temperature or precipitation, and extreme events are caused by climate change are not known, there is general agreement by the scientist that extreme events will get worse, and trends in most variables will change in response to warming and that the consequences are already visible in many areas of the world (Bates *et. al.,* 2008).

In Nigeria, the Federal Ministry of Environment (2003) analyses of available meteorological data from 1920 to 2003 on surface air temperature for Kano, Calabar and Lagos show evidence of increasing surface air temperatures of about 0.25^0C for Calabar and Kano and 0.25 to 0.50^0C for Lagos (Onyenechere and Igbozurike, 2010). Also, there are indications that other climate variables especially rainfall has declined both in magnitude and temporal distribution (Onyenechere and Igbozurike, 2010).

The impact of climate change on water resources will be overwhelming. Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates et.al; 2008). According to Rosenberg *et al.,* (1999), water is considered as the most critical factor associated with climate impacts compared with many sectors of the natural and man-made environment that are expected to be affected by climate change. A similar idea is also highlighted by Houghton

(1997) who stated that the most important impact of global warming is on water supplies which are in any case becoming increasingly critical in many places.

In contrast to the assessment of global or large scale variations of the climate driving forces for global hydrology by IPCC, the impact of climate change on the regional hydrology is still unknown for most regions of the world (Kim *et al*., 2006). Although climate change is a global phenomenon, the trends and impact may be different on a local scale.

In the continent of Africa, the observational records show that the climate has been warming through the 20th century at the rate of about 0.05°C per decade (IPCC, 2001).The water demand is continuously increasing due to lot of reasons, some of which are increase in population, increase in evapotranspiration and drought due to climate change, economic development, environmental considerations etc. As a result the risk that the required amounts of water will not be available is increasing more especially in semi-arid river basins areas, as such access to water needs to be secured in those regions. By 2025, it is assumed that 22 countries in Africa will experience a water-stress situation due to rapid population growth, expanding urbanisation, increased economic development and climate change (http://www.grida.no/graphicslib/detail/water-availability-in-africa_3368).

Nigerians do not enjoy adequate water supply, and the rapid pace of population growth in the country has been accompanied by increased demand of fresh water for domestic, industrial and agricultural use. The problem of water shortage is more prominent and severe in the northern areas of the country that have limited rainfall water between May to October and harsh weather conditions associated with frequent drought.

Available individual and collective researches at regional levels show that Nigeria like most parts of the world is experiencing the basic features of climate change. Some localities are experiencing extreme weather conditions as a result of increasing temperature and an associated changing climate (Olaniran 2002; Ayoade 2003; Odjugo 2005). Ayoade (2003) recorded a slight drop in air temperatures within the late 1940s and early 1950s in Nigeria. According to Mabo (2006) and Ikhile (2007), a sharp increase in temperature between 1971 and 2005 could be linked to the effect of climate change and its associated global warming.

Temperature anomalies confirm the facts that global warming is unequivocal (IPCC 2007b). According to Odjugo (2010), increasing temperature is already present in Nigeria. The changes in climate such as temperature rise, erratic rainfall, sand storms, desertification, low agricultural yield; drying up of water bodies and flooding are physically present in the North Western region of Nigeria (Onyenechere and Igbozurike, 2010). Odjugo and Ikhuoria (2003) and Adefolalu (2007) report that increasing temperature and decreasing rainfall in the semi-arid region of Sokoto, Katsina, Kano, Nguru, and Maiduguri may have resulted in the increasing evapotranspiration, drought and desertification in Nigeria. Indeed, Sokoto basin is one of the few areas fingered for having the potential for more acute climate change impacts in Nigeria (Odjugo, 2010).

Analysis of monthly rainfall data from 1911 to 1980 by the Federal Ministry of Environment (2003) reveals a changing pattern in annual precipitation. The results obtained suggest that, there appears to be a definite decline in the 1941 – 1980 eras. Other researchers show evidence of other indicators (Fasona and Omojola 2005; Chindo and Nyelong 2005; Ikhile, 2007; Nwafor 2007; Umoh 2007). Fasona and Omojola (2005), Obioha (2008) and Odjugo (2005, 2009) have observed decreasing rainfall in Nigeria especially in the northern part. The

decreasing rainfall, increasing temperature and evapotranspiration have resulted in either reduction of water levels or total drying up of some rivers and lakes in Northern Nigeria, while Lake Chad in Nigeria is reported to be shrinking in size at an alarming rate since the 1970s (Chindo and Nyelong 2005; Odjugo 2007). Nkomo *et al*., (2006), Molega (2006) and Nnodu *et al,*. (2007) confirm the existence of unusual or extreme weather related events such as erratic rainfall pattern, floods and sea level rise in Nigeria. Also, rainfall data analysis undertaken by Adejuwon (2002) indicates rainfall decline in several locations in Nigeria thereby authenticating the findings of previous researchers. Several past research studies on climate trends (Oladipo 1995; Anyadike 1993; Olaniran and Summer 1989; Clerk 2002; Nkeiruka and Apagu 2005) have also shown significant variation in temperature and other climatic elements.

Ekpoh and Ekpenyong (2011) proposed that further scientific studies be undertaken at regional levels of the Sahel, due to significant variations in the climate of the region predicted by General Circulation Models (GCMs) so as to provide society with accurate information on the real and potential impacts of climate change, as well as, the mitigation and adaptation options available**.**

Previous studies done within the study area have not focused on the impact of climate change on water availability. Most of the related studies in the region focus on water infrastructure development (Oyebande, 1990; Okoye and Achakpa, 2007; Yekinni*et.al.*, 2015), irrigation (Adams, 2003; Yahaya, 2002; Wiggins, 2000) and Water quality (Hassan, *et.al*, 2014).

Therefore, considering the above statements this study focused on the assessment of relationships between climate change, water availability, water demand and supply

management on a catchment scale, and analysis of how water quantity will be affected by climatic change in the SRRB. This was done by using integrated water resources planning system (known as “Water Evaluation and Planning" WEAP) that calculates water demand, supply, runoff, infiltration, flows, and storage under varying hydrologic and temperature hypothetical scenarios.

This study will considerably improve our understanding of climate change, and can significantly improve early warning systems by providing prior information, which have become a powerful instrument for anticipating on and mitigating the negative effects of climate variability in many areas of the world. It will also provide data and method of analysis using WEAP for the determination of climate change impact on water availability to be used for management decisions and application to other basins. This is the first study of its kind that used this tool in the region. The reliability estimates described in this study also inform anticipatory adaptation actions such as investment in increased water use efficiency measures.

1.3 Aim and Objectives of the study

The aim of this study is to analyse how sensitive the SRRB is to climatic change with regards to its surface water availability, by developing a Model of the basin using WEAP and proposing some mitigation measures that can minimize the negative impact within the basin by the principle of mass balance of the hydrologic quantity of the whole area.

The specific objectives are to:

i. Evaluate the present hydrological condition (streamflow) of the entire SRRB using available data.

ii. Apply WEAP model to the SRRB to evaluate the impact of climate change for current and future water availability using water balance concept.
iii. Calculate surface water availability and demand for each sub-basin within the entire River Basin by considering watershed characteristics and the demographic trends.
iv. Produce a simulation of the projected water availability and to compare the water availability with and without the effect of climate change in the study area and analyse the water resources trend in the part of the basin towards 2064.

1.4 Limitations of the study

The study focused on the application of the WEAP model to the SRRB for the purpose of defining how the basin could respond to major stresses of climate change in terms of the water availability at the catchment scale. However, it is beyond the scope of this study to identify the problem of flooding if it may happen under future climate scenarios. The study also does not take into account the effect of climate change on the ground water availability and water quality.

CHAPTER TWO

LITERATURE REVIEW

2.1 Description of the study area

The study area is Sokoto-Rima River Basin (SRRB) home to over 15million people and one of the seven basins demarcated in Nigeria. It is located in the North-Western region of Nigeria between latitudes 10° N and 14° N and longitudes 3° E and 8°E (Figure 2.1 and 2.2). It covers a land area of approximately 131,600 km^2 and shares its borders with Niger Republic to the north, and covers Sokoto, Kebbi, Zamfara and large part of Katsina States to the East; it also borders Niger State to the South-east, and Benin Republic to the west. The whole basin can be described as Sudan and Sahel Savannah, and it extends beyond the border to Niger republic and the northern part of Benin Republic. The basin has six major rivers namely; River Bunsuru, Gagere, Rima, Sokoto, Zamfara and Ka. Its topography consists of a vast floodplain (fadama land) and rich alluvial soils that is suitable for the cultivation of different variety of crops. There are also isolated hills (inselberg) and hill ranges scattered all over the area (Ekpoh and Ekpenyong, 2011). The diverse geography and climate characteristics of the basin play an important role in water availability and water utilisation activities, although threatens by combination of human population growth, unsustainable use of resources, deforestation, desertification and climate change.

In this section the climate, hydrology, hydrogeology, land use/land cover, demography, two major reservoirs and irrigation schemes of the study area were discussed.

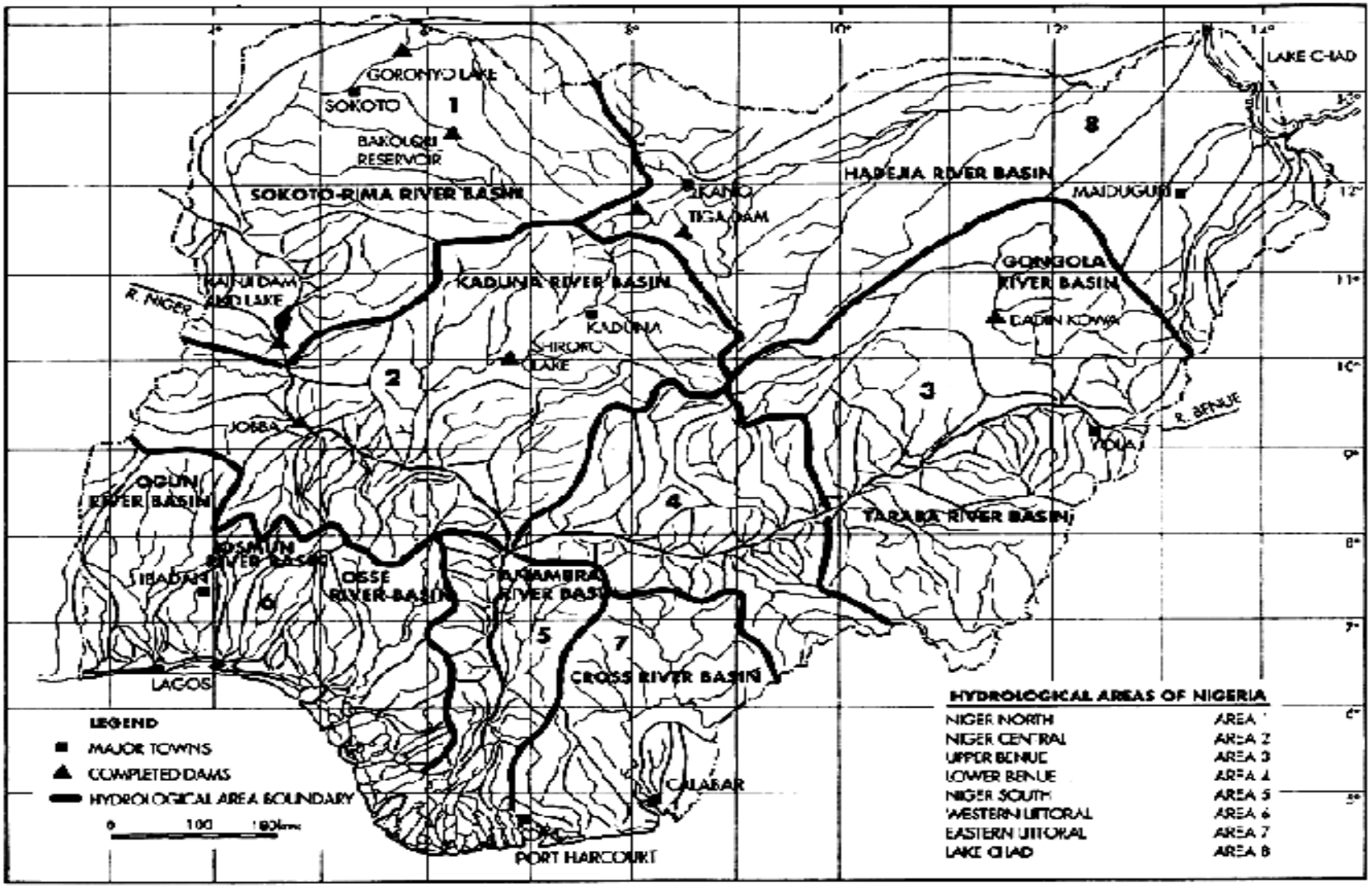


Figure 2.1: Hydrological map of Nigeria showing the major inland waters (Source: Ita, 1993).

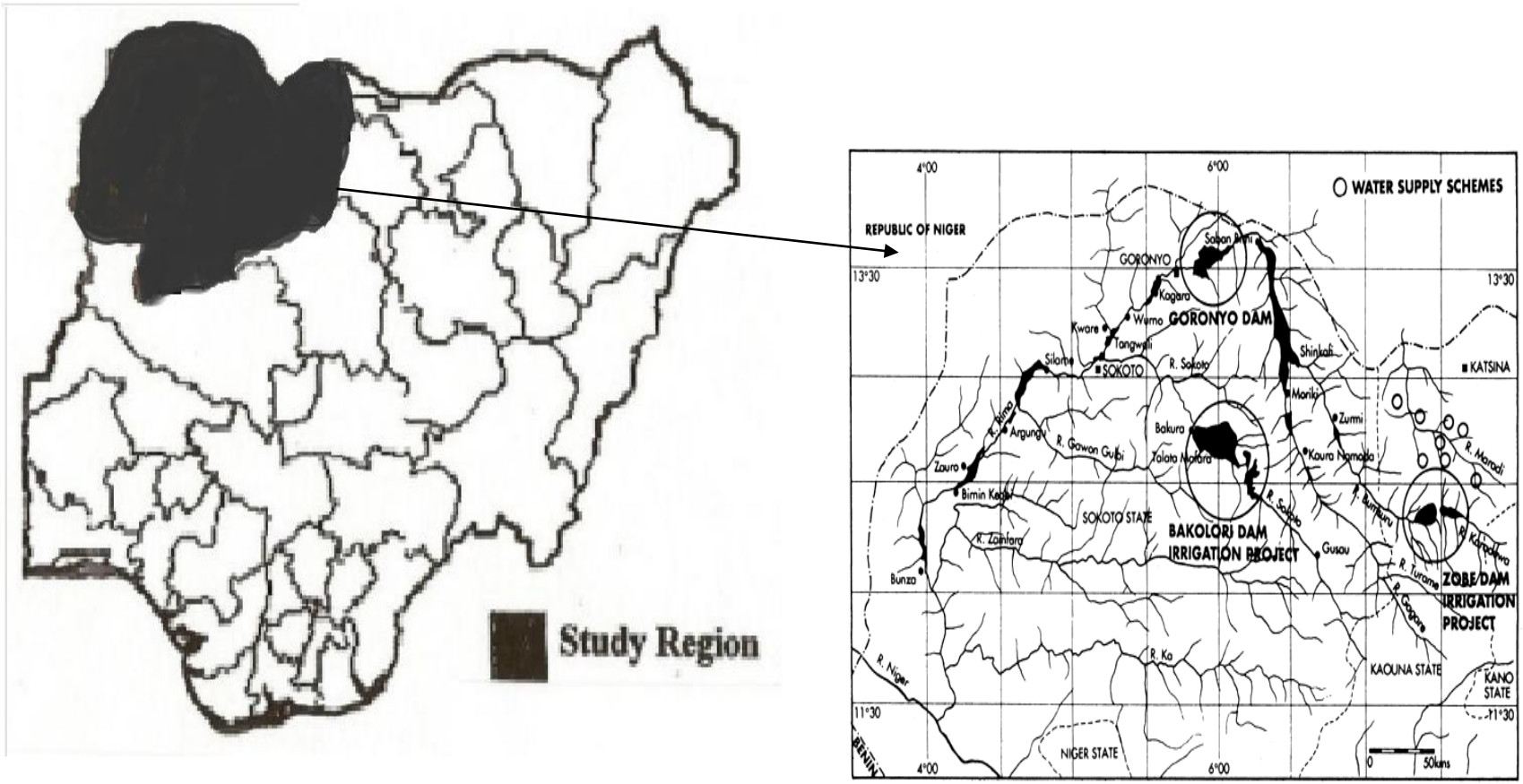


Figure 2.2: Sokoto-Rima River Basins in Nigeria (Source: FAO, 1997)

2.1.1 Climate of the study area

Like the rest of West Africa, the climate of the region is controlled largely by the two dominant air masses affecting the sub- region. These are the dry, dusty, tropical- continental (cT) air mass (which originates from the Sahara region), and the warm, tropical- maritime (mT) air mass (which originates from the Atlantic Ocean). The influence of both air masses on the region is determined largely by the movement of the Inter-Tropical Convergence Zone (ITCZ), a zone representing the surface demarcation between the two air masses. The interplay of these two air masses gives rise to two distinct seasons within the sub-region. The wet season is associated with the tropical maritime air mass, while the dry season is a product of the tropical continental air mass. The influence and intensity of the wet season decreases from the West African coast northwards. Therefore, precipitation in the whole sub-region of West Africa depends on thunderstorm activity which occurs along disturbance lines called "line squalls" and, about 80 percent of the total annual rainfall for most places within the basin is associated with line squall activities which are prevalent between June and September. In terms of climatic statistics, the annual rainfall for Sokoto ranges between 300 mm and 800 mm. The average annual rainfall for 35 years is about 470mm. Much of the rain falls between the months of May to September, while the dry months are October to April.

The Sokoto basin falls within the hottest parts of Nigeria. The critical zone, located above latitude 10^{o}N, belongs to the Sahel region of Africa, an area most affected by the droughts. Temperatures are generally extreme, with average daily minimum of 16^{o}C during cool months of January and December, and in the hottest month of April to June, an average maximum of 38^{o}C and minimum of 24^{o}C. Throughout the year the average maximum is 36^{o}C and average

daily minimum is 21^{o}C. The mean annual temperature is 34.5 ^{0}C, although dry season temperatures in the region often exceed 40^{0}C. (Ekpoh and Ekponyong, 2011)

Evaporation is high ranging from 80mm in July to about 210mm in April to May. A monthly average evaporation range of about 140mm represent 30% of monthly average precipitation into the catchment. The hottest months of April to May are periods of highest evaporation. Relative humidity is low most of the year and only increases during the wet seasons of June to September. The vegetation is typically Sudan savannah and is characterized by stunted and thorny shrubs, invariably of the acacia species.

2.1.2 Hydrology

The basin is essentially drained by the River Sokoto, a prominent part of Niger River drainage system (Figure 2.1). The Sokoto River main tributaries are the Rima Zamfara, and Ka, They arise from the 600 to 900 meters high Mashika and Dunia highland areas bordering the eastern part of the basin, and flows down, rather sluggishly down a gentle slope toward the Northwest, River Rima joined it in the north around Sokoto town, after that it makes a southward swing, collecting the Zamfara and Ka before entering in to the River Niger. The river systems, thus effectively drains the whole basin. At the source areas in the east where it is joined by River Konni, the Sokoto River system is only seasonal. However in the western parts of the basin, the river becomes perennial as it begins to receive substantial ground water contribution to its flow.

2.1.3 Hydrogeology

The stratigraphy of the basin is divided in to nine different formations. They are: Gwandu formation which is Eocene by age; Kalambaina and Dange formations which are Palaeocene by age and grouped as Sokoto group; Wurno, Dukamaje, Taloka and Illo formations which are Maastrichtian by age and grouped as Rima group; Gundumi formation which is Premaestrichitan by age; and Basement complex which is pre Cambrian by age. The Gwandu formation is the best known aquifer in the Sokoto Basin. The groundwater discharge is relatively low, at the Wamako gauging station. This is related to the geology of the area drained by the river, comprising impermeable marly clay and calcareous formations. At the lower limb, where the Zamfara River joins the system, groundwater contribution increases from the more permeable beds of the Gwandu formation (Offodile, 1992).

2.1.4 Land use and Land cover

The land use and land cover within the basin are grouped in to five major categories: Settlements, Agricultural Land, Vegetative Cover, Water Bodies and Bare and Rocky Surfaces. Agricultural land is divided in to three categories: (a) “Fadama” , or land which historically has been seasonally flooded or irrigated; (b) “Tudu” , or land which lies above the flood plain and is dependent on rainfall for its moisture; and (c) land farmed by modern methods of irrigation for example Talata-Mafara Irrigation scheme. The land use pattern isdescibed in Table 1.1, andMap of Land Use and Land Cover of the part of the basin is shown in Figure 2.3 to 2.5.

Table 2.1: Land Use and Land Cover of Sokoto-Rima River Basin

Category	**Area in Km^2**	**Percentage**
Forest land/wood land	2,755	2%
Grass land	46,615	35%
Agricultural land	69,520	53%
Wet land	970	0.74%
Bare land	10,330	7.85%
Water area	1,400	1.06%
Urban land	10	0.007%
Grand Total	**131,600**	**100%**

(Source: JICA, 1995)

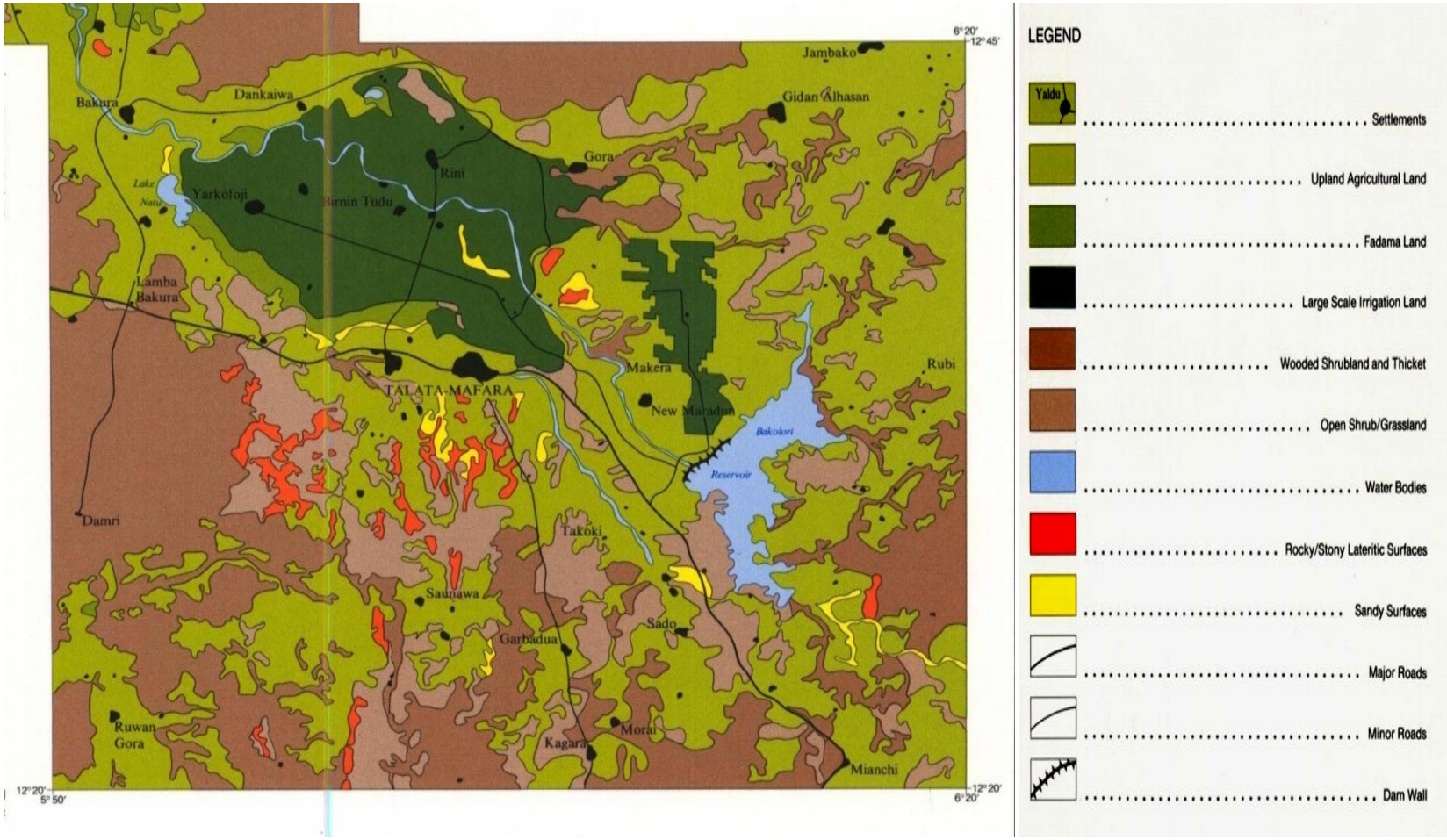


Figure 2.3: Map of Land Use and Land Cover of the upper part of Sokoto-Rima basin (source: Panagos *et al.*, 2011).

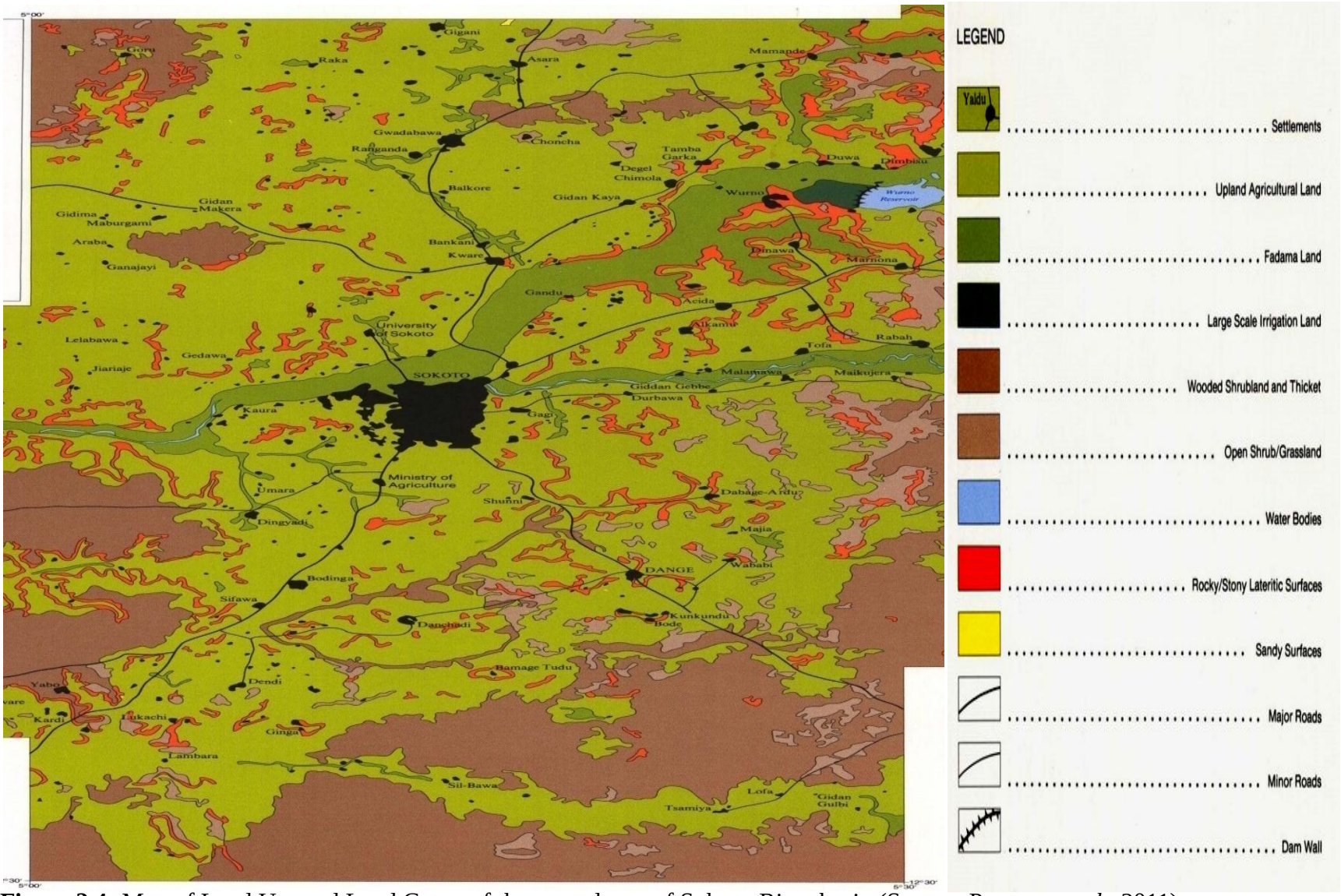


Figure 2.4: Map of Land Use and Land Cover of the central part of Sokoto-Rima basin (Source: Panagos *et al.*, 2011).

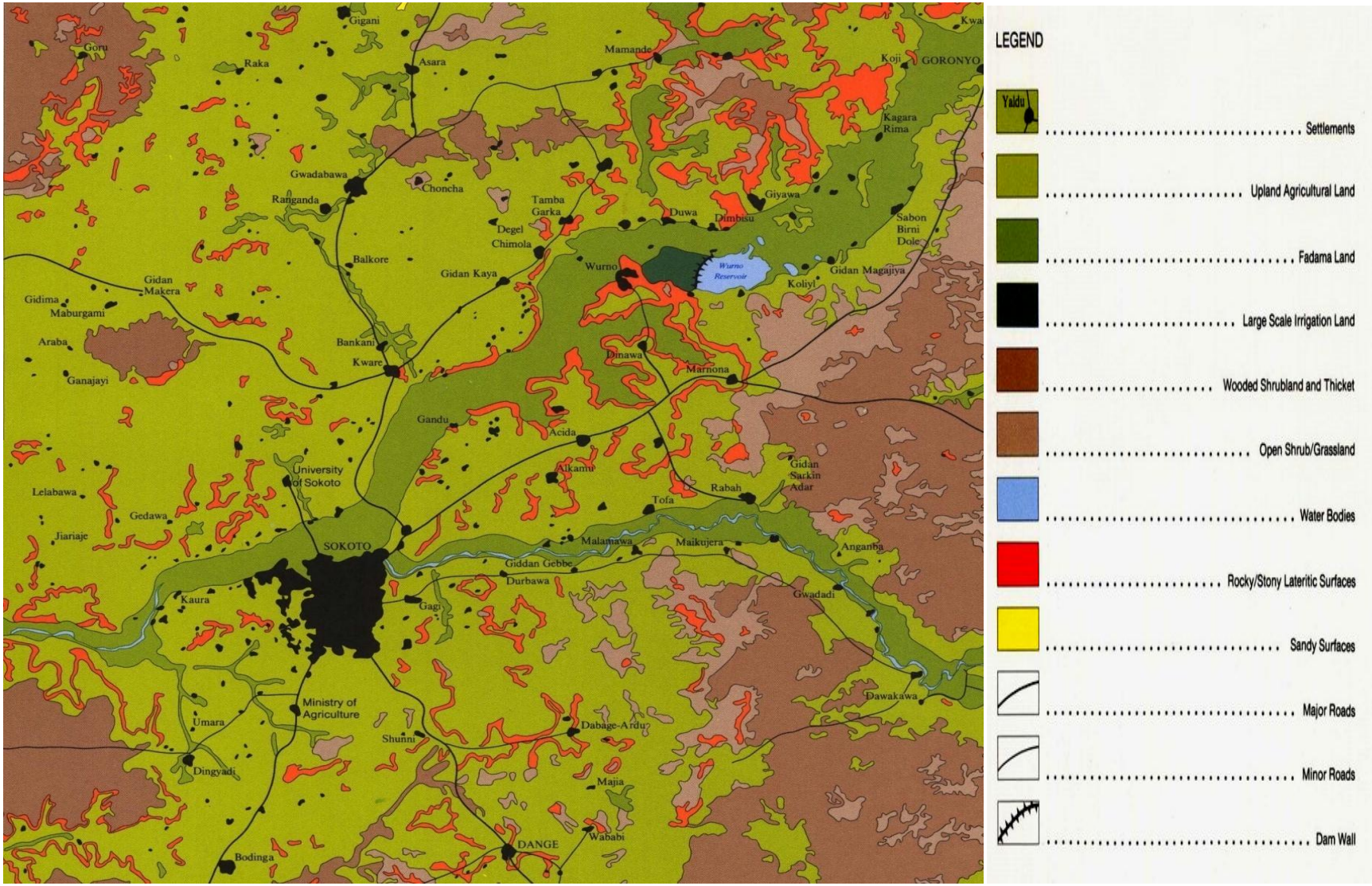


Figure 2.5: Map of Land Use and Land Cover of the lower part of Sokoto-Rima basin (source: Panagos *et al.*, 2011).

2.1.5 Demography

The population growth in Africa shows a very rapid growth rate more especially in urban area. In 1991, the population in the states of Katsina, Kebbi, Sokoto, and Zamfara total to 10,291,799 people, and consists of Urban and rural population. While the total population according to 2006 census for those states is 16,039,674 people, as shown in Table 2.2 below. The whole states within the basin have an average inter census growth rate of 3.11 and the average population density of 130.35 in the year 2006.

Table 2.2: Population Census of the states in Sokoto-Rima River Basin

States	Census 1991, Total Population	Census 2006, Total Population			Land Size Km^2	Inter Census Growth Rate	Population Density
		Male	Female	Both Sexes			
Katsina	3,753,133	2,948,279	2,853,305	5,801,584	24,971.22	3.04	232.3
Kebbi	2,068,490	1,631,629	1,624,912	3,256,541	37,727.97	3.17	86.3
Sokoto	2,397,000	1,863,713	1,838,963	3,702,676	33,776.89	3.03	109.6
Zamfara	2,073,176	1,641,623	1,637,250	3,278,873	35,170.63	3.2	93.2

2.1.6 Two Major Dams within the Basin

The two major dams in the SRRB are the Bakolori and Goronyo dams. The Bakolori Dam is in Zamfara State, it was completed in 1978 and its reservoir filled by 1981. It is a major reservoir on the Sokoto River, a tributary of the Rima River, which in turn feeds the Niger River. Water from the dam supplies the Bakolori Irrigation Project in Talata Mafara. The dam has a capacity of 450million cubic meters, with a reservoir covering 8,000 hectares extending 19 km (12 mi) upstream, other operation parameters of the two dams are shown in Table 2.3 (JICA, 1995)

The Goronyo Dam impounds Rima River at Goronyo in Goronyo local government area of Sokoto State. It was completed in 1984 and commissioned in 1992. The dam is a sand-fill structure with a height of 21 m and a total length of 12.5 km. It has a storage capacity of 976million cubic meters (MCM). The dam is controlling floods and releasing water in the dry season for the planned Zauro polder project downstream in Kebbi State. Other large dams within the basin are Gusau dam with height of 22m and total length of 800m located in Zamfara state and Zuru dam with height of 15m and total length of 700m located in Kebbi state. There are also some small dams within the basin which include Zurmi, Marina and Shagari dams.

Table 2.3: Physical and Operation Parameters of the Goronyo and Bakolori Dams

Name of the dam	**Goronyo dam**	**Bakolori dam**
Type	Earth	Concrete
Catchment Area	21445 Km^2	4857 Km^2
Storage Capacity Active Capacity Dead Capacity	942 Million m^3 933 Million m^3 9 Million m^3	450 Million m^3 403 Million m^3 47 Million m^3
Full Water Level Lower Water Level	288.0 m 279.5 m	334.0 m 320.0 m
Planned Irrigation Area Operated Irrigation Area	69 000 Ha 17 000 Ha	23 000 Ha 23 000 Ha
Reservoir Area	200 Km^2	80 Km^2
Mean annual Inflow	656 Million m^3	757 Million m^3
Height	20 m	48 m
Length	5285 m	5500 m
Maximum Hydraulic outflow	1697 m^3/s	3750 m^3/s

(Source: JICA, 1995)

2.1.7 Existing Irrigation Schemes within the basin

Irrigated agriculture, by far the largest water-use sector globally, is affected by changes in water availability that are caused by climate change. Climate change will bring increased evaporation and moisture deficits. These deficits will produce changes in the need to increase the amount of water needed for irrigation. Higher temperatures and more variable rainfall tend to increase water demand per unit of irrigated area, unless total rainfall increases sufficiently in compensation. However, water demand to produce a given amount of food will increase less (or decrease more) than demand per unit of irrigated area, as crop water productivity increases due to higher carbon dioxide concentrations (Gerten *et al.*, 2014).

The climatic condition of SRRB enhances the need for irrigation particularly for their cereal and vegetable dominant farming system. Farming is undoubtedly, the major occupation in the area (Ekpoh and Ekpenyong, 2011).

The small scale irrigation projects in the basin, that are located at Gagere, Bakura, and Kware covers a total area of 950km^2 as shown in Table 2.4. The farmers in those places usually grow rice, tomato, and water melon. They have carrying capacity of 5m^3/s to 20m^3/sec and different capacity of the supply canals and spillways.

Table 2.4: Existing Small Scale Irrigation

Existing Small Scale Irrigation			
Project	**River**	**Water Source Works**	**Irrigation area (km^2)**
Gagere	Gagere	Weir	100
Bakura	Lake Natu	Pump	50
Kware	Rima	Pump	800

(Source: JICA, 1995)

The medium scale irrigation projects located at Bakalori, Wurno, Rima Valley, and Zauro in the basin cover total area of 44,000 km^2 as shown in Table 2.5. The Bakolori project was designed to supply irrigation water to 15,000 km^2 area by gravity and 8,000 km^2 area by sprinkler. The system is serviced by a 15km long concrete lined supply canal which is crossed by 35 culverts, foot and vehicular bridges. It has a reported carrying capacity of 30m^3/sec and at the end of the supply canal there is a spillway and automatic siphons to prevent overloading.

Table 2.5: Existing Medium Scale Irrigation

Existing Medium Scale Irrigation			
Project	**River**	**Water Source Works**	**Irrigation Area (Km^2)**
Bakolori	Sokoto	Dam	23000
Wurno	Rima	Dam	1500
Middle Rima Valley	Rima	Dam	6500
Zauro Folder	Rima	Dam/Boreholes	13000

(Source: JICA, 1995)

2.2 Climate change

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant factors over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization.

The most dominant climate drivers for water availability are precipitation, temperature and evaporative demand (determined by net radiation at the ground, atmospheric humidity and wind speed, and temperature). Temperature is particularly important in snow-dominated

basins and in coastal areas, the latter due to the impact of temperature on sea level (static sea-level rise due to thermal expansion of water).

Warming of the climate system in recent decades is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. Net anthropogenic radiative forcing of the climate is estimated to be positive (warming effect), with a best estimate of 1.6 Wm^{-2} for 2005 (relative to 1750 pre-industrial values). The Intergovernmental Panel on Climate Change (IPCC) developed the variation of the earth temperature from the improved analysis of Brohan *et al*. (2006) and Trenberth *et.al*, (2007) as shown in Figure 2.6.

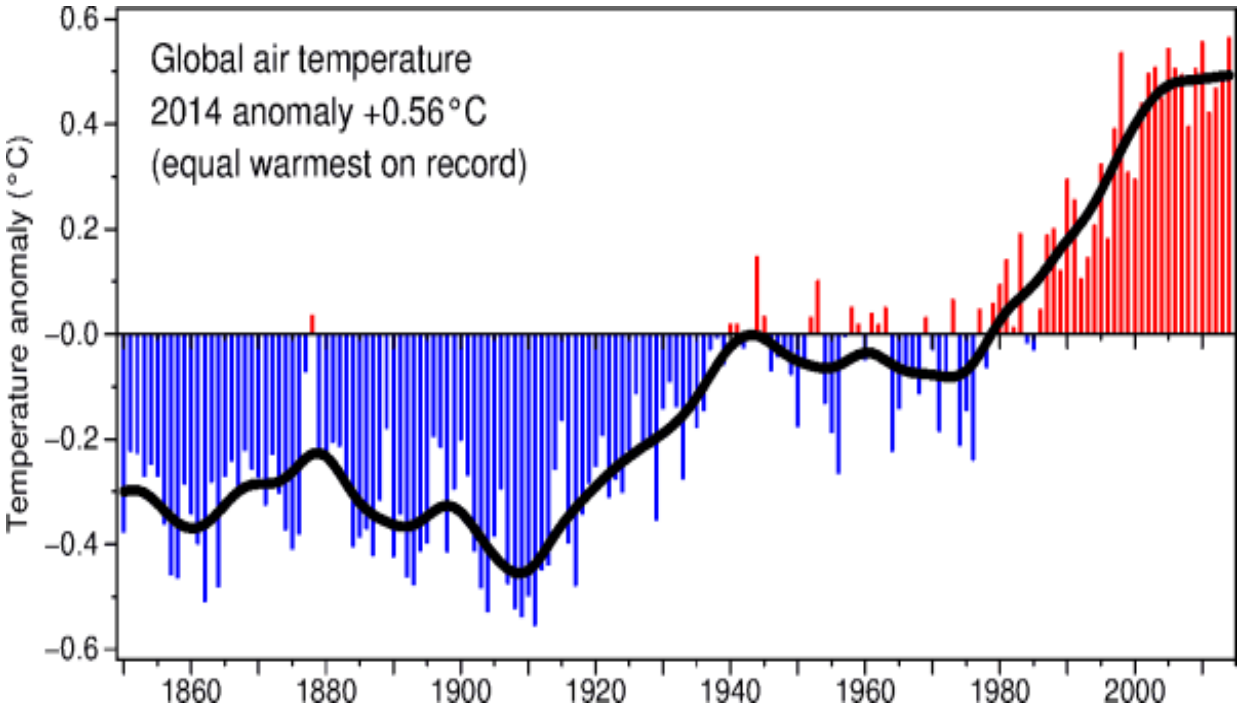


Figure 2.6: Variation of the earth temperature for the past 140 years

(Source: Trenberth *et.al*, 2007)

The best-estimate linear trend in global surface temperature from 1906 to 2010 is a warming of 0.74°C (likely range 0.56 to 0.92°C), with a more rapid warming trend over the past 50 years. New analyses show warming rates in the lower- and mid-troposphere that are similar to rates at the surface. Attribution studies show that most of the observed increase in global temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. At the continental scale, it is likely that there has been significant anthropogenic warming over the past 20 years averaged over each of the continents except Antarctica (Figure 2.7). For widespread regions, cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent over the past 20 years.

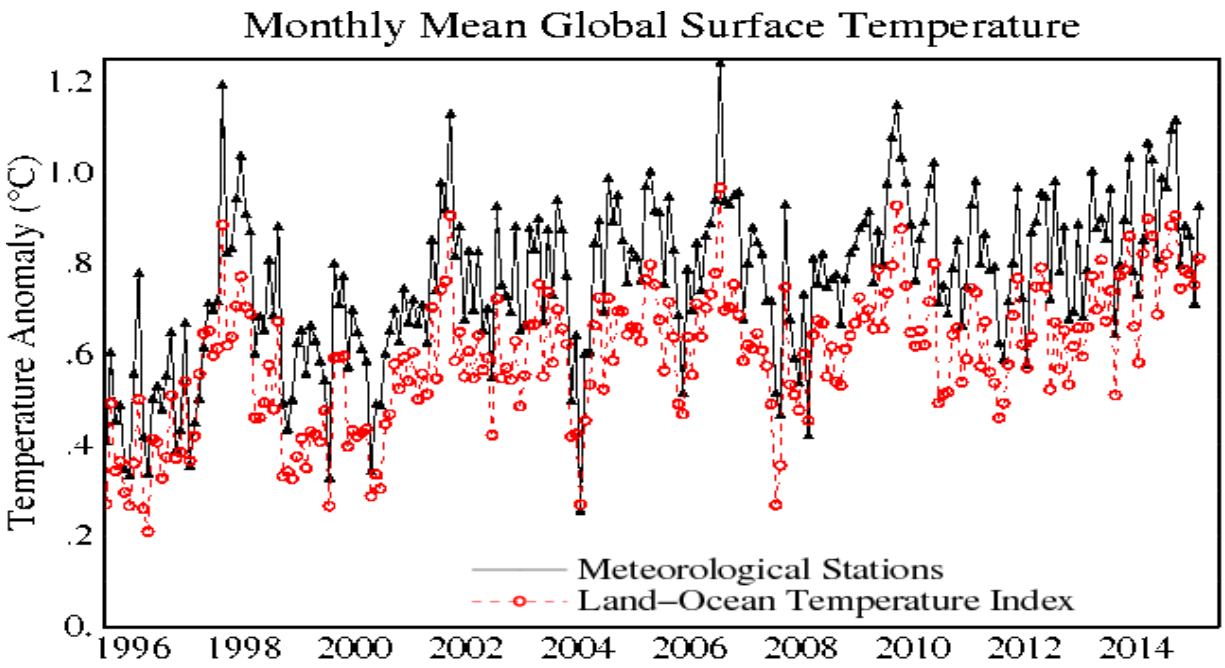


Figure 2.7: Variation of the earth temperature for the last 20 years
(Source: http://www.giss.nasa.gov/)

Atmospheric warming is not evenly spread around the world. Analysis of historical records suggests that the temperature of land areas will increase more rapidly than the global average.

The greatest warming has occurred in the high northern latitudes, especially in northern Canada and Alaska. The map below (Figure 2.8) shows differences between surface temperatures in 2011 and average global temperatures calculated for the period from 1951 to 1980 by NASA at 250 km resolution. The global mean anomaly, averaged over the area with a defined anomaly is 0.51°C for 1200 km resolution. This resolution analysis is believed to provide the better estimate for the full global anomaly, because it fills in estimated anomalies in Africa, Canada, Siberia, and especially in the Arctic, as discussed by Hansen *et al.* (2010).The 2011 was only the ninth warmest year in the analysis of global temperature change, yet nine of the ten warmest years in the instrumental record (since 1880) have occurred in the 21st century (http://www.giss.nasa.gov/).

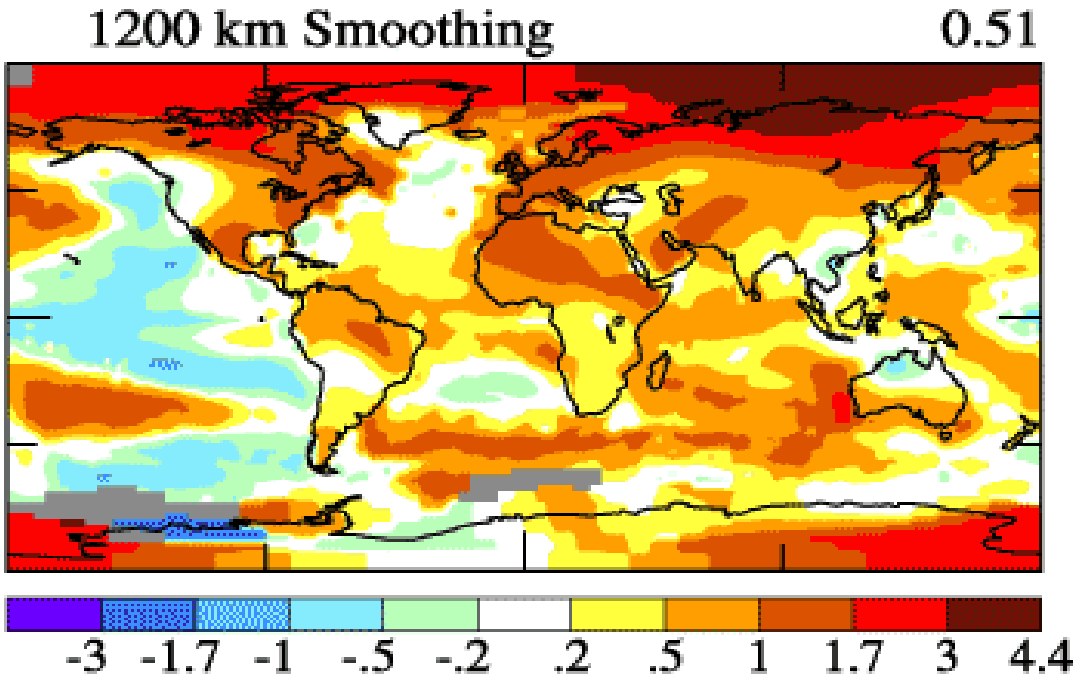
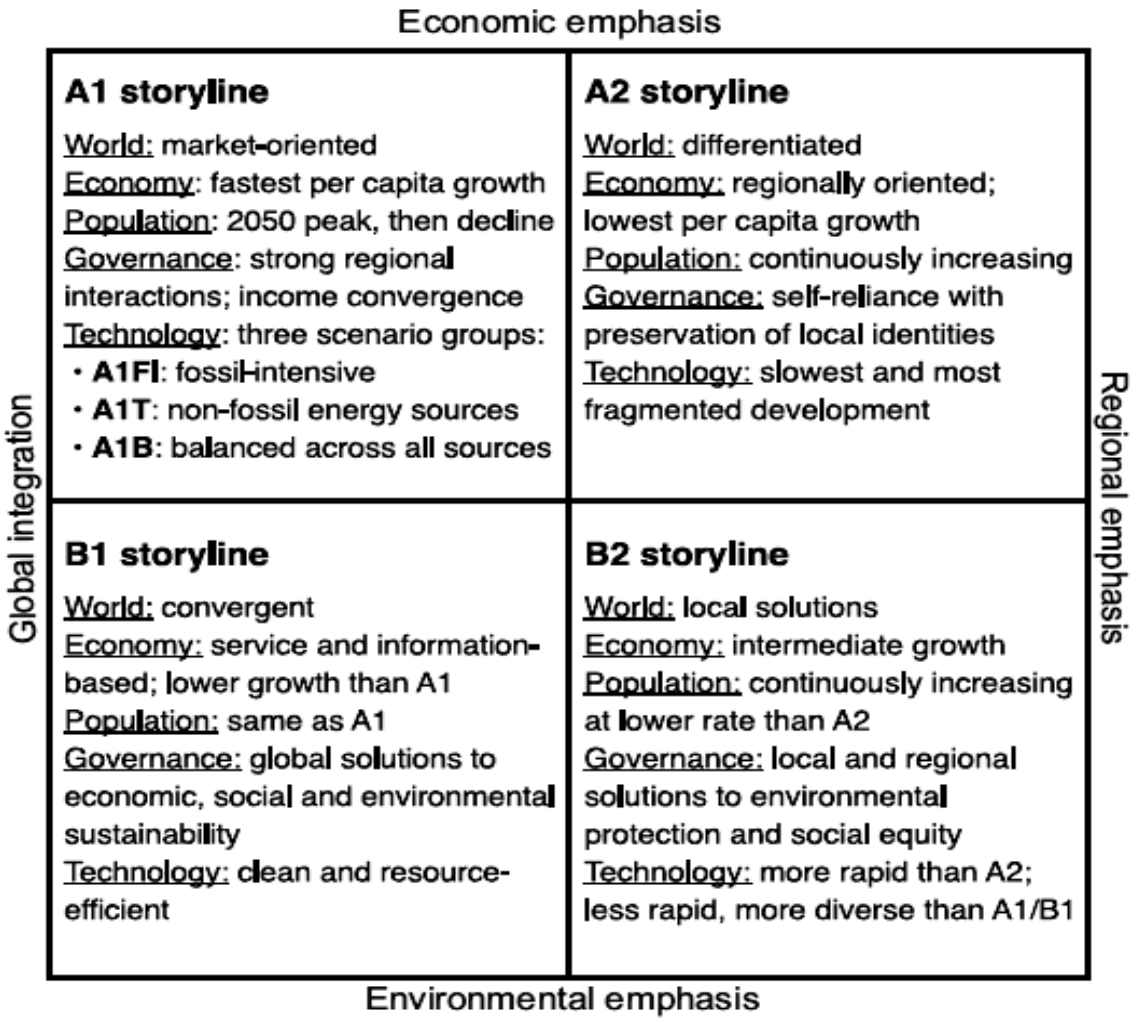


Figure 2.8: Differences between surface temperatures in 2011 and average global temperatures calculated for the period from 1951 to 1980. (Source: NASA Global temperature anomalies for 2015)

2.3 Prediction of Climate change

Scientists have developed mathematically-based climate models to help predict future climate changes. The starting point for each projection of future emissions was a ‘storyline’, describing the way world population, economies and political structure may evolve over the next few decades (Arnell, 2003).Each model uses different assumptions about the future to predict how atmospheric CO_2 levels and temperatures will change.

The four IPCC SRES (Special Report on Emissions Scenarios: Nakićenović and Swart, 2000) storylines, which form the basis for many studies of projected climate change and water resources, consider a range of plausible changes in Population growth rate; Economic development; Energy use; Efficiency of energy use; Mix of energy technologies over the 21st century (Figure 2.9).



Swart, 2000)

A1 and B1 are the scenarios that assume a world economy dominated by global trade and alliances, global population is expected to increase from 6.6 billion and peak at8.7 billion in 2050, while A2 and B2 are the scenarios with less globalisation and co-operation, global population is expected to increase until 2100, reaching 10.4 billion (B2) and 15 billion (A2) by the end of the century. In general, all SRES scenarios depict a society that is more affluent than today, with world gross domestic product (GDP) rising to 10–26 times today's levels by 2100. A narrowing of income differences between world regions is assumed in all SRES scenarios – with technology representing a driving force as important as demographic change

and economic development. The graph in Figure 2.10 shows the results from three climate models used by the IPCC, with predictions starting in 1990 and ending in the year 2100. In all three, the global population rate rises during the first half of the century, and then declines.

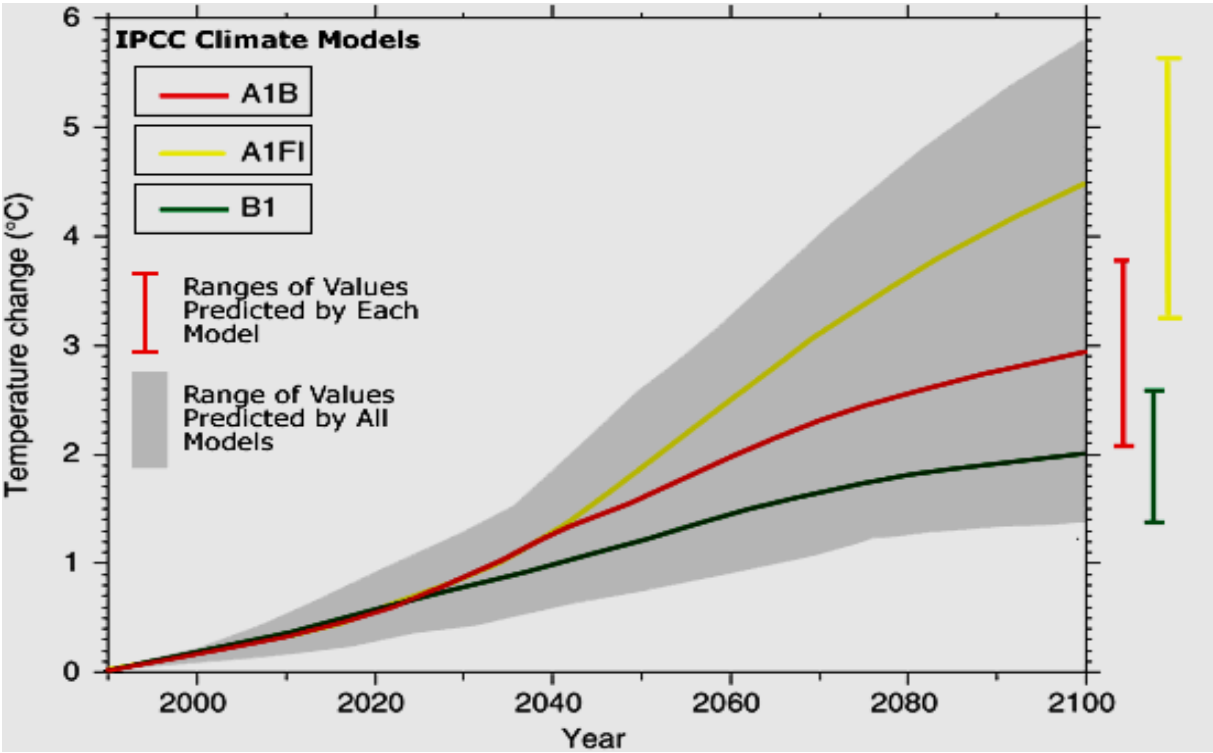


Figure 2.10: Global temperature increases predicted by different IPCC climate models.

The A1B model assumes rapid economic growth and increased equity—the reduction of regional differences in per-person income. New and more efficient technologies are introduced, without relying heavily on a single energy source.

The A1F1 model is the same as A1B, but assumes the continued use of fossil fuel-intensive technologies.

In the B1 model, the world moves rapidly from a producer-consumer economy toward a service and information economy. There is a reduction in the use of raw materials, and an

emphasis on clean and efficient technologies and improved equity. Other models A1T, A2, and B2 were also developed, each based upon a different set of assumptions adapted from IPCC, Third Assessment Report on Climate Change, as shown in Figure 2.11.

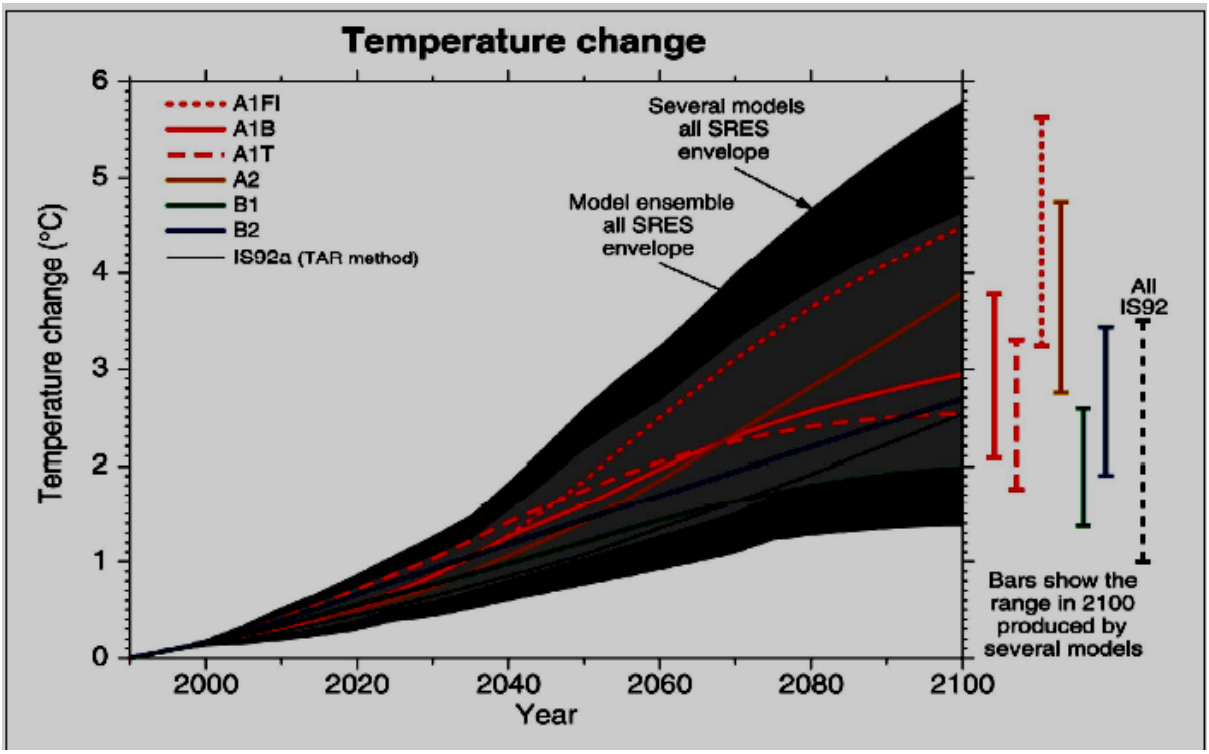


Figure 2.11: Global temperature increases predicted by three different IPCC climate models.

Although differing in degree, all these climate prediction models show similar trends. They indicated that projected rate of global warming in the future is much larger than the rate of global warming during the 20th century. They also predicted rates of global warming are greater than any seen in the past 10,000 years.

2.4 Impacts of Climatic Change on Hydrology and Water Resources

Water is involved in all components of the climate system (atmosphere, hydrosphere, cryosphere, land surface and biosphere). Therefore, climate change affects water through a number of mechanisms. The hydrological cycle is intimately linked with changes in

atmospheric temperature and radiation balance. Climate warming observed over the past several decades is consistently associated with changes in a number of components of the hydrological cycle and hydrological systems such as: changing precipitation patterns, intensity and extremes; widespread melting of snow and ice; increasing atmospheric water vapour; increasing evaporation; and changes in soil moisture and runoff. There is significant natural variability – on interannual to decadal time-scales – in all components of the hydrological cycle, often masking long-term trends. There is still substantial uncertainty in trends of hydrological variables because of large regional differences, and because of limitations in the spatial and temporal coverage of monitoring networks (Huntington, 2006).

The climate response to forcing agents is also complex. For example, one effect of absorbing aerosols (e.g., black carbon) is to intercept heat in the aerosol layer which would otherwise reach the surface, driving evaporation and subsequent latent heat release above the surface. Hence, absorbing aerosols may locally reduce evaporation and precipitation. Many aerosol processes are omitted or included in somewhat simple ways in climate models, and the local magnitude of their effects on precipitation is in some cases poorly known.

It was also observed that the trends in land precipitation have been analysed using a number of data sets; notably the Global Historical Climatology Network (GHCN: Peterson and Vose, 1997), the Precipitation Reconstruction over Land (PREC/L: Chen *et al.*, 2002), the Global Precipitation Climatology Project (GPCP: Adler, 2003), the Global Precipitation Climatology Centre (GPCC: Beck *et al.*, 2005) and the Climatic Research Unit (CRU: Mitchell and Jones, 2005). Precipitation over land generally increased over the 20th century between 30°N and 85°N, but notable decreases have occurred in the past 30–40 years from 10°S to 30°N (Figure 2.12).

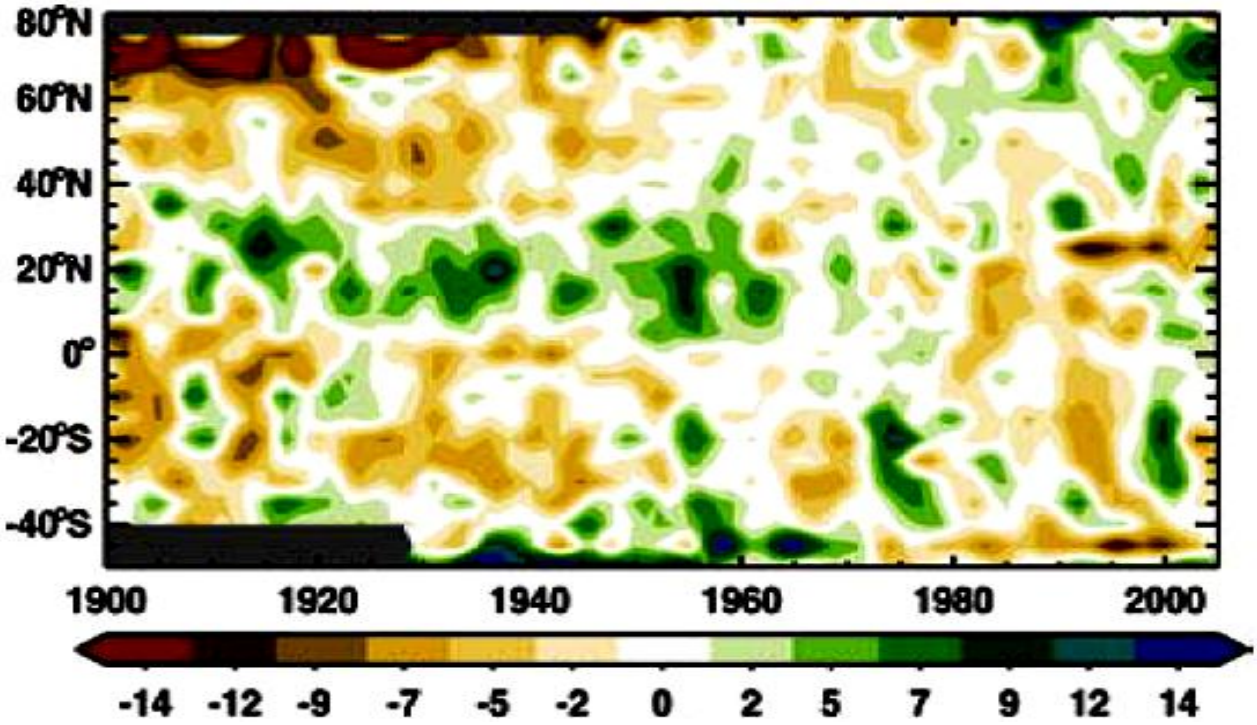


Figure 2.12: Latitude–time section of average annual anomalies for precipitation (%) over land from 1900 to 2005, relative to their 1961–1990 means (Bates *et. al.*, 2008).

From 10°N to 30°N, precipitation increased markedly from 1900 to the 1950s, but declined after about 1970. Global changes are not linear in time, showing significant decadal variability, with a relatively wet period from the 1950s to the 1970s, followed by a decline in precipitation. Global averages are dominated by tropical and sub-tropical precipitation.

However, at present, documenting inter-annual variations and trends in precipitation over the oceans remains a challenge. Understanding and attribution of observed changes also presents a challenge. During the 20th century there have been many studies related to trends in river flows at scales ranging from catchment to global. Some of these studies have detected significant trends in some indicators of river flow, and some have demonstrated statistically significant links with trends in temperature or precipitation; and globally homogeneous trend

has been reported by IPCC (2007b). Many studies, however, have found no trends, or have been unable to separate the effects of variations in temperature and precipitation from the effects of human interventions in the catchment, such as land-use change and reservoir construction. Variation in river flows from year to year is also very strongly influenced in some regions by large-scale atmospheric circulation patterns and other variability systems that operate at within-decadal and multi-decadal time-scales. At the global scale, there is evidence of a broadly coherent pattern of change in annual runoff, with some regions experiencing an increase (Tao *et.al.,* 2003a, b, for China; Hyvarinen, 2003, for Finland; Walter *et.al.,* 2004, for the coterminous USA; Nkomo and Van der zaag, 2004, for Komati South Africa;), particularly at higher latitudes, and others a decrease, for example in parts of West Africa, southern Europe and southern Latin America (Milly *et.al*., 2005). Labat *et.al.,* (2004) claimed a 4% increase in global total runoff per 1°C rise in temperature during the 20th century, with regional variation around this trend. For hydrological variables such as runoff, non-climate-related factors may play an important role locally (e.g., changes in extraction).

Increased populations in Africa are expected to experience water stress before 2025, i.e., in less than decade from the publication of this research, mainly due to increased water demand. Climate change is expected to exacerbate this condition. In some assessments, the population at risk of increased water stress in Africa, for the full range of SRES scenarios, is projected to be 75–250 million and 350–600 million people by the 2020s and 2050s, respectively (Arnell, 2003).

2.5 WEAP Model

The Water Evaluation and Planning (WEAP) model has a long history of development and use in the water planning arena (Yates *et al.,* 2005). It was developed by the Stockholm

Environment Institute (SEI). WEAP operates on the basic principle of water balance accounting and aim to incorporate an integrated approach to water development, which places water supply projects in the context of demand-side issues, as well as issues of water quality and ecosystem preservation. WEAP is comprehensive, straight forward and easy-to-use, and attempts to assist rather than substitute for the skilled planner. As a database, WEAP provides a system for maintaining water demand and supply information. As a forecasting tool, WEAP simulates water demand, supply, runoff, streamflows, storage, pollution generation, treatment and discharge, and instream water quality. As a policy analysis tool, WEAP evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems. This make it a robust tool for analysis of future climate scenarios as they were asserted on the natural watershed, leading to associated hydrologic responses, all in the context of potential adaptation at a decisions level relevant to local water managers (Yates *et al*., 2005). WEAP represents a new generation of water planning software that utilizes the powerful capability of today's personal computers to give water professionals everywhere access to appropriate tools. The design of WEAP is guided by a number of methodological considerations: an integrated and comprehensive planning framework; use of scenario analyses in understanding the effects of different development choices; Demand-management capability; Environmental assessment capability; and Ease-of-use.

WEAP applications generally involve the following four steps (Sieber *et. al.*, 2005):

(1) **Study definition:**

The study definition sets up the time frame, spatial boundary, system components and configuration of the problem. When the WEAP software is open for the first time, a project

area called “Weaping River Basin” will appear. A window, as shown in Figure 2.13, will appear in which the “Initially Blank” option can be selected to create a new, blank area. The next steps, is to select the geographic area for your project from the world map that appears and name the area. In the next screen, the cursor is used to draw a rectangle around the area that the selected project will represent.

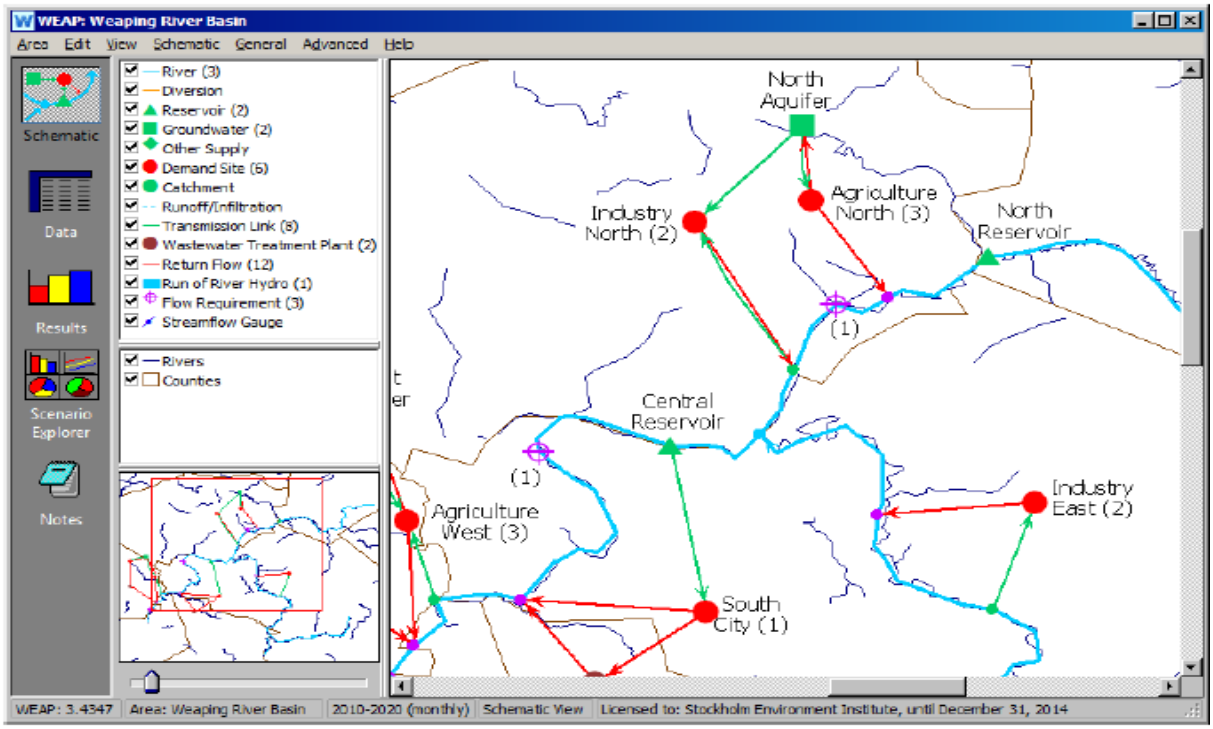


Figure 2.13: A screen copy of project area called “Weaping River Basin” that appear first.

The GIS-based Raster and Vector maps can be added to the selected project area - these maps can help to orientate and construct the system and refine area boundaries. The Raster or Vector layer can be added by right clicking in the middle window located at the left of the Schematic and selecting “Add a Raster Layer” or “Add a Vector Layer." WEAP reads vector information in the SHAPEFILE format. This format can be created by most GIS software.

(2) **Current accounts:**

The Current Accounts provide a snapshot of actual water demand, resources and supplies for the system. Alternative sets of future assumptions are based on technological development and other factors that affect demand, supply and hydrology. With WEAP, Current Accounts of the water system under study is created first by using the graphical capability of the graphic user interface (GUI), the “General” menu is used in setting Years and Time Steps as shown in Figure 2.14. Then, based on a variety of economic, demographic, hydrological, and technological trends, data available a "reference" or "business-as-usual" scenario is established, referred to as a Reference Scenario. This serves as a point of comparison for other scenarios in which changes may be made to the system data.

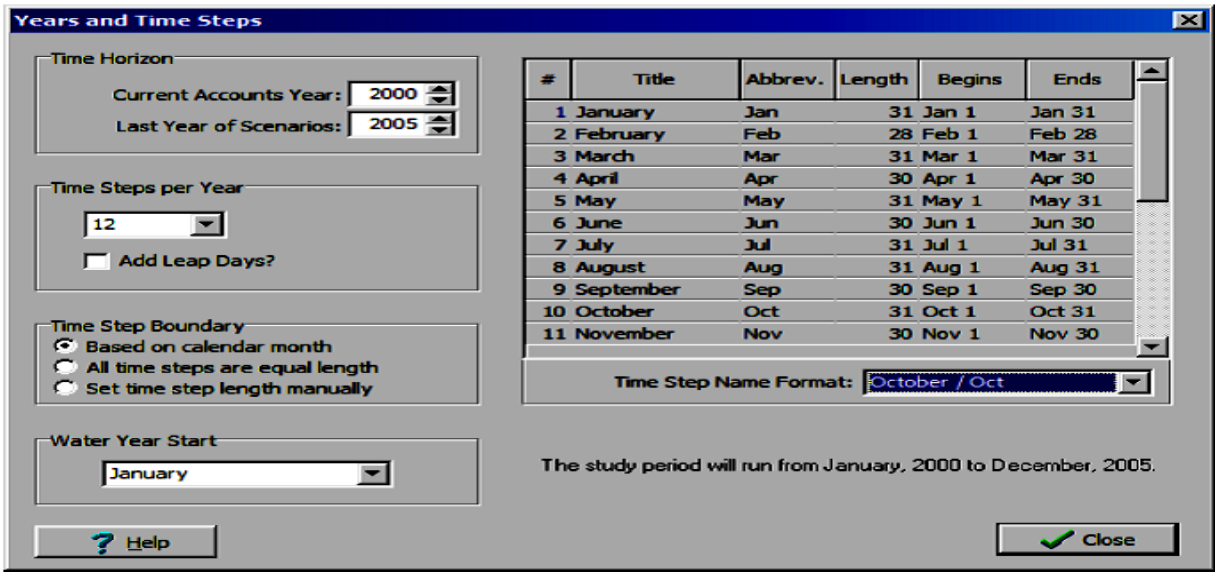


Figure 2.14: Graphic User interface for setting the current account

Scenarios are a set of alternative assumptions about future impacts of climate, on hydrology. (Possible scenario opportunities are presented in the section 3.2 and Table 3.1). They are constructed by considering different sets of assumptions considered by IPCC and other researchers in this field. Finally, the scenarios are evaluated with regard to water sufficiency,

costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

(3) **Entering Elements into the Schematic and Data:**

The river system within the catchment can be drawn by using the "River" symbol in the element window of the schematic view of the WEAP, starting from the upstream to the downstream. The first point drawn will be the head of the river from where water will flow. The catchment is created by using the "Catchment" object in the schematic view to simulate headflow for the river (Figure 2.15).

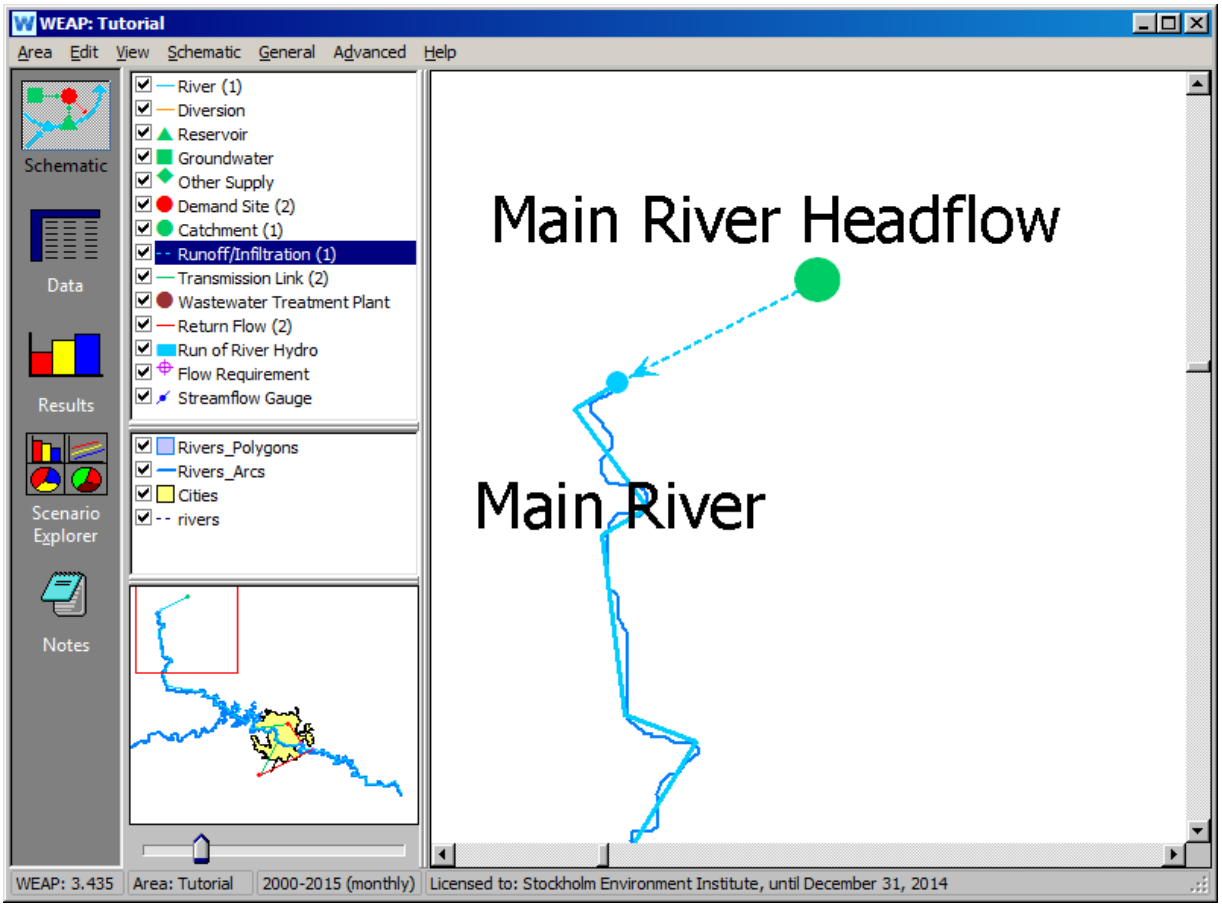


Figure 2.15: Creating Catchment and headflow diagram

The model of the catchment is set as “Rainfall Runoff (Soil moisture model) “.The land use, Irrigation areas and climatic data for the catchment are entered by using the data view symbol on the main screen (Figure 2.16).

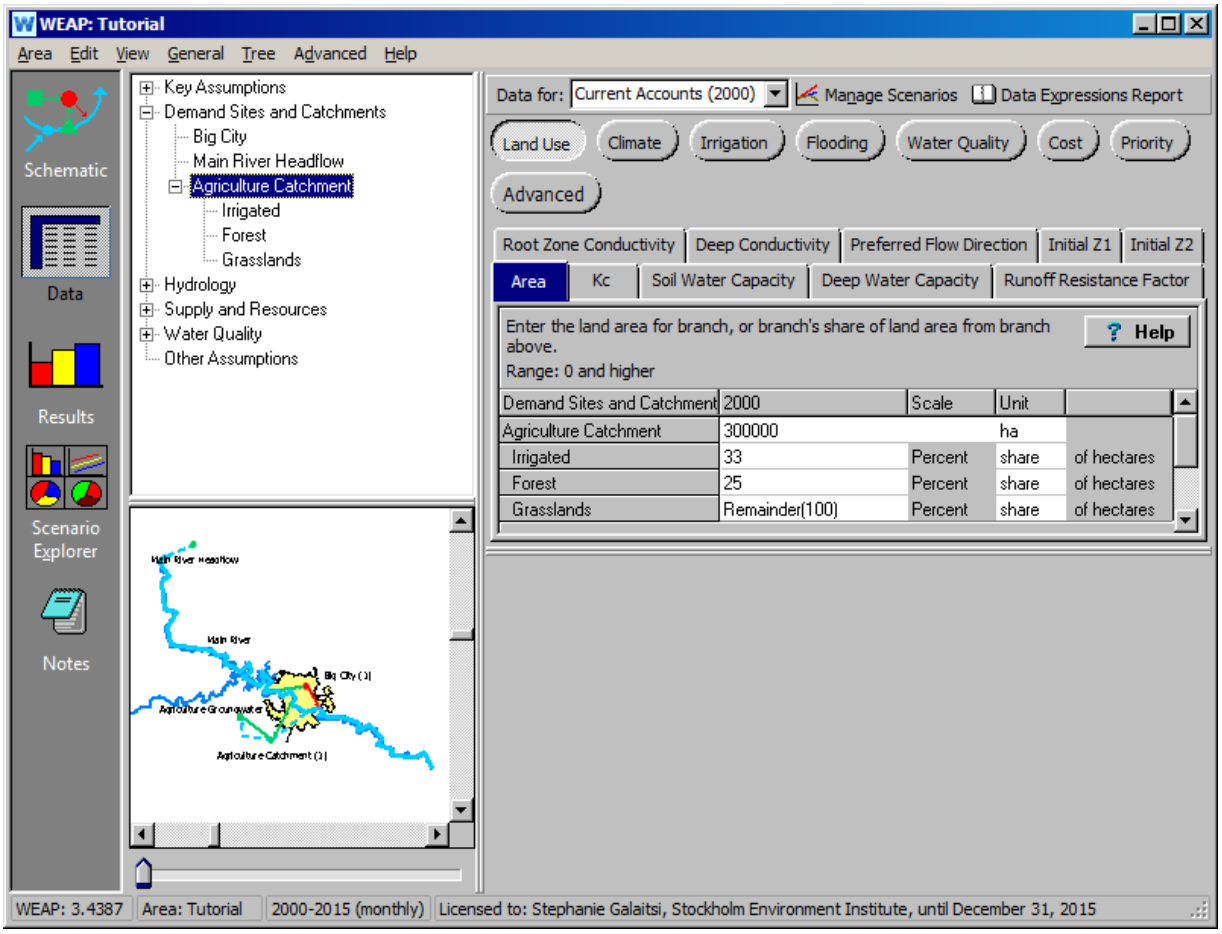


Figure 2.16: Entering the data in the model.

WEAP, provide wide range of techniques for users to build or enter time series data and borrows an approach made popular in spreadsheets to construct models using mathematical expressions. After successfully setting up the Reference Scenario of the model, the new scenarios are then created by using the data view or Schematic view and selecting “Manage Scenario” icon as shown in Figure 2.17. The data for each scenario is entered as described previously in the Reference scenario.

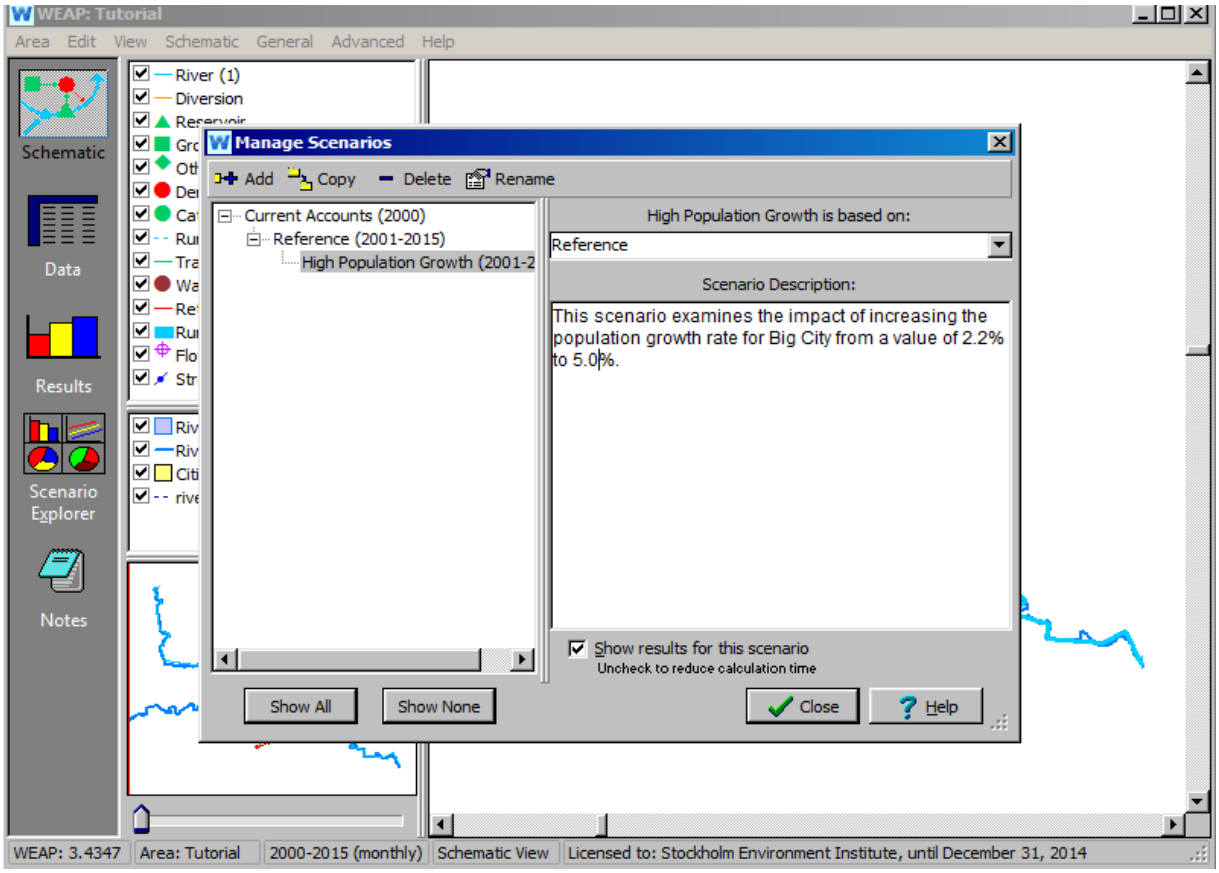


Figure 2.17: Creating the new scenarios in the model

(4) **Result and Evaluation:**

The result is obtained from the “Result” view on the main screen of the WEAP software. The different results can be presented graphically or in tabular form.

The scenarios are evaluated with regard to water availability and sensitivity to uncertainty in key variables. They can address a broad range of "what if" questions, such as: What if population growth and economic development patterns change? What if water conservation is introduced? What if ecosystem requirements are tightened? What if climate change alters the temperature and hydrology? These scenarios may be viewed simultaneously in the results for easy comparison of their effects on the water system.

2.5.1 Catchment Simulation Methods

There are four methods in WEAP to simulate catchment processes such as evapotranspiration, runoff, infiltration and irrigation demands. These methods include:

(1) The Rainfall Runoff: This method determines evapotranspiration for irrigated and rainfed crops using crop coefficients, the same as in the Irrigation Demands Only method. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links.

(2) Irrigation Demands Only (Simplified Coefficient Approach): This method is the simplest. It uses crop coefficients to calculate the potential evapotranspiration in the catchment, then determines any irrigation demand that may be required to fulfil that portion of the evapotranspiration requirement that rainfall cannot meet. It does not simulate runoff or infiltration processes, or track changes in soil moisture.

(3) The Soil Moisture Method: This method is the most complex of the four methods, representing the catchment with two soil layers, as well as the potential for snow accumulation. In the upper soil layer, it simulates evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow, and changes in soil moisture. This method allows for the characterization of land use and/or soil type impacts to these processes. Baseflow routing to the river and soil moisture changes are simulated in the lower soil layer. Correspondingly, the Soil Moisture Method requires more extensive soil and climate parameterization to simulate these processes, and it is described in detail in section 2.5.2.

(4) The MABIA Method: This method is a daily simulation of transpiration, evaporation, irrigation requirements and scheduling, crop growth and yields, and includes modules for estimating reference evapotranspiration and soil water capacity. It was derived from the MABIA suite of software tools, developed at the "Institut National Agronomique de Tunisie". The choice of method depends on the level of complexity desired for representing the catchment processes and data availability.

2.5.2 Soil Moisture Method

This is one dimensional, 2-compartment (or "bucket") soil moisture accounting scheme which is based on empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff (i.e., interflow), and deep percolation for a watershed unit (Figure 2.18). This method allows for the characterization of land use and/or soil type impacts to these processes. The deep percolation within the watershed unit can be transmitted to a surface water body as baseflow or directly to groundwater storage if the appropriate link is made between the watershed unit node and a groundwater node.

Land Use: The following parameters were used in the Soil Moisture method to give the approximate representation of the stream flow within the basin.

Area: Land area for land cover class within branch or basin catchment.

Kc: The crop coefficient, relative to the reference crop, for a land class type.

Root Zone Water Capacity: The effective water holding capacity of the top layer of soil, represented in mm.

Deep Water Capacity: Effective water holding capacity of lower, deep soil layer (bottom "bucket"), represented in mm. This is given as a single value for the catchment and does not

vary by land class type. This is ignored if the demand site has a return flow link to a groundwater node.

Deep Conductivity: Conductivity rate (length/time) of the deep layer (bottom "bucket") at full saturation (when relative storage $z_2 = 1.0$), which controls transmission of baseflow. This is given as a single value for the catchment and does not vary by land class type. Baseflow will increase as this parameter increases. This is ignored if the demand site has a return flow link to a groundwater node.

Runoff Resistance Factor: Used to control surface runoff response. It is related to factors such as leaf area index and land slope. Runoff will tend to decrease with higher values (range 0.1 to 10). This parameter can vary among the land class types.

Root Zone Conductivity: Root zone (top "bucket") conductivity rate at full saturation (when relative storage $z_1 = 1.0$), which will be partitioned, according to Preferred Flow Direction, between interflow and flow to the lower soil layer. This rate can vary among the land class types.

Preferred Flow Direction: Preferred Flow Direction: 1.0 = 100% horizontal, 0 = 100% vertical flow is used to partition the flow out of the root zone layer (top "bucket") between interflow and flow to the lower soil layer (bottom “bucket") or groundwater. This value can vary among the land class types.

Initial Z_1: Initial value of Z_1 at the beginning of a simulation. Z_1 is the relative storage given as a percentage of the total effective storage of the root zone water capacity.

Initial Z_2: Initial value of Z_2 at the beginning of a simulation. Z_2 is the relative storage given as a percentage of the total effective storage of the lower soil bucket (deep water capacity).

This parameter is ignored if the demand site has a runoff/infiltration link to a groundwater node. This rate cannot vary among the land class types.

A watershed unit can be divided into N fractional areas representing different land uses/soil types, and a water balance is computed for each fractional area, j of N. Climate is assumed uniform over each sub-catchment, and the water balance is given as:

$$\boldsymbol{Rd_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t) k_{c,j}(t) \left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_e(t) z_{1,j}^{RRF_j} - f_j k_{s,j} z_{1,j}^2 - (1 - f_j) k_{z,j} z_{1,j}^2} \quad (2.1)$$

Where: $z_{1,j} = [1,0]$ is the relative storage given as a fraction of the total effective storage of the root zone, Rd_j (mm) for land cover fraction, j, the effective precipitation, P_e, excluding the snowmelt since snow is not experienced in the study area.

The effective precipitation, P_e, is then computed using Effective rainfall formula of USDA Soil Conservation Service:

$$\boldsymbol{P_e = P_m * (125 - 0.2 * P_m)/125 \text{ …….. For } P_m \leq 250 \text{ mm}} \quad (2.2)$$

$$\boldsymbol{P_e = 125 + 0.1 * P_m \text{ ……. For } P_m > 250 \text{ mm}} \quad (2.3)$$

In Equation 2.1, PET is the Penman-Monteith reference crop potential evapotranspiration, where $k_{c,j}$ is the crop/plant coefficient for each fractional land cover. The third term represents surface runoff, where RRF_j is the Runoff Resistance Factor of the land cover. Higher values of RRF_j lead to less surface runoff. The fourth and fifth terms are the interflow and deep percolation terms, respectively, where the parameter $k_{s,j}$ is an estimate of the root zone saturated conductivity (mm/time) and f_j is a partitioning coefficient related to soil, land cover

type, and topography that fractionally partitions water both horizontally and vertically. Thus total surface and interflow runoff, RT, from each sub-catchment at time t is,

$$\boldsymbol{RT(t)} = \sum_{\boldsymbol{j=1}}^{\boldsymbol{N}} \boldsymbol{A_j}\left(\boldsymbol{P_e(t)z_{1,j}^{RRF_j}} + \boldsymbol{f_j k_{z,} z_{1,j}^2}\right) \tag{2.4}$$

For applications where no return flow link is created from a catchment to a groundwater node, baseflow emanating from the second bucket will be computed as:

$$\boldsymbol{S_{max}\frac{dz_2}{dt}} = \left[\sum_{\boldsymbol{j=1}}^{\boldsymbol{N}} \boldsymbol{(1 - f_j) k_{s,j} z_{1,j}^2}\right] - \boldsymbol{k_{s,2} z_2^2} \tag{2.5}$$

Where the inflow to this storage, S_{max} is the deep percolation from the upper storage given in Eqn. 2.1, and K_{s2} is the saturated conductivity of the lower storage (mm/time), which is given as a single value for the catchment and therefore does not include a subscript, *j*. Equations 2.1 and 2.5 are solved using a predictor-corrector algorithm.

When an alluvial aquifer is introduced into the model and a runoff/infiltration link is established between the watershed unit and the groundwater node, the second storage term in Eqn.2.5 is ignored, and recharge R (volume/time) to the aquifer is

$$\boldsymbol{R} = \sum_{\boldsymbol{j=1}}^{\boldsymbol{N}} \boldsymbol{A_j (1 - f_j) k_{z,j} z_{1,j}^2} \tag{2.6}$$

Where A is the watershed unit's contributing area. The stylized aquifer characterizes the height of the water table relative to the stream, where individual river segments can either gain or lose water to the aquifer.

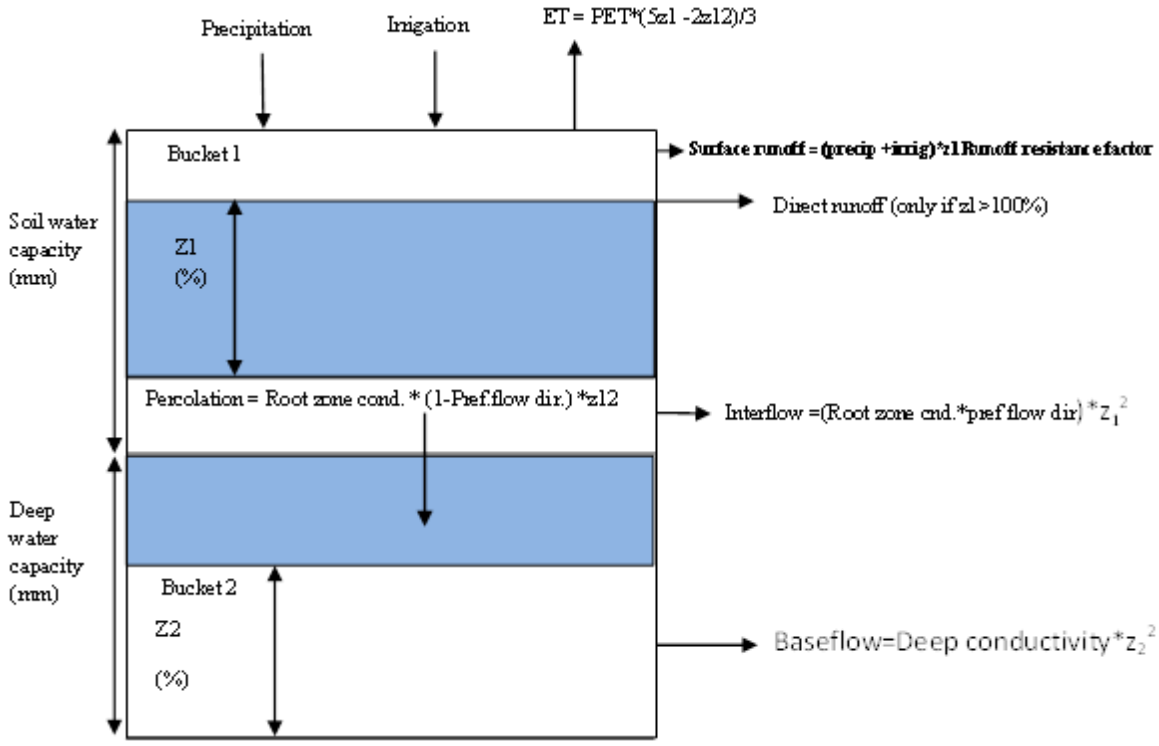


Figure 2.18: Conceptual diagram and equations incorporated in the Soil Moisture model

2.5.3 Evapotranspiration calculations

Evapotranspiration is the combination of soil evaporation and crop transpiration. Weather parameters, crop characteristics, management and environmental aspects affect evapotranspiration. The evapotranspiration rate from a reference surface is called the reference evapotranspiration and is denoted as ET_o. A large uniform grass (or alfalfa) field is considered worldwide as the reference surface. The reference grass crop completely covers the soil, is kept short, well-watered and is actively growing under optimal agronomic conditions.

The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices in the area. As water is abundantly available at the reference evapotranspiring

surface, soil factors do not affect ET_o. Relating evapotranspiration to a specific surface provides a reference to which evapotranspiration from other surfaces can be related. ET_o values measured or calculated at different locations or in different seasons are comparable as they refer to the evapotranspiration from the same reference surface. The only factors affecting ET_o are climatic parameters. Consequently, ET_o is a climatic parameter and can be computed from weather data. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors (Allen et al., 1998). Therefore, Evapotranspiration can be used to determine the impact of climate change on water resources, since a change in temperature will significantly affect it.

Owing to the difficulty of obtaining accurate field measurements, ET_o is commonly computed from weather data. A large number of empirical or semi-empirical equations have been developed for assessing reference evapotranspiration from meteorological data. Numerous researchers have analysed the performance of the various calculation methods for different locations. As a result of an Expert Consultation held in May 1990, the FAO (Foods and Agricultural Organisation) Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference evapotranspiration ET_o.

The reference evapotranspiration from meteorological data is assessed in the ET_o calculator software by means of the FAO Penman-Monteith equation. This method has been selected by FAO as the reference because it closely approximates grass ET_o at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters.

The relatively accurate and consistent performance of the Penman-Monteith approach in both arid and humid climates has been indicated in both the ASCE and European studies. The FAO Penman-Monteith equation (Allen et al., 1998) is given by:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,U_2)} \qquad (2.7)$$

Where ET_o is the reference evapotranspiration [mm day^{-1}], R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [°C], U_2 is the wind speed at 2 m height [m s^{-1}], e_s is the saturation vapour pressure [kPa], e_a is the actual vapour pressure [kPa], e_s-e_a is the saturation vapour pressure deficit [kPa], Δ is the slope vapour pressure curve [kPa $°C^{-1}$], γ is the psychrometric constant [kPa $°C^{-1}$].

In Equation 2.7, the value 0.408 converts the net radiation R_n expressed in MJ/m^2.day to equivalent evaporation expressed in mm/day. Because soil heat flux is small compared to R_n, particularly when the surface is covered by vegetation and calculation time steps are 24 hours or longer, the estimation of G is ignored in the ET_o calculator and assumed to be zero. This corresponds with the assumptions reported in the FAO Irrigation and Drainage Paper no. 56 for daily and 10-daily time periods. Allen *et.al.*, (1998) state that the soil heat flux beneath the grass reference surface is relatively small for that time period.

2.5.4 Water Year Method

The water year method is a means to represent variation in climatic data like stream flow and rainfall. The method involves defining how different climatic regime (e.g. Very Dry, Dry,

Very Wet, and Wet) compare relative to normal year, which is given a value of one (1). Normal water year define each non-Normal water year type (Very Dry, Dry, Wet, Very Wet), specify how much more or less water flows into the system in that year relative to a Normal water year. Dry years have a value less than one (< 1), Very wet have a value greater than one (> 1) For example, if a Wet year has 35% more inflow than a Normal year, 1.35 will be entered for the Wet year. These fractions are derived from a statistical analysis of historical rainfall data obtained. First the years are grouped into five bins (quintiles), then how they vary from the norm are computed using the mean value of the entire data as shown in the Figure 2.19.

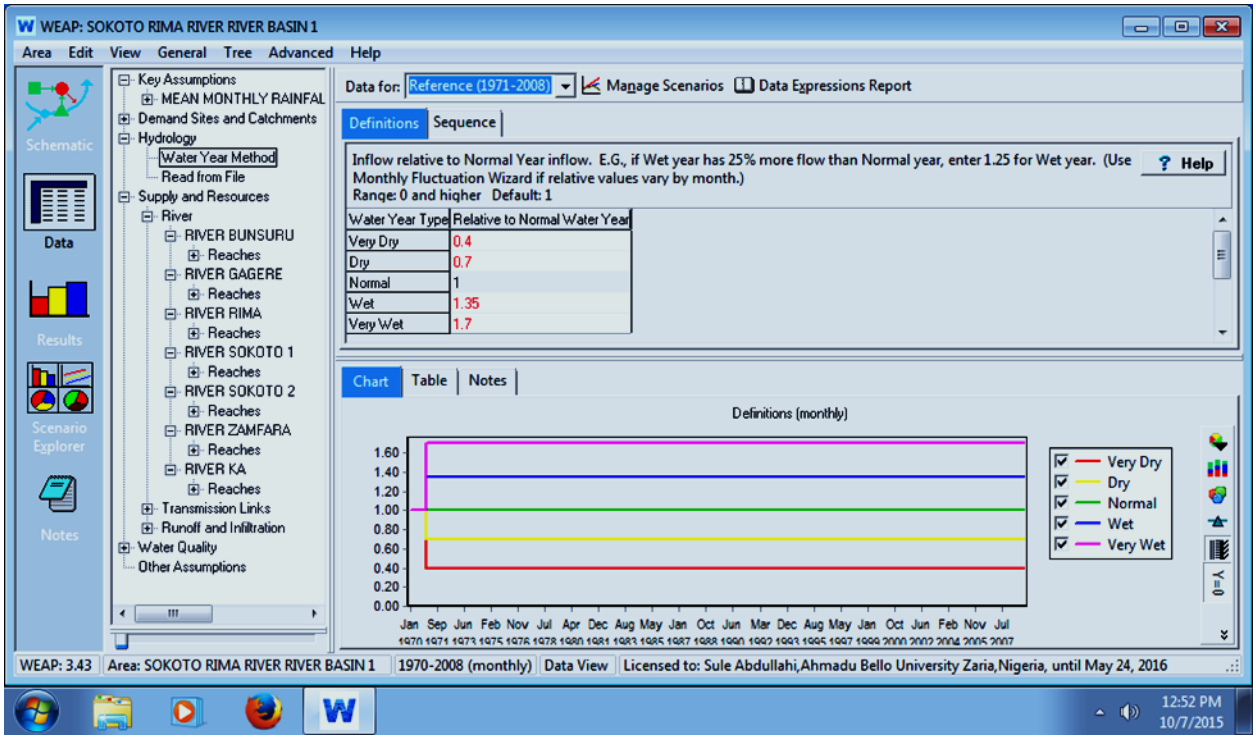


Figure 2.19: Water Year Values

CHAPTER THREE

MATERIALS AND METHODS

3.1 Research Protocol

This research follow four specific objectives to achieve the main aim of analysing the sensitivity of the SRRB to climatic change with regards to its water availability as follows: Firstly, to evaluate the present hydrological condition (streamflow) of the entire SRRB, the climatic data was obtained and used to simulate the surface water resources situation with WEAP model. Figure 3.1 shows the screen of WEAP for the precipitation, and Figure 3.2 shows that of Temperature.

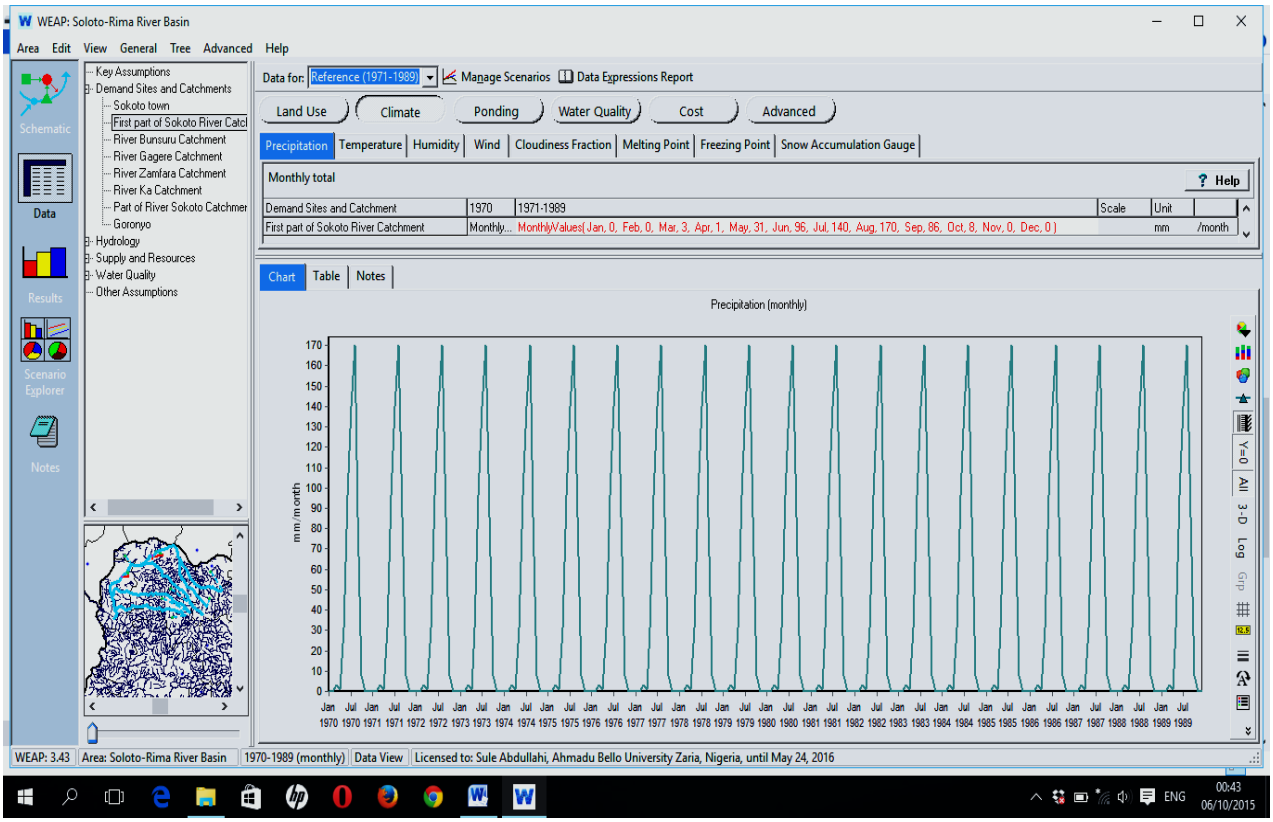


Figure 3.1: The screen of WEAP for the precipitation data.

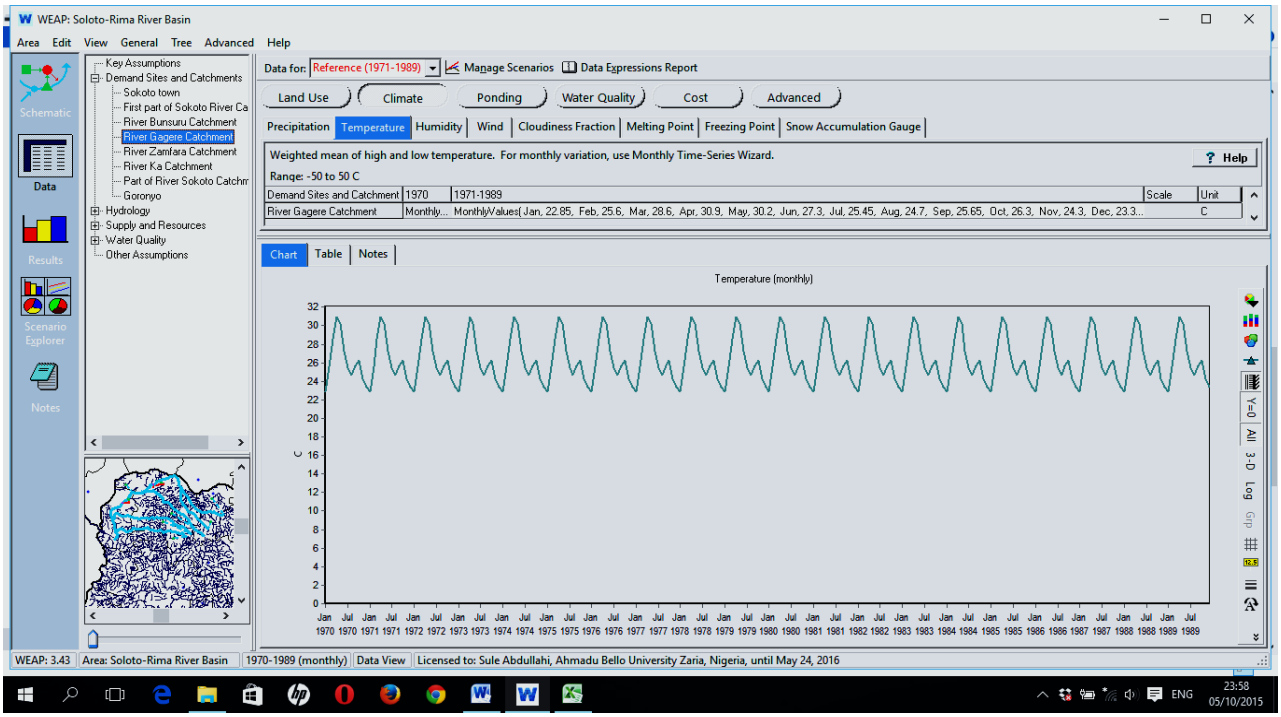


Figure 3.2: The screen of WEAP for the temperature data.

Secondly, the data was projected based on the initial model output and compared with the existing hydraulic condition (streamflow) of the basin. The comparison involved calibration and validation with the physical measurement of the river flow at some selected sites. Thirdly, the hypothetical climatic change scenarios were applied to the model to observe what happen if climate changes. Thereafter, the model was used to analyse the linkage between the water resources and the demand in some selected section within the basin based on the demography and Agricultural demands. Fourthly, the trend of the data was used for the projection of streamflow of the modelled basin to analyse the water availability in the future time up to the year 2064 which is 50 years from the time of this research. The WEAP model allows extending the trend of the data.

The following are detailed procedures adopted for the study:

(A) Preliminary investigation was conducted to analyse the hydraulic nature and human activities related to water resources in the basin.

The rainfall, streamflow, temperature, evaporation, relative humidity and sunshine data was collected from the data stations in the area for the period of 1970 – 2008, and were analysed statistically (described in chapter four).

The above mentioned data was obtained from the following data stations:

(1) Sokoto, Nigeria, latitude: 13-01N, longitude: 005-25E, and elevation: 302 m

(2) Gusau, Nigeria, latitude: 12-16N, longitude: 006-07E, and elevation: 469 m

(3) Yelwa, Nigeria, latitude: 10-88N, longitude: 004-75E, and elevation: 24 m, and from the literature.

(B) The Hydrological map of the area showing the major inland water ways and land use map of the area was digitized with the GIS-ILWIS (Integrated Land and Water Information System) software and they were converted to shape file (i.e. .shp file) that can be accepted by the WEAP software. The georeferencing was done by specifying reference points (tie points) that relate for distinct points with the corresponding X, Y coordinate.

ILWIS (Integrated Land and Water Information System) is a GIS / Remote sensing software for both vector and raster processing. ILWIS features include digitizing, editing, analysis and display of data as well as production of quality maps.

(C) The basin was divided into six sub-catchments based on the six major rivers (i.e. Bunsuru, Gagere, Rima, Sokoto, Zamfara and Ka) identified in the basin and the hydrological characteristics of each sub-catchment was represented with its set of parameters by using the obtained data and the existing land use (shown in Figure 3.3).

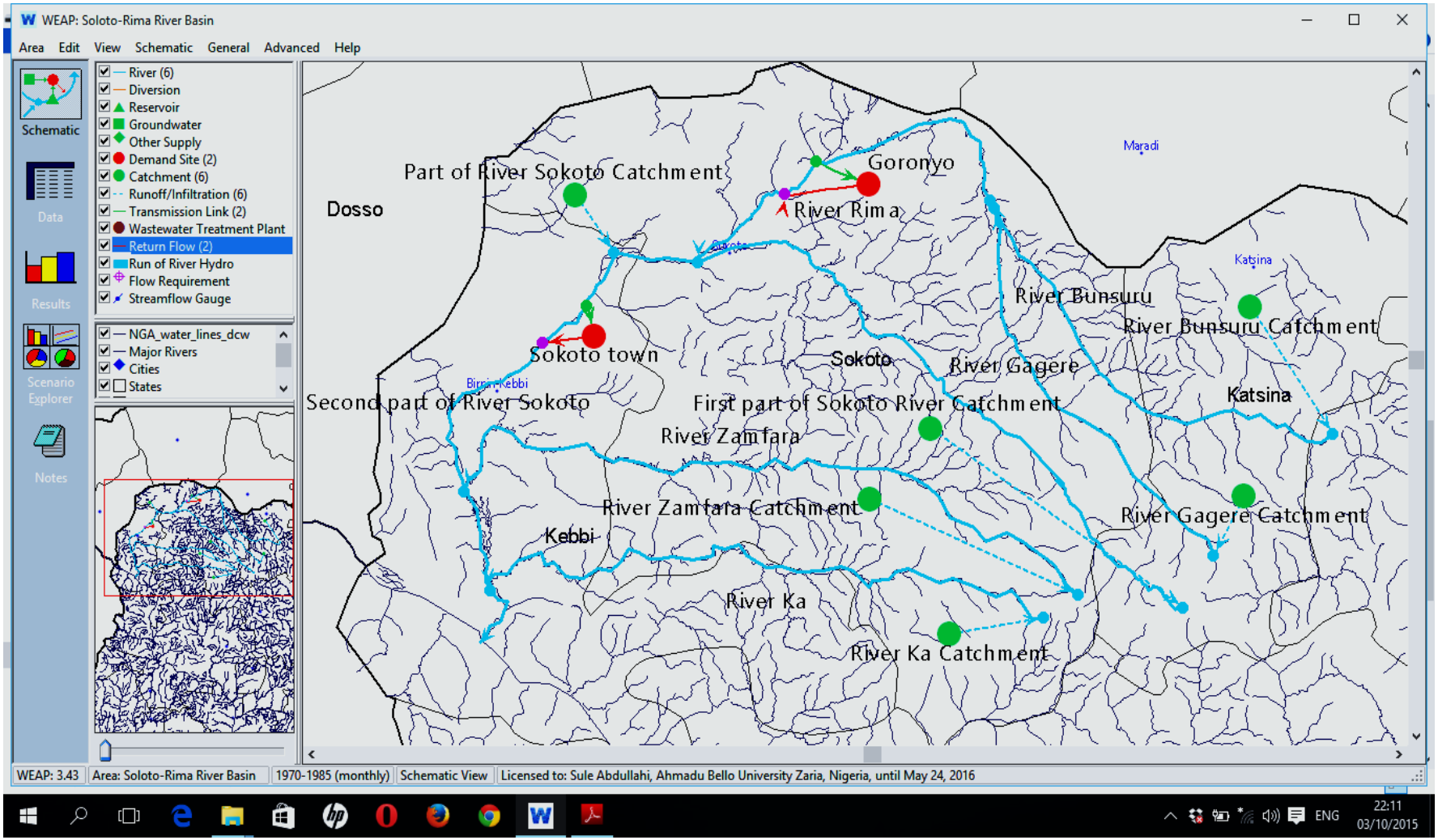


Figure 3.3: The map of the rivers in the study area as represented in WEAP.

(D) The soil moisture modelling method of rainfall/runoff was used to generate current stream flows as the model of available water in the area because it captures the hydrological processes in greater detail than the other options and also because of availability of data for its successful setup as shown in Figure 3.4.

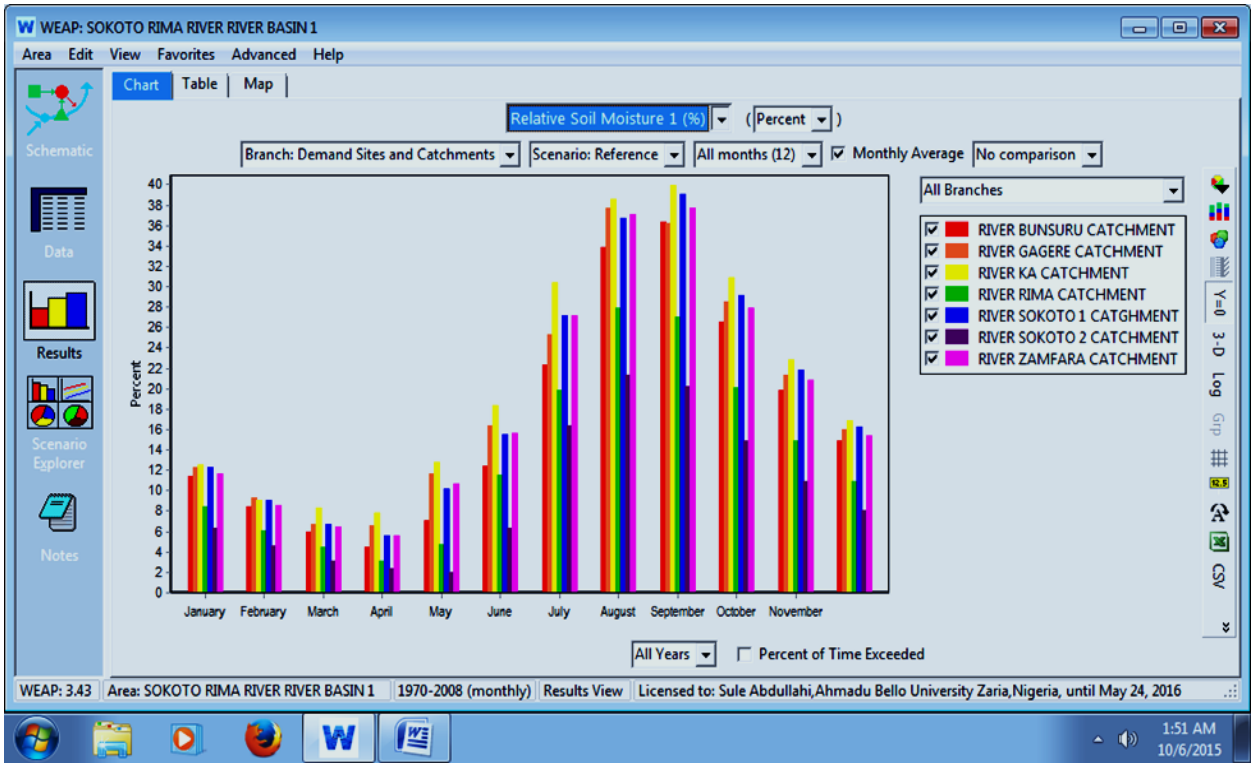


Figure 3.4: Soil moisture used to generate current stream flows

(E) The hypothetical climatic change scenarios were applied to the model to observe what happen if climate changes.

(F) The model was used to analyse the linkage between the water resources and the demand in some selected sections within the basin based on the demography and Agricultural water demands.

3.2 Analysis of the Temperature trend for Generating Climate Scenarios

The annual average maximum temperature of the basin was analysed statistically. The maximum average annual temperature and minimum temperature with mean and standard deviation of the data were determined. The linear trend was fit into the data and the gradient of the trend was determined. The trend analysis result in a linear equation obtained was used for the projection of temperature increase for this region by considering temperature variation over four decades.

3.3 Analysis of the Rainfall trend for Generating Climate Scenarios

The average annual rainfall of the basin was also analysed statistically. The maximum average rainfall value and minimum average value with mean and standard deviation of the data were determined. The linear trend was fit into the data and the gradient of the trend was determined. The trend analysis leads to a linear equation relating the rainfall to time. The obtained trend was used for the projection of climate change for this region by considering average rainfall value variation over four decades.

3.4 Adopted Method of Generating Climate Scenarios

The preferred methods in projecting future scenarios are usually those derived from GCMs (Global Climatic Models) but their limitations of grid-point predictions make them very difficult to adapt to the regional analysis. Nevertheless, use of hypothetical scenario is another option used by researchers in climatic impact studies (Islam *et.al*, 2005). Many published works were done in this way (e.g. Gleick, 1987; McCabe and Wolock, 1991; Skiles and Hanson, 1994; Yates, 1996; Boorman and Sefton, 1997; Bobba*et.al*, 1999; Hailemariam,

1999; Xu, 1999, 2000; Islam*et.al,* 2005). From this perspective and aiming at the objective of the study to apply WEAP model to the basin in order to evaluate the impact of climate change for current and future water availability using water balance, the hypothetical scenario was chosen to generate scenarios.

Whereas the linear trend was used in evaluating the pattern of temperature and rainfall, the hypothetical scenarios are used in answering the question of what if the climate changes. Six hypothetical scenarios were adopted as follows, first scenario considered an increase in temperature of about +0.5^{o}C over the entire basin (Table 3.3), second scenario considered an increase in temperature of about +0.5^{o}C and an increase in precipitation of around +10% over the entire basin (Table 3.4), third scenario considered an increase in temperature of about +0.5^{o}C and decrease in precipitation of around -10% over the entire basin (Table 3.5), Fourth scenario considered an increase in temperature of about +1^{o}C over the entire basin (Table 3.6), Fifth scenario considered an increase in temperature of about +1^{o}C and an increase in precipitation of around +10% over the entire basin(Table 3.7), while the sixth scenario consider increase in temperature of about +1^{o}C and decrease in precipitation of around -10% over the entire basin(Table 3.8).The seven (7) developed climate change scenarios are shown in Table 3.1 and Table 3.2 shows the reference scenario.

The IPCC (2014) indicate that the globally averaged combined land and ocean surface temperature data show shows regional variation in the global trend, but overall the entire globe has warmed during the period 1901–2012.{WGI AR5 SPM} Future warming is very likely to be larger over land areas than over oceans. {WGI AR5 SPM}. While the observed precipitation trends show a high degree of spatial and temporal variability, with different areas projected to experience positive or negative changes (WGI AR5).

Table 3.1: Hypothetical climate change scenarios

Scenarios	Change in Temperature $\Delta T(^oC)$	Change in Precipitation P (%)
Reference	0	0
Scenario 1	+ 0.5	0
Scenario 2	+0.5	+10%
Scenario 3	+0.5	-10%
Scenario 4	+1.0	0
Scenario 5	+1.0	+10%
Scenario 6	+1.0	-10%

3.5 Water Year Classification

For the analysis of hydrological processes in the SRRB, all natural hydrological watershed details and demand points for water resources management are represented in the WEAP model (Figure 3.3).

The sensitivity to climate change was explored by defining six scenarios. The reference scenario (Table 3.2) was adopted using the Water Year Method to reproduce the observed variation in hydrology from the historical record. The remaining scenarios were adopted using the first as a starting point, but altering each water year type according to predicted effects of climate change (i.e., increase in temperature and increase or decrease in Rainfall).

Table 3.2. shows the Hypothetical Climate Change Reference Scenario Data of average annual temperature, Sunshine, relative humidity, and rainfall with the corresponding classification of the year type, derived based on the description of water year method in section 2.4.5.

Table 3.2: Hypothetical Climate Change Reference Scenario Data

REFERENCE SCENARIO						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^2)**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**water year type**
1970	35	6.6	38	634	1.02	NORMAL
1971	33.6	6.7	38	483	0.77	DRY
1972	33.6	6,7	38	609	0.98	NORMAL
1973	33.7	6.7	38	390	0.62	VERY DRY
1974	33.8	6.2	39	476	0.76	DRY
1975	33.8	6.7	39	496.7	0.80	DRY
1976	33.9	6.8	39	874	1.40	VERY WET
1977	34	6.8	39	812	1.30	WET
1978	34.6	7.9	41.9	690	1.11	WET
1979	34.9	8	41	600	0.96	NORMAL
1980	29.3	8.2	43.2	540.8	0.87	DRY
1981	34.8	8	39	580.9	0.93	DRY
1982	34.9	7.6	38.8	550.6	0.88	DRY
1983	31.9	6.9	38.57	610.4	0.98	NORMAL
1984	36	7.1	36.3	280.9	0.45	VERY DRY
1985	35.4	6.7	37.6	440.8	0.71	DRY
1986	36.1	7.6	39.5	480.73	0.77	DRY
1987	36	6.11	36	370.2	0.59	VERY DRY
1988	34.64	6.07	41.5	715.3	1.15	WET
1989	34.28	5.09	42	680.8	1.09	NORMAL
1990	35.4	5.03	41.7	660.9	1.06	NORMAL
1991	34.85	6.18	45.1	780.5	1.25	WET
1992	34.68	6.4	42.1	770.3	1.23	WET
1993	34.74	6.6	39.6	380.2	0.61	VERY DRY
1994	34.9	5.9	45.5	540.1	0.87	DRY
1995	35.6	6.2	42.2	620.8	0.99	NORMAL
1996	35.9	6.08	44.1	670.2	1.07	NORMAL
1997	35.4	7.01	47	710.5	1.14	WET
1998	35.7	6.43	46.8	770.9	1.23	WET
1999	35.5	7.21	45.1	760.1	1.22	WET
2000	35.1	7.15	42.5	770.6	1.23	WET
2001	35.4	7	43.4	790.7	1.27	WET
2002	35.4	7.56	45	731.2	1.17	WET
2003	35.7	8.12	45.4	768.7	1.23	WET
2004	35.7	8.43	45	649.5	1.04	NORMAL
2005	35.9	8	43.9	634.6	1.02	NORMAL
2006	35.1	8.2	43.1	716.9	1.15	WET
2007	35.9	7.9	42.8	636.2	1.02	NORMAL
2008	35.5	8	41.4	667.6	1.07	NORMAL

Table 3.3. shows the Hypothetical Climate Change Scenario1 data of average annual temperature, Sunshine, relative humidity, and rainfall with the corresponding classification of the year type, derived based on the description of water year method in section 2.4.5. The +0.5 ^{0}C increase in temperature is within the range of expected climate change and is expected to increase evaporation and evapotranspiration, this will subsequently affect the runoff obtained from the rainfall, with all other parameters being equal. This scenario will tend to answer the question of what will happen to the surface water under an increase in temperature by +0.5^{0}C due to climate change.

Table 3.3: Hypothetical Climate Change scenario 1 Data

SCENARIO 1 +0.5 ^{O}C,						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^2)**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**Water Year Type**
1970	35.5	6.6	38	634	1.06	NORMAL
1971	34.1	6.7	38	483	0.77	DRY
1972	34.1	6,7	38	609	0.98	NORMAL
1973	34.2	6.7	38	390	0.62	VERY DRY
1974	34.3	6.2	39	476	0.76	DRY
1975	34.3	6.7	39	496.7	0.80	DRY
1976	34.4	6.8	39	874	1.40	VERY WET
1977	34.5	6.8	39	812	1.30	WET
1978	35.1	7.9	41.9	690	1.11	WET
1979	35.4	8	41	600	0.96	NORMAL
1980	29.8	8.2	43.2	540.8	0.87	DRY
1981	35.3	8	39	580.9	0.93	DRY
1982	35.4	7.6	38.8	550.6	0.88	DRY
1983	32.4	6.9	38.57	610.4	0.98	NORMAL
1984	36.5	7.1	36.3	280.9	0.45	VERY DRY
1985	35.9	6.7	37.6	440.8	0.71	DRY
1986	36.6	7.6	39.5	480.73	0.77	DRY
1987	36.5	6.11	36	370.2	0.59	VERY DRY
1988	35.14	6.07	41.5	715.3	1.15	WET
1989	34.78	5.09	42	680.8	1.09	NORMAL
1990	35.9	5.03	41.7	660.9	1.06	NORMAL
1991	35.35	6.18	45.1	780.5	1.25	WET
1992	35.18	6.4	42.1	770.3	1.23	WET

SCENARIO 1 +0.5 ^{O}C,						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^{2})**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**Water Year Type**
1993	35.24	6.6	39.6	380.2	0.61	VERY DRY
1994	35.4	5.9	45.5	540.1	0.87	DRY
1995	36.1	6.2	42.2	620.8	0.99	NORMAL
1996	36.4	6.08	44.1	670.2	1.07	NORMAL
1997	35.9	7.01	47	710.5	1.14	WET
1998	36.2	6.43	46.8	770.9	1.23	WET
1999	36	7.21	45.1	760.1	1.22	WET
2000	35.6	7.15	42.5	770.6	1.23	WET
2001	35.9	7	43.4	790.7	1.27	WET
2002	35.9	7.56	45	731.2	1.17	WET
2003	36.2	8.12	45.4	768.7	1.23	WET
2004	36.2	8.43	45	649.5	1.04	NORMAL
2005	36.4	8	43.9	634.6	1.02	NORMAL
2006	35.6	8.2	43.1	716.9	1.15	WET
2007	36.4	7.9	42.8	636.2	1.02	NORMAL
2008	36	8	41.4	667.6	1.07	NORMAL

Table 3.4. shows the Hypothetical Climate Change Scenario 2 data of average annual temperature, Sunshine, relative humidity, and rainfall with the corresponding classification of the year type, derived based on the description of water year method in section 2.4.5. The +0.5 ^{0}C increase in temperature is within the range of expected climate change and is expected to increase evaporation and evapotranspiration, this will subsequently affect the runoff obtained from the rainfall, with all other parameters being equal. The 10% increase in rainfall is assigned due to the uncertainty in the change caused by climate change on the rainfall. Similar uncertainty effect was described by the IPCC (2014). This scenario will tend to answer the question of what will happen to the surface water under an increase in temperature by +0.5^{0}C and 10% rainfall due to climate change.

Table 3.4: Hypothetical Climate Change scenario 2 Data

SCENARIO 2 +0.5^{O}C, +10%P						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^{2})**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**water year type**
1970	35.5	6.6	38	697.4	1.12	WET
1971	34.1	6.7	38	531.3	0.85	DRY
1972	34.1	6,7	38	669.9	1.07	NORMAL
1973	34.2	6.7	38	429	0.69	DRY
1974	34.3	6.2	39	523.6	0.84	DRY
1975	34.3	6.7	39	546.37	0.88	DRY
1976	34.4	6.8	39	961.4	1.54	VERY WET
1977	34.5	6.8	39	893.2	1.43	VERY WET
1978	35.1	7.9	41.9	759	1.22	WET
1979	35.4	8	41	660	1.06	NORMAL
1980	29.8	8.2	43.2	594.88	0.95	NORMAL
1981	35.3	8	39	638.99	1.02	NORMAL
1982	35.4	7.6	38.8	605.66	0.97	NORMAL
1983	32.4	6.9	38.57	671.44	1.08	NORMAL
1984	36.5	7.1	36.3	308.99	0.49	VERY DRY
1985	35.9	6.7	37.6	484.88	0.78	DRY
1986	36.6	7.6	39.5	528.803	0.85	DRY
1987	36.5	6.11	36	407.22	0.65	DRY
1988	35.14	6.07	41.5	786.83	1.26	WET
1989	34.78	5.09	42	748.88	1.20	WET
1990	35.9	5.03	41.7	726.99	1.16	WET
1991	35.35	6.18	45.1	858.55	1.38	VERY WET
1992	35.18	6.4	42.1	847.33	1.36	VERY WET
1993	35.24	6.6	39.6	418.22	0.67	DRY
1994	35.4	5.9	45.5	594.11	0.95	NORMAL
1995	36.1	6.2	42.2	682.88	1.09	NORMAL
1996	36.4	6.08	44.1	737.22	1.18	WET
1997	35.9	7.01	47	781.55	1.25	WET
1998	36.2	6.43	46.8	847.99	1.36	VERY WET
1999	36	7.21	45.1	836.11	1.34	WET
2000	35.6	7.15	42.5	847.66	1.36	VERY WET
2001	35.9	7	43.4	869.77	1.39	VERY WET
2002	35.9	7.56	45	804.32	1.29	WET
2003	36.2	8.12	45.4	845.57	1.35	VERY WET
2004	36.2	8.43	45	714.45	1.14	WET
2005	36.4	8	43.9	698.06	1.12	WET
2006	35.6	8.2	43.1	788.59	1.26	WET
2007	36.4	7.9	42.8	699.82	1.12	WET
2008	36	8	41.4	734.36	1.18	WET

Table 3.5. shows the Hypothetical Climate Change Scenario 3 data of average annual temperature, Sunshine, relative humidity, and rainfall with the corresponding classification of the year type, derived based on the description of water year method in section 2.4.5. The +0.5 ^{0}C increase in temperature is within the range of expected climate change and is expected to increase evaporation and evapotranspiration, this will subsequently affect the runoff obtained from the rainfall, with all other parameters being equal. However, the 10% decrease in rainfall is assigned due to the uncertainty in the change caused by climate change on the rainfall. Similar uncertainty effect was described by the IPCC (2014). This scenario will tend to answer the question of what will happen to the surface water under an increase in temperature by +0.5^{0}C and 10% decrease in rainfall due to climate change.

Table 3.5: Hypothetical Climate Change scenario 3 Data

SCENARIO 3 +0.5^{O}C, -10%P						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^2)**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**water year type**
1970	35.5	6.6	38	570.6	0.91	DRY
1971	34.1	6.7	38	434.7	0.70	DRY
1972	34.1	6,7	38	548.1	0.88	DRY
1973	34.2	6.7	38	351	0.56	VERY DRY
1974	34.3	6.2	39	428.4	0.69	DRY
1975	34.3	6.7	39	447.03	0.72	DRY
1976	34.4	6.8	39	786.6	1.26	WET
1977	34.5	6.8	39	730.8	1.17	WET
1978	35.1	7.9	41.9	621	0.99	NORMAL
1979	35.4	8	41	540	0.87	DRY
1980	29.8	8.2	43.2	486.72	0.78	DRY
1981	35.3	8	39	522.81	0.84	DRY
1982	35.4	7.6	38.8	495.54	0.79	DRY
1983	32.4	6.9	38.57	549.36	0.88	DRY
1984	36.5	7.1	36.3	252.81	0.40	VERY DRY
1985	35.9	6.7	37.6	396.72	0.64	VERY DRY
1986	36.6	7.6	39.5	432.657	0.69	DRY
1987	36.5	6.11	36	333.18	0.53	VERY DRY
1988	35.14	6.07	41.5	643.77	1.03	NORMAL

SCENARIO 3 +0.5^{O}C, -10%P						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^{2})**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**water year type**
1989	34.78	5.09	42	612.72	0.98	NORMAL
1990	35.9	5.03	41.7	594.81	0.95	NORMAL
1991	35.35	6.18	45.1	702.45	1.13	WET
1992	35.18	6.4	42.1	693.27	1.11	WET
1993	35.24	6.6	39.6	342.18	0.55	VERY DRY
1994	35.4	5.9	45.5	486.09	0.78	DRY
1995	36.1	6.2	42.2	558.72	0.89	DRY
1996	36.4	6.08	44.1	603.18	0.97	NORMAL
1997	35.9	7.01	47	639.45	1.02	NORMAL
1998	36.2	6.43	46.8	693.81	1.11	WET
1999	36	7.21	45.1	684.09	1.10	NORMAL
2000	35.6	7.15	42.5	693.54	1.11	WET
2001	35.9	7	43.4	711.63	1.14	WET
2002	35.9	7.56	45	658.08	1.05	NORMAL
2003	36.2	8.12	45.4	691.83	1.11	WET
2004	36.2	8.43	45	584.55	0.94	DRY
2005	36.4	8	43.9	571.14	0.91	DRY
2006	35.6	8.2	43.1	645.21	1.03	NORMAL
2007	36.4	7.9	42.8	572.58	0.92	DRY
2008	36	8	41.4	600.84	0.96	NORMAL

Table 3.6. shows the Hypothetical Climate Change Scenario 4 data of average annual temperature, Sunshine, relative humidity, and rainfall with the corresponding classification of the year type, derived based on the description of water year method in section 2.4.5. The +1.0 ^{0}C increase in temperature is within the range of expected climate change and is expected to increase evaporation and evapotranspiration, this will subsequently affect the runoff obtained from the rainfall, with all other parameters being equal. This scenario will tend to answer the question of what will happen to the surface water under an increase in temperature by +1.0^{0}C due to climate change.

Table 3.6: Hypothetical Climate Change scenario 4 Data

SCENARIO 4 +1.0 ^{O}C						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^{2})**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**water year type**
1970	36	6.6	38	634	1.02	NORMAL
1971	34.6	6.7	38	483	0.77	DRY
1972	34.6	6,7	38	609	0.98	NORMAL
1973	34.7	6.7	38	390	0.62	VERY DRY
1974	34.8	6.2	39	476	0.76	DRY
1975	34.8	6.7	39	496.7	0.80	DRY
1976	34.9	6.8	39	874	1.40	VERY WET
1977	35	6.8	39	812	1.30	WET
1978	35.6	7.9	41.9	690	1.11	WET
1979	35.9	8	41	600	0.96	NORMAL
1980	30.3	8.2	43.2	540.8	0.87	DRY
1981	35.8	8	39	580.9	0.93	DRY
1982	35.9	7.6	38.8	550.6	0.88	DRY
1983	32.9	6.9	38.57	610.4	0.98	NORMAL
1984	37	7.1	36.3	280.9	0.45	VERY DRY
1985	36.4	6.7	37.6	440.8	0.71	DRY
1986	37.1	7.6	39.5	480.73	0.77	DRY
1987	37	6.11	36	370.2	0.59	VERY DRY
1988	35.64	6.07	41.5	715.3	1.15	WET
1989	35.28	5.09	42	680.8	1.09	NORMAL
1990	36.4	5.03	41.7	660.9	1.059	NORMAL
1991	35.85	6.18	45.1	780.5	1.25	WET
1992	35.68	6.4	42.1	770.3	1.23	WET
1993	35.74	6.6	39.6	380.2	0.61	VERY DRY
1994	35.9	5.9	45.5	540.1	0.87	DRY
1995	36.6	6.2	42.2	620.8	0.99	NORMAL
1996	36.9	6.08	44.1	670.2	1.07	NORMAL
1997	36.4	7.01	47	710.5	1.14	WET
1998	36.7	6.43	46.8	770.9	1.23	WET
1999	36.5	7.21	45.1	760.1	1.22	WET
2000	36.1	7.15	42.5	770.6	1.23	WET
2001	36.4	7	43.4	790.7	1.27	WET
2002	36.4	7.56	45	731.2	1.17	WET
2003	36.7	8.12	45.4	768.7	1.23	WET
2004	36.7	8.43	45	649.5	1.04	NORMAL
2005	36.9	8	43.9	634.6	1.02	NORMAL
2006	36.1	8.2	43.1	716.9	1.15	WET
2007	36.9	7.9	42.8	636.2	1.02	NORMAL
2008	36.5	8	41.4	667.6	1.07	NORMAL

Table 3.7. shows the Hypothetical Climate Change Scenario 5 data of average annual temperature, Sunshine, relative humidity, and rainfall with the corresponding classification of the year type, derived based on the description of water year method in section 2.4.5. The +1.0 ^{0}C increase in temperature is within the range of expected climate change and is expected to increase evaporation and evapotranspiration, this will subsequently affect the runoff obtained from the rainfall, with all other parameters being equal. The 10% increase in rainfall is assigned due to the uncertainty in the change caused by climate change on the rainfall. Similar uncertainty effect was described by the IPCC (2014). This scenario will tend to answer the question of what will happen to the surface water under an increase in temperature by +1.0^{0}C and 10% increase in rainfall due to climate change.

Table 3.7: Hypothetical Climate Change scenario 5 Data

SCENARIO 5 +1.0^{O}C, +10%P						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^2)**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**water year type**
1970	36	6.6	38	697.4	1.12	WET
1971	34.6	6.7	38	531.3	0.85	DRY
1972	34.6	6,7	38	669.9	1.07	NORMAL
1973	34.7	6.7	38	429	0.69	DRY
1974	34.8	6.2	39	523.6	0.84	DRY
1975	34.8	6.7	39	546.37	0.88	DRY
1976	34.9	6.8	39	961.4	1.54	VERY WET
1977	35	6.8	39	893.2	1.43	VERY WET
1978	35.6	7.9	41.9	759	1.22	WET
1979	35.9	8	41	660	1.06	NORMAL
1980	30.3	8.2	43.2	594.88	0.95	NORMAL
1981	35.8	8	39	638.99	1.02	NORMAL
1982	35.9	7.6	38.8	605.66	0.97	NORMAL
1983	32.9	6.9	38.57	671.44	1.08	NORMAL
1984	37	7.1	36.3	308.99	0.50	VERY DRY
1985	36.4	6.7	37.6	484.88	0.78	DRY
1986	37.1	7.6	39.5	528.803	0.85	DRY
1987	37	6.11	36	407.22	0.65	DRY
1988	35.64	6.07	41.5	786.83	1.26	WET

SCENARIO 5 +1.0^{O}C, +10%P						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^{2})**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**water year type**
1989	35.28	5.09	42	748.88	1.20	WET
1990	36.4	5.03	41.7	726.99	1.16	WET
1991	35.85	6.18	45.1	858.55	1.38	VERY WET
1992	35.68	6.4	42.1	847.33	1.36	VERY WET
1993	35.74	6.6	39.6	418.22	0.67	DRY
1994	35.9	5.9	45.5	594.11	0.95	NORMAL
1995	36.6	6.2	42.2	682.88	1.09	NORMAL
1996	36.9	6.08	44.1	737.22	1.18	WET
1997	36.4	7.01	47	781.55	1.25	WET
1998	36.7	6.43	46.8	847.99	1.36	VERY WET
1999	36.5	7.21	45.1	836.11	1.34	WET
2000	36.1	7.15	42.5	847.66	1.36	VERY WET
2001	36.4	7	43.4	869.77	1.39	VERY WET
2002	36.4	7.56	45	804.32	1.29	WET
2003	36.7	8.12	45.4	845.57	1.35	VERY WET
2004	36.7	8.43	45	714.45	1.14	WET
2005	36.9	8	43.9	698.06	1.12	WET
2006	36.1	8.2	43.1	788.59	1.26	WET
2007	36.9	7.9	42.8	699.82	1.12	WET
2008	36.5	8	41.4	734.36	1.18	WET

Table 3.8. shows the Hypothetical Climate Change Scenario 6 data of average annual temperature, Sunshine, relative humidity, and rainfall with the corresponding classification of the year type, derived based on the description of water year method in section 2.4.5. The +1.0 ^{0}C increase in temperature is within the range of expected climate change and is expected to increase evaporation and evapotranspiration; this will subsequently affect the runoff obtained from the rainfall, with all other parameters being equal. However, the 10% decrease in rainfall is assigned due to the uncertainty in the change caused by climate change on the rainfall. Similar uncertainty effect was described by the IPCC (2014). This scenario will tend to answer the question of what will happen to the surface water under an increase in temperature by +0.5^{0}C and 10% decrease in rainfall due to climate change.

Table 3.8: Hypothetical Climate Change scenario 6 Data

SCENARIO 6 +1.0^{O}C, -10%P						
Year	**Temperature (^{0}C)**	**Sunshine (w/m^{2})**	**Relative Humidity (%)**	**Rainfall (mm)**	**Water Year Value**	**water year type**
1970	36	6.6	38	570.6	0.91	DRY
1971	34.6	6.7	38	434.7	0.70	DRY
1972	34.6	6,7	38	548.1	0.88	DRY
1973	34.7	6.7	38	351	0.56	VERY DRY
1974	34.8	6.2	39	428.4	0.69	DRY
1975	34.8	6.7	39	447.03	0.72	DRY
1976	34.9	6.8	39	786.6	1.26	WET
1977	35	6.8	39	730.8	1.17	WET
1978	35.6	7.9	41.9	621	0.99	NORMAL
1979	35.9	8	41	540	0.87	DRY
1980	30.3	8.2	43.2	486.72	0.78	DRY
1981	35.8	8	39	522.81	0.84	DRY
1982	35.9	7.6	38.8	495.54	0.79	DRY
1983	32.9	6.9	38.57	549.36	0.88	DRY
1984	37	7.1	36.3	252.81	0.40	VERY DRY
1985	36.4	6.7	37.6	396.72	0.64	VERY DRY
1986	37.1	7.6	39.5	432.657	0.69	DRY
1987	37	6.11	36	333.18	0.53	VERY DRY
1988	35.64	6.07	41.5	643.77	1.03	NORMAL
1989	35.28	5.09	42	612.72	0.98	NORMAL
1990	36.4	5.03	41.7	594.81	0.95	NORMAL
1991	35.85	6.18	45.1	702.45	1.12	WET
1992	35.68	6.4	42.1	693.27	1.11	WET
1993	35.74	6.6	39.6	342.18	0.55	VERY DRY
1994	35.9	5.9	45.5	486.09	0.78	DRY
1995	36.6	6.2	42.2	558.72	0.89	DRY
1996	36.9	6.08	44.1	603.18	0.97	NORMAL
1997	36.4	7.01	47	639.45	1.02	NORMAL
1998	36.7	6.43	46.8	693.81	1.11	WET
1999	36.5	7.21	45.1	684.09	1.10	NORMAL
2000	36.1	7.15	42.5	693.54	1.11	WET
2001	36.4	7	43.4	711.63	1.14	WET
2002	36.4	7.56	45	658.08	1.05	NORMAL
2003	36.7	8.12	45.4	691.83	1.11	WET
2004	36.7	8.43	45	584.55	0.94	DRY
2005	36.9	8	43.9	571.14	0.91	DRY
2006	36.1	8.2	43.1	645.21	1.03	NORMAL
2007	36.9	7.9	42.8	572.58	0.92	DRY
2008	36.5	8	41.4	600.84	0.96	NORMAL

3.6 Calibration and Validation of the WEAP Model

One very simple interpretation of calibration is to adjust a set of parameters associated with a computational science and engineering code so that the model agreement is maximized with respect to a set of experimental data. One very simple interpretation of validation is to quantify our belief in the predictive capability of a computational code through comparison with a set of experimental data (Trucano *et al.*, 2006).

The twenty years climatological records (1970- 1989) was used in setting up the model by fallowing the steps described in section 2.5,as shown in Figure 3.5.

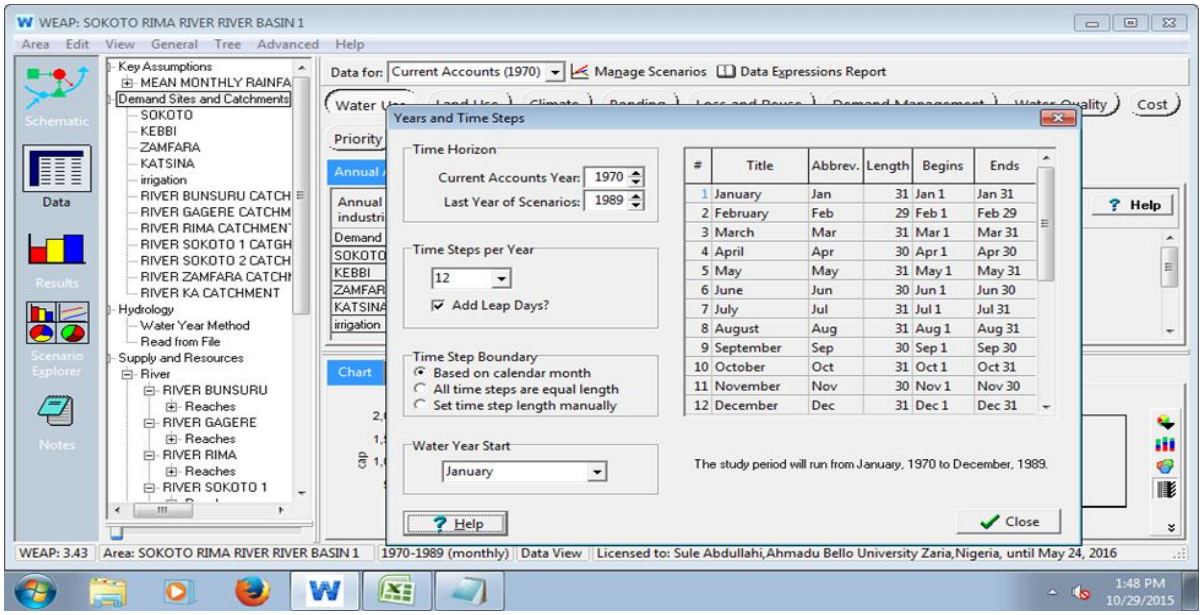


Figure 3.5: Setting up the model.

The calibration of the model was carried out by adjusting the values of Runoff Resistance Factor of the land cover (range 0.1 to 10) and the relative storage of the root zone water capacity assuming a large uniform grass (or alfalfa) field and the data of 1990 to 2008 as shown in Figure 3.6.

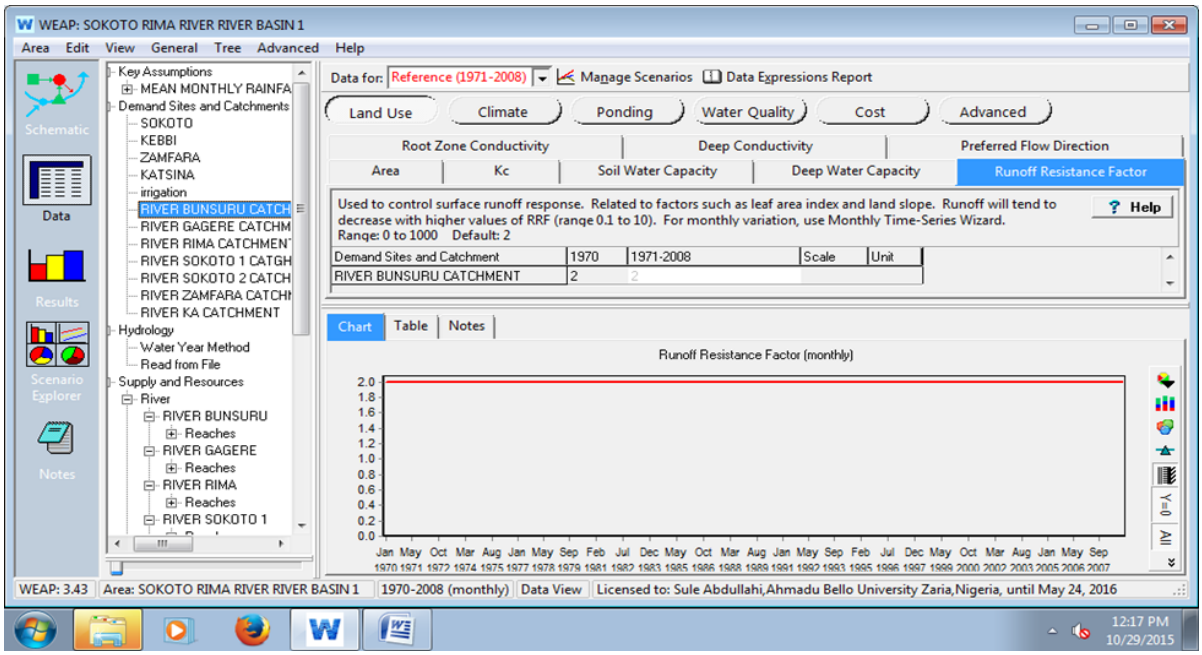


Figure 3.6: Adjusting the values of Runoff Resistance Factor

The calibration was also done by visual check of the modelled versus observed streamflow graph (shown in chapter four) to ascertain the accuracy of the output. This modifies the model structure to attain a representation of the streamflow that satisfies the measured streamflow data.

The model was validated by using measured flow data for each sub-catchment. The current and possible future streamflow was validated by comparing with the actual observation from the data (as shown in chapter four). This was to ensure that the projections are reasonable in terms of how well the estimated curve fits the historical data**.** WEAP enable the validation by providing various statistics describing the curve-fit: the R^2 value, the standard error, and the number of observations. More detailed analysis was done by using the data analysis features built-in to Microsoft Excel, and then linking the results to WEAP analysis.

In this study, the objective functions that were used for validation are coefficient of determination (R^2), Nash-Sutcliffe coefficient of efficiency (CE), percentage error in total runoff volume *(VE)* and percentage error in peak discharge *(PE).* A brief summary of each objective function used is presented below:

a. **Correlation Coefficient:**

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i} - \bar{Q}_{sim})^2}}\right]^2 \qquad (3.1)$$

Where, $Q_{obs,i}$= measured discharge at the ith time interval, Q_{obs}= mean of the measured discharge, $Q_{sim,i}$= simulated discharge at the ith interval, Q_{sim}= mean of the simulated discharge, n = number of observations. The range of R^2 lies between 0 and 1 for perfect fit. The coefficient of determination is useful because it gives the proportion of the variance (fluctuation) of one variable that is predictable from the other variable. It is a measure that allows us to determine how certain one can be in making predictions from a certain model.

b. **Nash-Sutcliffe coefficient of efficiency (*CE).***

$$CE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs,i})^2} * 100\% \qquad (3.2)$$

Where: CE is the Nash-Sutcliffe coefficient of efficiency; $Q_{obs,i}$ is the observed discharge at the time step i, $Q_{obs,i}$ is the mean of the observed discharge; $Q_{sim,i}$ = the simulation discharge at the time step I, and n is the number of observations

The Nash-Sutcliffe coefficient of efficiency indicates how well the plot of observed versus simulated value fits the 1:1 line and is commonly used in hydrologic model evaluations. If the measured variable is estimated most accurately by the model, then CE = 1; If the CE is negative,

the quality of the model results is smaller than the average value of the measured variables (Nashand Sutcliffe 2012).

c. **Percentage error in total runoff volume*:***

$$VE = \frac{\sum_{i=1}^{n}(Q_{sim,i} - Q_{obs,i})}{\sum_{i=1}^{n} Q_{obs,i}} * 100\% \quad (3.3)$$

Where: *VE* = percentage error in total runoff volume, $Q_{sim,i}$= the simulated discharge at the time step i, $Q_{obs,i}$= the observed discharge at the time step i , For a perfect model, *VE* equals to 0. The smaller the VE value, the better the performance of the model.

d. **Percentage error in peak discharge:**

$$PE = \frac{\sum_{i=1}^{m}(Q_{sim,p,i} - Q_{obs,p,i})}{\sum_{i=1}^{n} Q_{obs,p,i}} * 100\% \quad (3.4)$$

Time difference between observed and simulated peaks *(PT):*

$$PT = T_{sim,p} - T_{obs,p} \quad (3.5)$$

Where, $Q_{sim,p,i}$= the simulated peak flows, $Q_{obs,p,i}$= the observed peak flows. *m* = the number of peak flows, $T_{sim,p}$= time the simulated peak occur, $T_{obs,p}$= time the observed peak occur.

PE provides an indication of the relative absolute accuracy of models in predicting peak flows and ranges from -∞ to +∞ (negative values indicate a general underestimation of peak flows while positive values indicate a general overestimation of peak flows). The *PT* is a measure of the timing difference between the observed and simulated peak flows. It is generally used in conjunction with the *PE* criterion. Given the observed and simulated peak flow where the *PE* is small and the *PT* is large, one can conclude that both peak flows share a similar volume but their timing is not as close. Thus a good agreement in timing and volume requires *PE* and *PT* to be small.

The First year (1970) in the reference scenario data (Table 3.2) which is Current Account year for this analysis happen to be a normal water year. A single variation fraction is specified for an entire water year type and for all the proposed scenarios. Once the model is simulating the stream flow (calibration) satisfactorily, seven (7) developed climate change scenarios (Table 3.1) for the study area were applied to the WEAP model for simulation. Then, the runoff, evapotranspiration, water demand, water supplied series was obtained as output of the WEAP model.

3.7 Analysis of Climate Change Impact on Water Availability

The final stage is to quantify the water availability in all scenarios from the simulation of the model (Figure 3.7). The water availability within each catchment for the different scenarios shown in Table 3.4 to Table 3.8 was obtained by using the catchment water year values as shown in Figure 3.8.

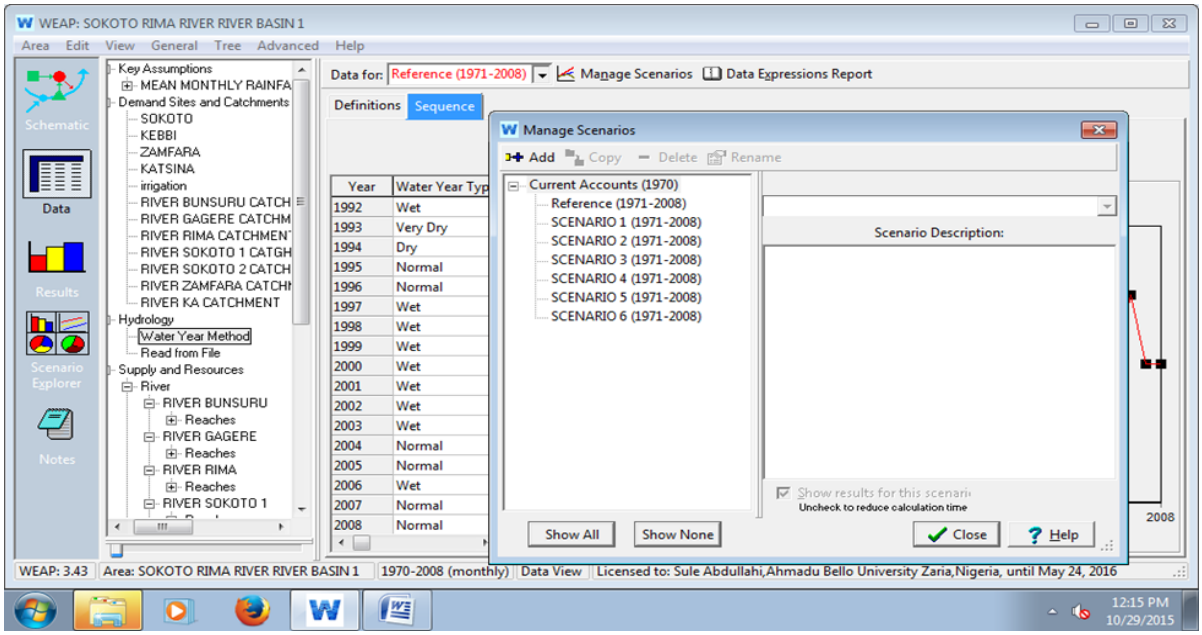


Figure 3.7: Setting up of all scenarios

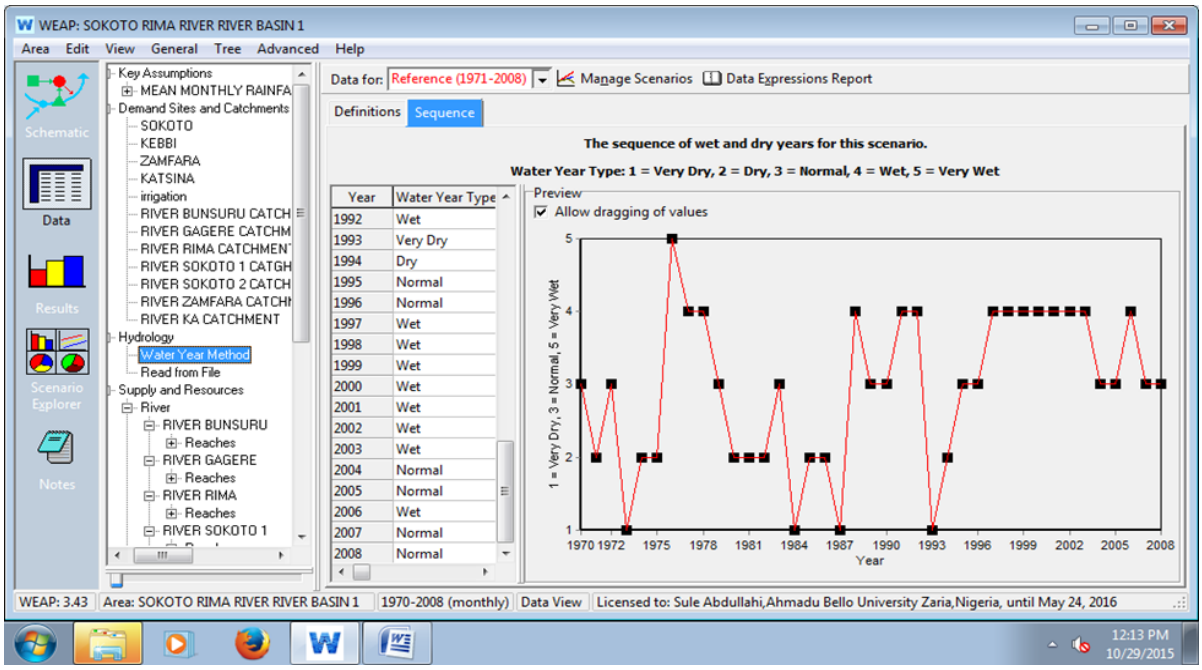


Figure 3.8: Catchment water year values

The obtained values for each scenario generate runoff based on its climatic water year value. The runoff values obtained are shown in chapter four, section 4.6.The water availability within the catchments was evaluated based on the difference between the total available water within the catchment under a scenario and the total water demand within the catchment of the model:

The water availability in each scenario is then analysed in order to evaluate the sensitivity and reliability of the study area based on the climate change scenario using the relation:

$$\text{Percentage Impact} = \frac{\text{AvailableremainingWaterUnderagivenScenario}}{\text{AvailableWaterfromtheobservation(actual)data}} * 100\% \qquad (3.6)$$

The impact of climate change on water demand and supply can easily be analysed based on the availability of the water within the basin.

3.7.1 The Water Demand

The Food and Agriculture Organization of the United Nations (2010), online Water use database, indicate that the water use in Nigeria ranges from 78.67 to 118.6 litre per capita per day. Therefore, the value of 120 litres per capita per day was used as the approximate maximum water use value. The industrial demand was assumed to be 10% of the domestic water use as suggested by Adelegan & Adelegan (2001), due to lack of industrial water demand data in the area.

The demographic data of the basin was projected by using the inter census growth rate of 1991 and 2006 population census. The demand of some selected sites was observed and compared with the flows that pass through such areas. The domestic, industrial and agricultural demands for those sites are shown in Figure 3.2 and Table 3.9.

Table 3.9: The domestic, industrial and agricultural demands for some selected sites.

Selected Demand Sites	Population Projection to 2064	Domestic Water use (Mm^3/annum)	Industrial use (Mm^3/annum)	Agricultural use (Mm^3/annum)
Argungu	1,223,678	53.6	5.4	125.15
Birnin-Kebbi	1,641,487	71.9	7.2	167.5
Goronyo	1,028,603	45.05	4.5	105
Sokoto North	1,316,052	57.64	5.8	134.3
Sokoto South	1,116,531	48.9	4.9	113.94

The water demand for some selected sites is shown in Figure 3.5. (my calculation)

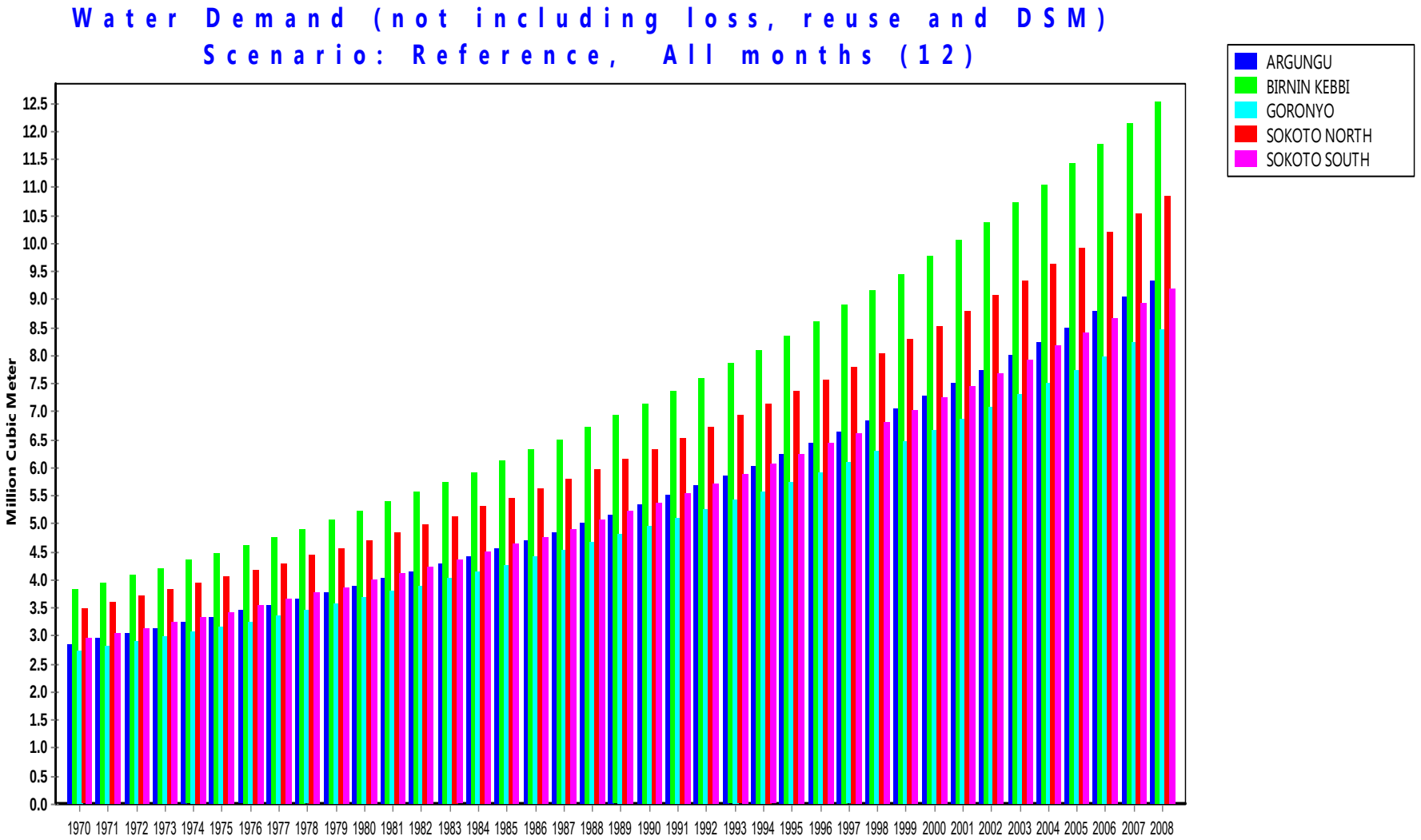


Figure 3.9: Projected water demand of some selected sites.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Initial analyses

The study area location is shown in Figure 2.1 and 2.2, and the six major rivers within the basin are delineated in the WEAP as shown in Figure 3.3 following their location on the base map developed in GIS using the map of North-Western region of Nigeria, the area is located between latitude 10^0 04' to 14^0 N and Longitude 3^o - 8^0 14' E.

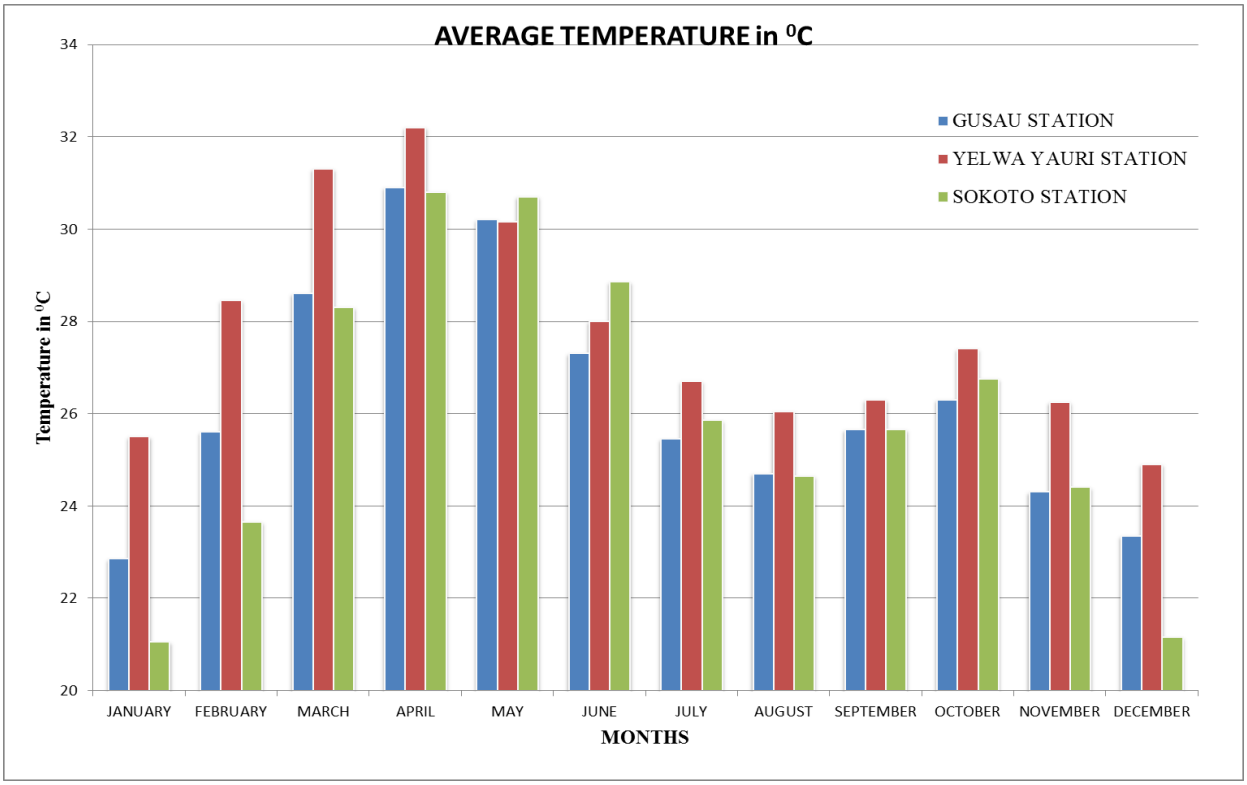


Figure 4.1: Mean Temperature of some data stations in the basin

Figure 4.1 shows the mean monthly temperature in degrees Celsius of some data stations in the basin. The average of these temperature values for Sokoto station is 26^0C, while the maximum value is 30.8^0C in the month of April; the minimum value is 21^0C in the month of

December and January. The standard deviation and variance of this data are 3.3 and 10.7 respectively.

The Gusau station data has average temperature value of 26.3^{0}C, with the maximum value of 30.9^{0}C in the month of April; the minimum value is 23^{0}C in the month of December and January. The standard deviation and variance of the data in this station are 2.5 and 6.5 respectively.

Furthermore, the average of these temperature values for Yelwa Yauri station is 27.8^{0}C, while the maximum value is 32.2^{0}C in the month of April; the minimum value is 25^{0}C in the month of December and January. The standard deviation and variance of this data are 2.3 and 5.5 respectively.

The graphs show similar pattern, which indicate that they share similar temperature characteristics.

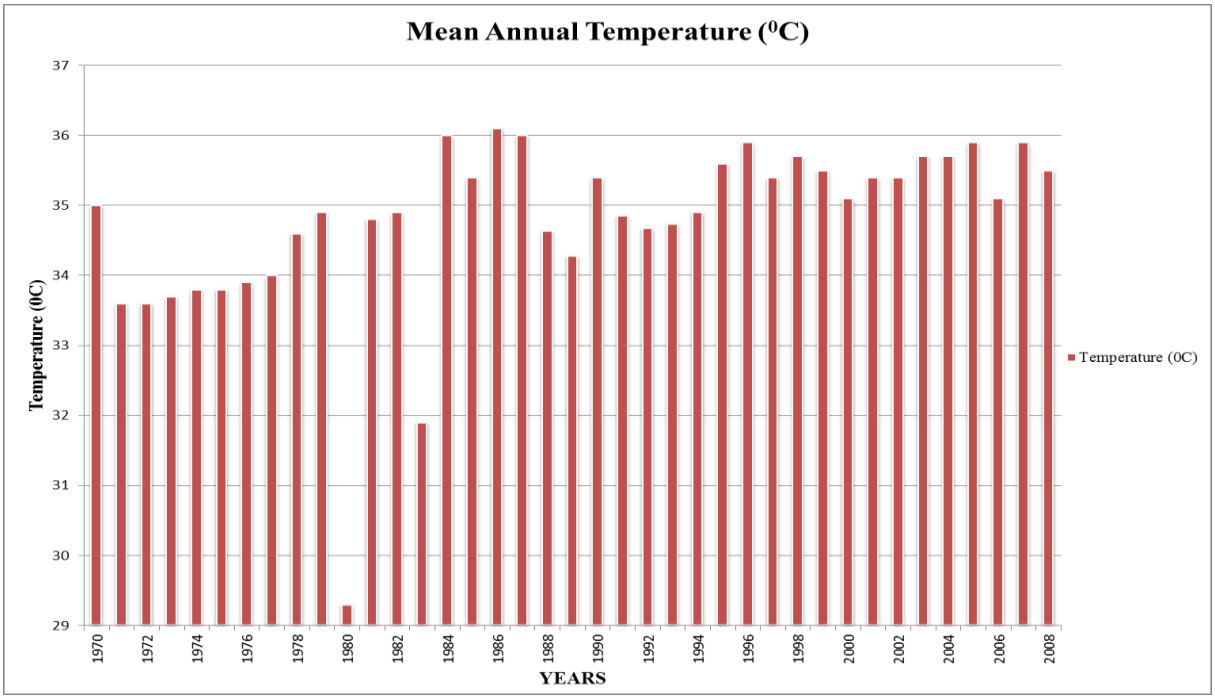


Figure 4.2: Annual Mean Temperature of the basin

The graph of annual average temperature range of the basin is shown in Figure 4.2. The data has average temperature value of 34.8^0C, with the maximum value of 36.1^0C in the year 1986; the minimum value is 29.3^0C in the year 1980. The standard deviation and variance of the data in the entire basin are 1.3 and 1.6 respectively.

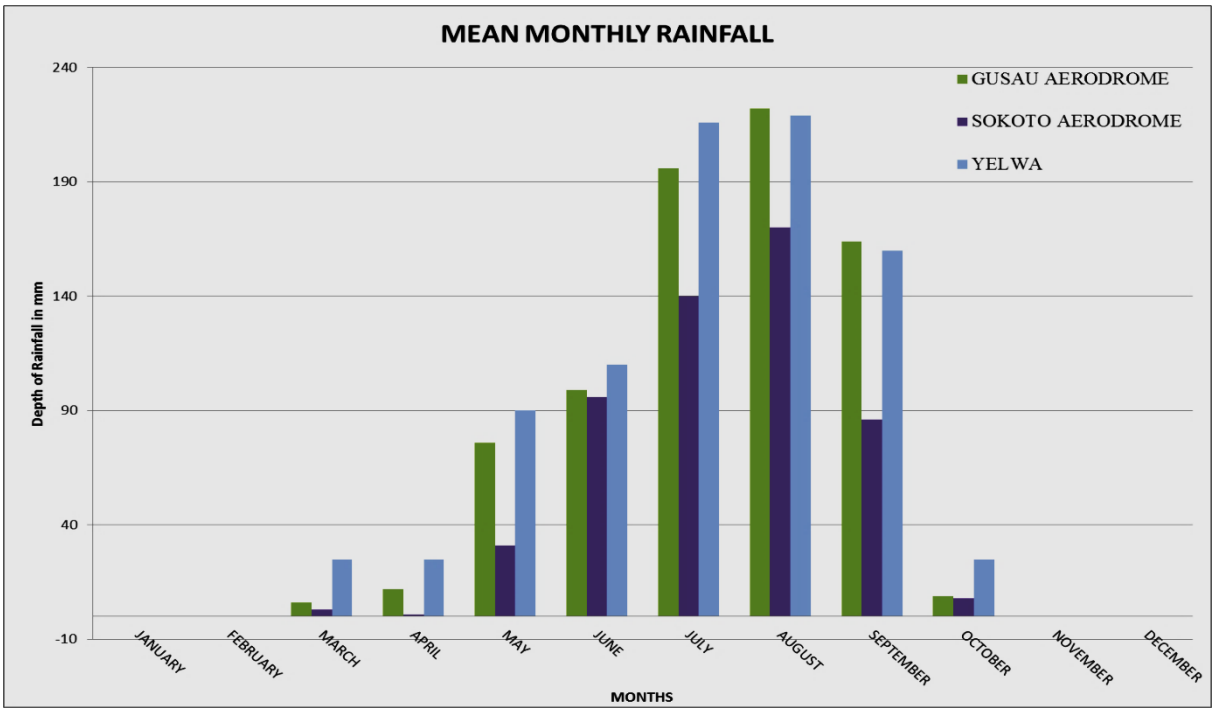


Figure 4.3: Mean Monthly Rainfall of some data stations in the basin

Figure 4.3 shows the mean monthly rainfall in millimetre of some data stations in the basin. The Gusau station data has average rainfall value of 65.3mm, with the maximum value of 222mm in the month of August, the months of January, February, November and December have no rainfall. The standard deviation and variance of the data in this station are 84.9 and 7201 respectively.

Additionally, the average of these rainfall values for Yelwa Yauri station is 72.5mm, while the maximum value is 219mm in the month of August, the months of January, February,

November and December have no rainfall. The standard deviation and variance of this data are 84.9 and 7201.5 respectively.

The average of these rainfall data values for Sokoto station is 44.6mm, while the maximum value is 170mm in the month of August, the months of January, February, November and December have no rainfall for this station also.

The graphs show similar pattern, which indicate that they share similar rainfall characteristics. The graphs of annual rainfall of the same data stations are shown in Figure 4.4.

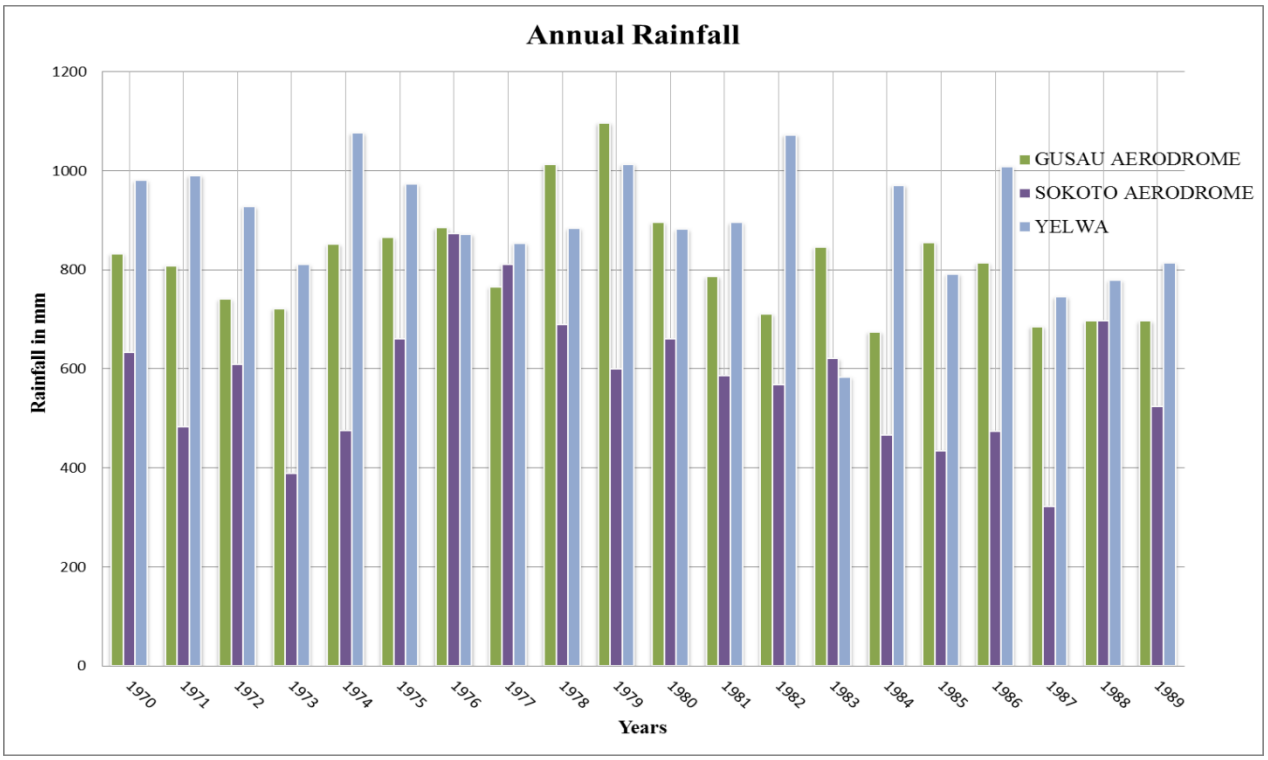


Figure 4.4: Annual Rainfall of some data stations in the basin

The mean annual rainfall of the whole basin is shown in Figure 4.5, this display the average pattern of rainfall in the whole basin from 1970 to 2008. The maximum and minimum average values of 874mm and 281mm are in the years 1976 and 1984 respectively.

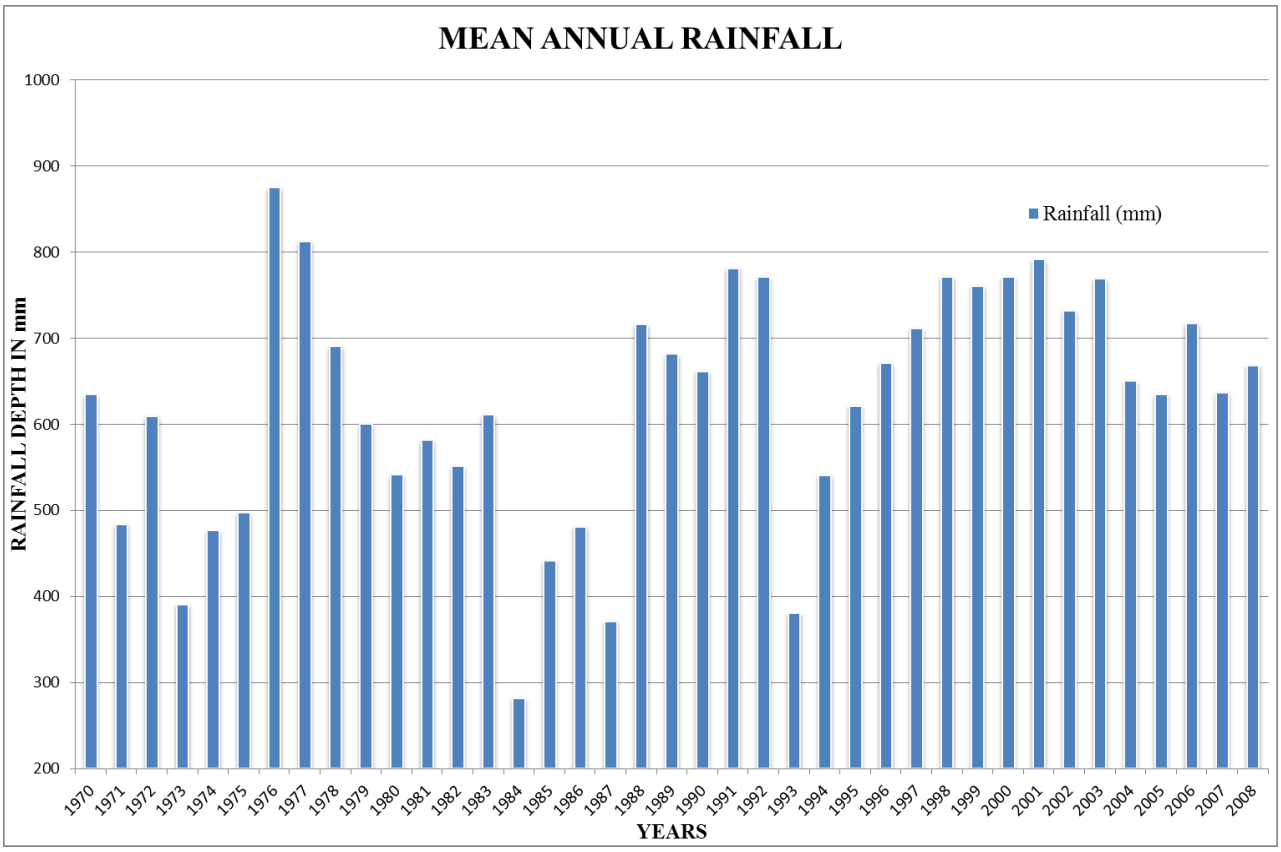


Figure 4.5: Mean Annual Rainfall of the basin

The streamflow data obtained from some gauging stations within the basin and from literature are the historical data of 1970 to 2008. The monthly average measured streamflow patterns of all major rivers in the basin are shown in Figure 4.6.

The measured monthly average streamflow volume data indicates a total volume of 1.93, 4.76, and 9.33 billion cubic metres (BCM), with the mean of 160.7, 396.6 and 777.7 million cubic metres (MCM) for River Bunsuru, Gagere, and Rima respectively. The data obtained from the first part of River Sokoto at Gusau gauging station indicates total average volume of 6.4 BCM and mean of 533.6 MCM. While River Zamfara, Ka and Sokoto (second part) have total of 7.31, 5.23, and 36.88 BCM and mean of 608.9, 436.1, and 3073.5 MCM respectively.

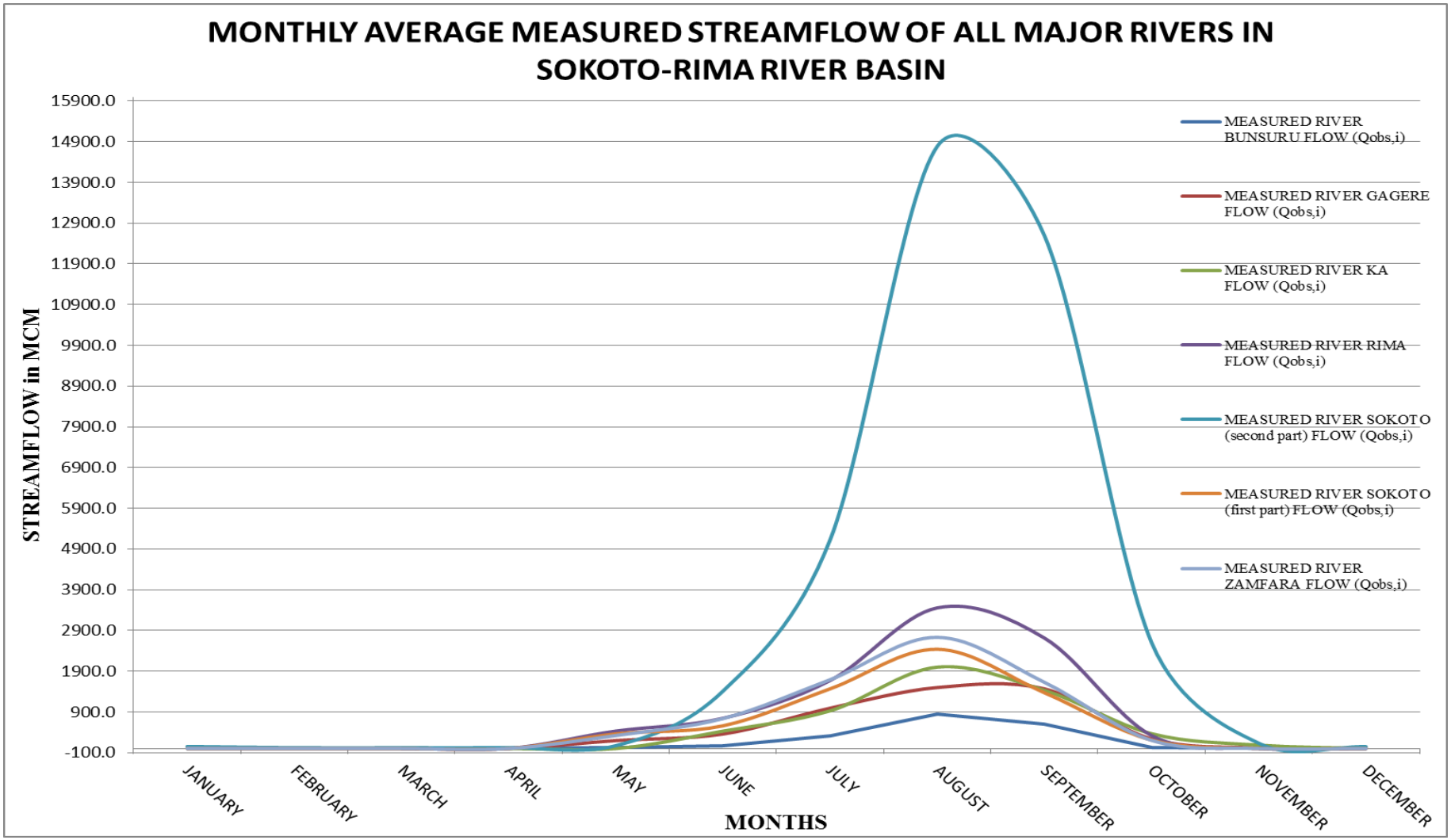


Figure 4.6: Monthly average measured streamflow volume of the six major rivers in the basin

4.2 Analysis of the Temperature trend for Generating Climate Scenarios

The annual average maximum temperature of the basin was analysed. It indicates a maximum average annual temperature of 36.1^{0}C and minimum temperature of 29.3^{0}C with mean of 34.8^{0}C and standard deviation of 1.2. The linear trend analysis in Figure 4.7 indicates a gradient of 0.05.This designates a decadal increase of about 0.5^{0}C. Therefore, the value of 0.5^{0}C and 1.0^{0}C was selected as the projection of temperature increase for this region by considering temperature variation over four decades.

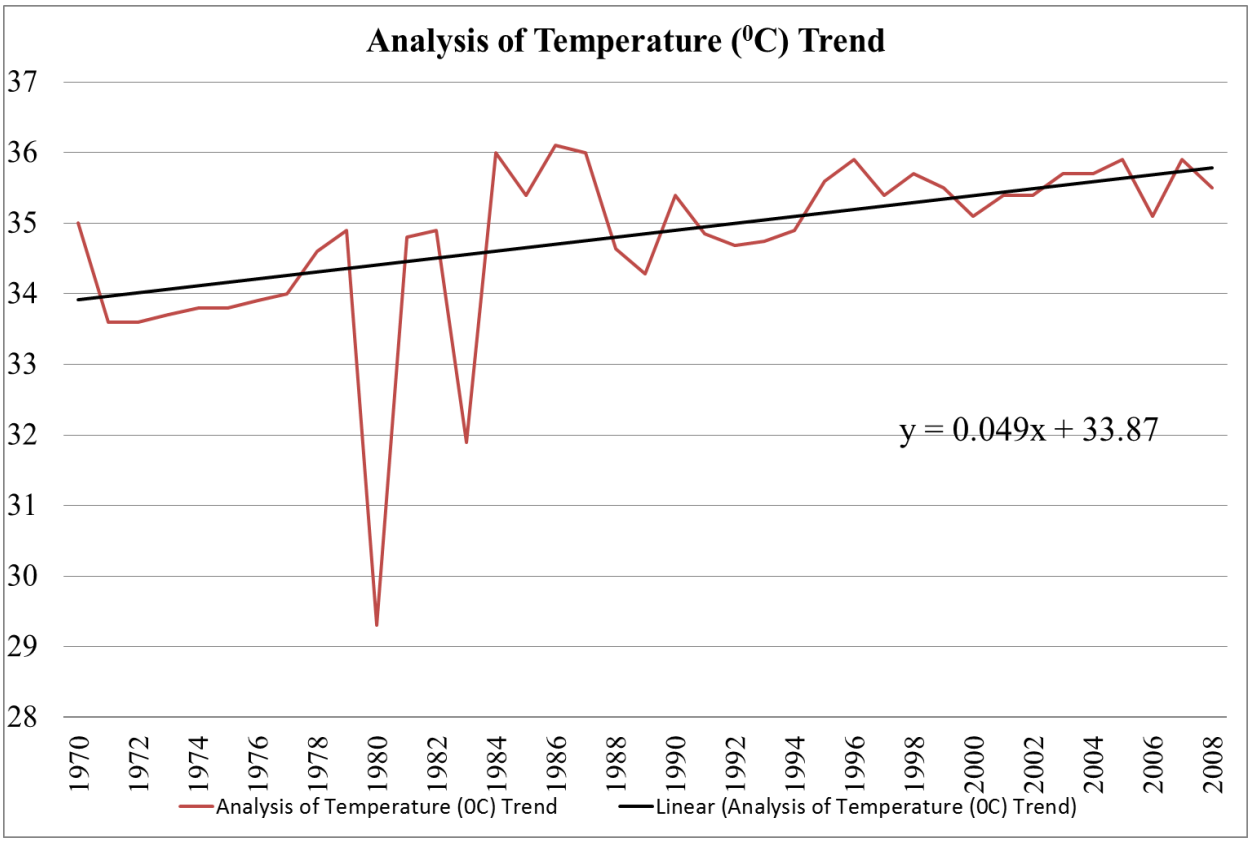


Figure 4.7: Analysis of Temperature Trend

4.3 Analysis of the Rainfall trend for Generating Climate Scenarios

The average annual rainfall of the basin was also analysed. It indicates a maximum average rainfall value of 874mm and minimum average value of 280.9mm with mean of 624.3mm and standard deviation of 135.5. The linear trend analysis in Figure 4.8 indicates a gradient of 10.0.This designates an annual increase of about 10%. Therefore, the value of 10% increase in rainfall and 10% decrease in rainfall was selected as the projection for climate change for this region by considering average rainfall value variation over four decades.

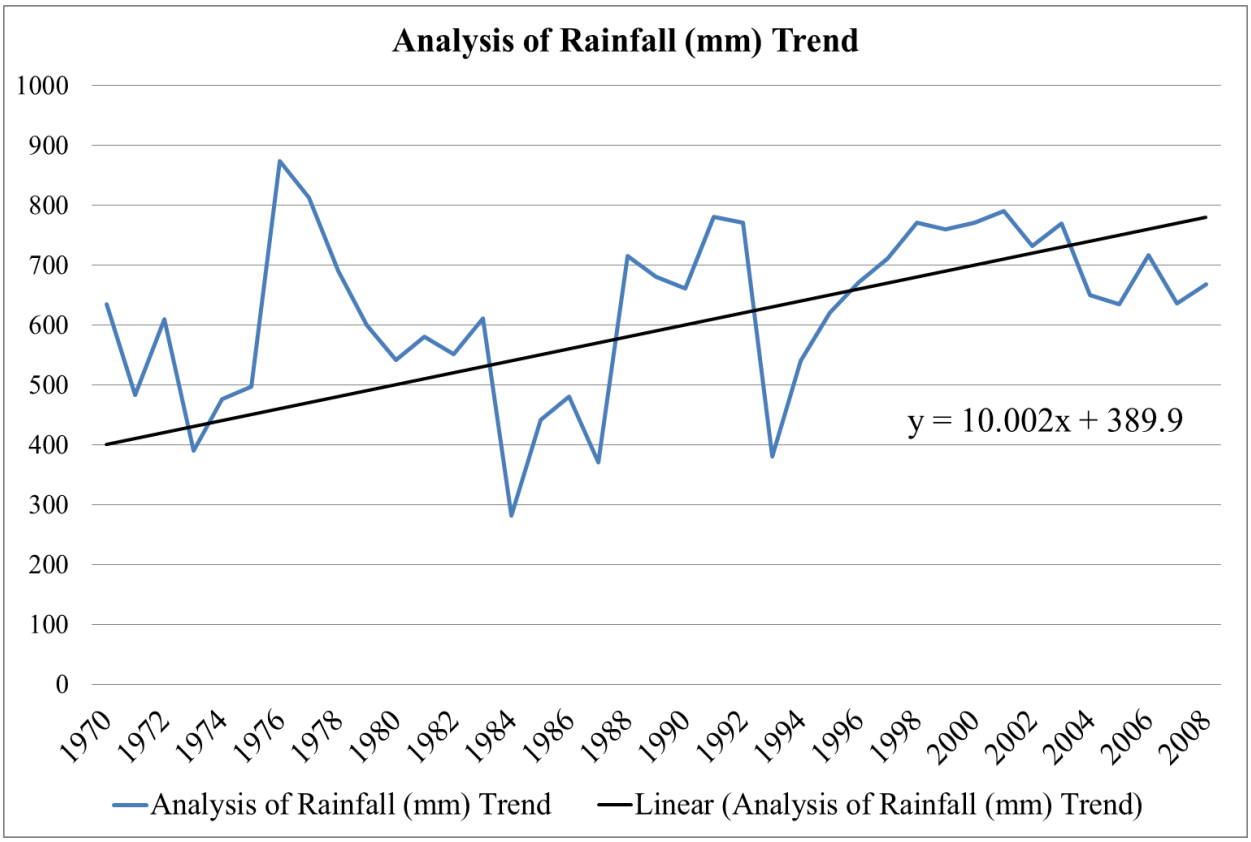


Figure 4.8: Analysis of Rainfall Trend

4.4 Streamflow Simulation

The average monthly streamflow volumes from the sub-catchments of the six major rivers in the basin for the period 1970 to 2008 simulated using the WEAP model are shown in Figure 4.9 and Table 4.1. The total monthly average volume of water from the basin was found to be 83.77 billion cubic meter (BCM). While the Sokoto River reaches where all the rivers drain shows a maximum monthly average stream flow of 15.67 BCM in August. Other rivers have less than that throughout the year. The minimum average streamflow is 12 million cubic meter (MCM) from River Bunsuru in the month of April which is considered the driest month in the region. River Bunsuru has maximum average streamflow of 920 MCM. River Gagere has maximum average streamflow of 1.48 BCM in the month of August, and minimum of 18.8 MCM in the month of April. River Rima where both River Bunsuru and River Gagere drain, has maximum average streamflow of 4.05 BCM in the month of August and minimum of 87.6 MCM in the month of April. River Zamfara have maximum average streamflow of 2.81 BCM in the month of August and minimum of 117 MCM in the month of February. River Ka has maximum average streamflow of 2.11 BCM in the month of August and minimum of 98.6 MCM in the month of February. First part of River Sokoto has maximum average streamflow of 2.86 BCM in the month of August and minimum of 138 MCM in the month of March, while the second part where all the other five rivers drain has maximum average streamflow of 15.6 BCM in the month of August and minimum of 307MCM in the month of February.

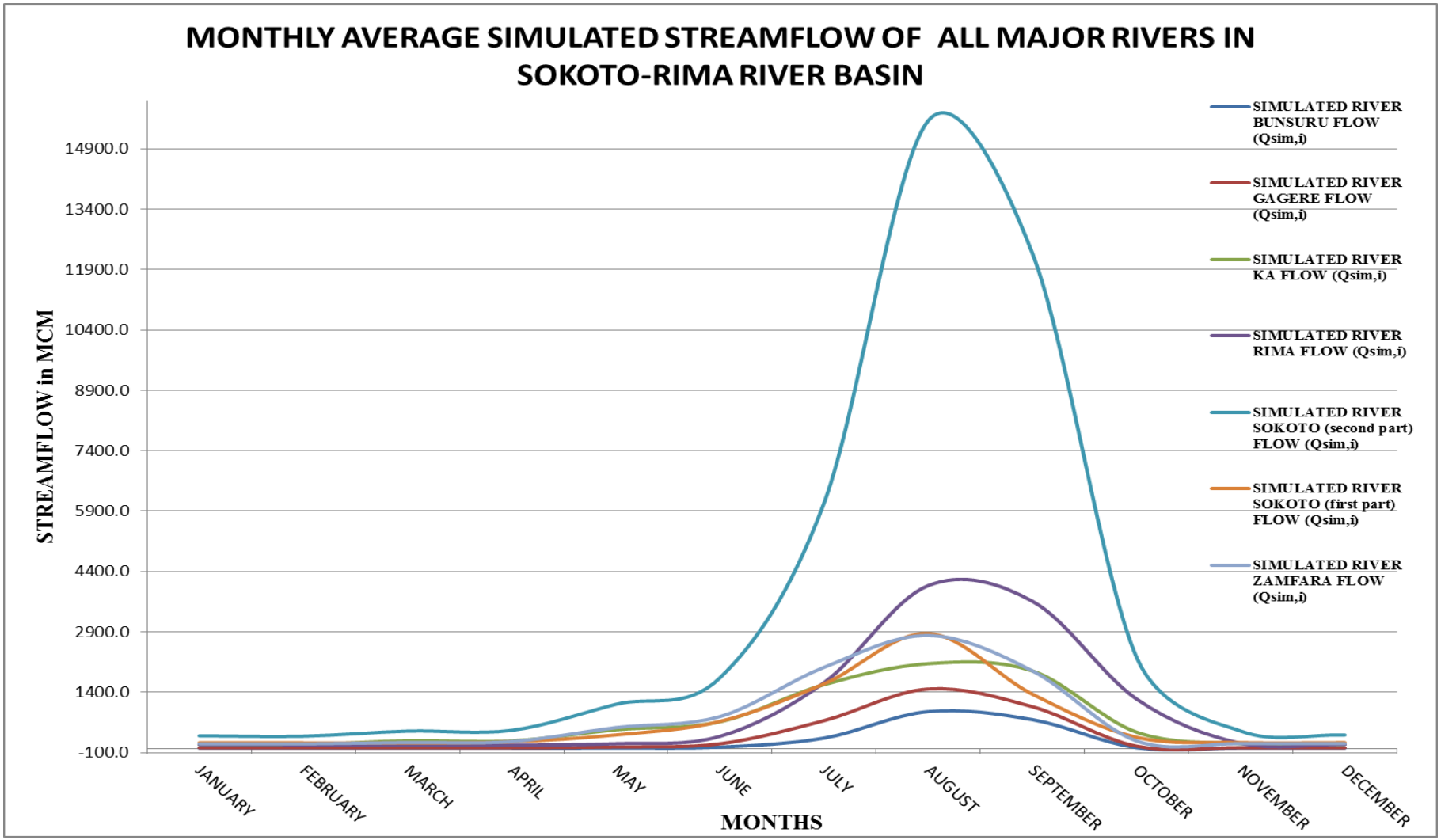


Figure 4.9: Monthly average simulated streamflow volume of the six major rivers in the basin

Table 4.1: The average monthly streamflow volume from the sub-catchments of the six major rivers in the basin

Monthly Average Streamflow (Million Cubic Meter) For some Selected Nodes, Scenario: Reference, All Rivers (6), All months (12)													
	January	February	March	April	May	June	July	August	September	October	November	December	**TOTAL**
RIVER BUNSURU	12.6	12.3	12.1	12.0	13.9	35.8	261	920	718	20.9	13.6	12.6	**2050**
RIVER GAGERE	20.1	19.4	18.9	18.8	39.5	120	695	1480	1040	58.2	22.9	21.1	**3560**
RIVER KA	100	98.6	197	191	469	666	1590	2110	1930	407	123	105	**7990**
RIVER RIMA	99.5	93.6	92.2	87.6	121	305	1640	4050	3660	1230	131	103	**11600**
RIVER SOKOTO (Second part)	317	307	435	454	1100	1760	6110	15600	12300	2260	436	337	**41500**
RIVER SOKOTO (First part)	143	141	138	170	339	674	1610	2860	1350	279	150	148	**8000**
RIVER ZAMFARA	119	117	151	175	521	795	2020	2810	1930	190	125	124	**9070**
TOTAL	**811.2**	**788.9**	**1044.2**	**1108.4**	**2603.4**	**4355.8**	**13926**	**29830**	**22928**	**4445.1**	**1001.5**	**850.7**	**83770**

4.5 Calibration and Validation Result

The climatic data of 1970 to 2008 was used to set up the model and calibrated by visual observation and adjusting the values of Runoff Resistance Factor of the land cover (range 0.1 to 10) and the relative storage of the root zone water capacity (range 0 to 100%) until the simulated values comes to an agreement with the streamflow data of 1990 to 2008. An obvious validation is first made by comparing graphically the simulated values with the observed values. This allows use of visual evaluation in the time series and simulated results obtained from the model. The efficiency criteria were applied to assess how well the model reproduces the observed measurements using excel capabilities. This is to reinforce the confidence in the results of the model simulations.

Figure 4.10 shows comparison of simulated and measured streamflow of River Bunsuru. The visual evaluation of the graph indicates similar pattern and coincidence in values. Table 4.2 shows the calculation of the objective functions that were used for determination of efficiency parameters of River Bunsuru streamflow simulations. The values obtained for coefficient of determination (R^2) is 0.99, for Nash-Sutcliffe coefficient of efficiency (CE) is 97.3%, for percentage error in total runoff volume *(VE)* is 6% and percentage error in peak discharge *(PE)* is 3.5%. The value of R^2 close to one indicates very good correlation between the simulated and measured values. The value of CE close to 100% indicates that measured streamflow was estimated most accurately by the model. The smaller value of the VE and PE indicates the better performance of the model in estimating total runoff volume and an indication of the relative absolute accuracy of the model in predicting peak flows, respectively.

Figure 4.11 shows comparison of simulated and measured streamflow of River Gagere. The visual evaluation of the graph indicates similar pattern. While, Table 4.3 shows the calculation of the efficiency parameters of River Gagere streamflow simulation. The values obtained for R^2, CE, VE, and PE are 0.94, 89.7%, -25.3% and - 0.4% respectively. The negative values of VE and PE are indication of better performance of the model and a general under estimation of peak flows in this river respectively.

Moreover, Figure 4.12 shows comparison of simulated and measured streamflow of River Rima. The visual evaluation of the graph indicates similar pattern and coincidence in some values. Table 4.4 shows the calculation of the efficiency parameters of River Rima. The values obtained for coefficient of determination (R^2) is 0.93, for Nash-Sutcliffe coefficient of efficiency (CE) is 84.4%, for percentage error in total runoff volume (VE) is 24.4% and percentage error in peak discharge (PE) is 6.4%.

Additionally, Figure 4.13, 4.14 and 4.15 show comparisons of simulated and measured streamflow of River Sokoto (first part), River Zamfara and River Ka respectively. The visual evaluation of these graphs also indicates similar pattern with agreement in some values. While Table 4.5, 4.6 and 4.7 shows the corresponding calculation of the efficiency parameters of River Sokoto (first part), River Zamfara and River Ka respectively. The values obtained for R^2 are 0.99, 0.99 and 0.94; for CE are 95%, 96.1%, 78%; for VE are 25%, 52.6% and 24.2%; and PE are 6.6%, 1.1%, and 2.1% respectively.

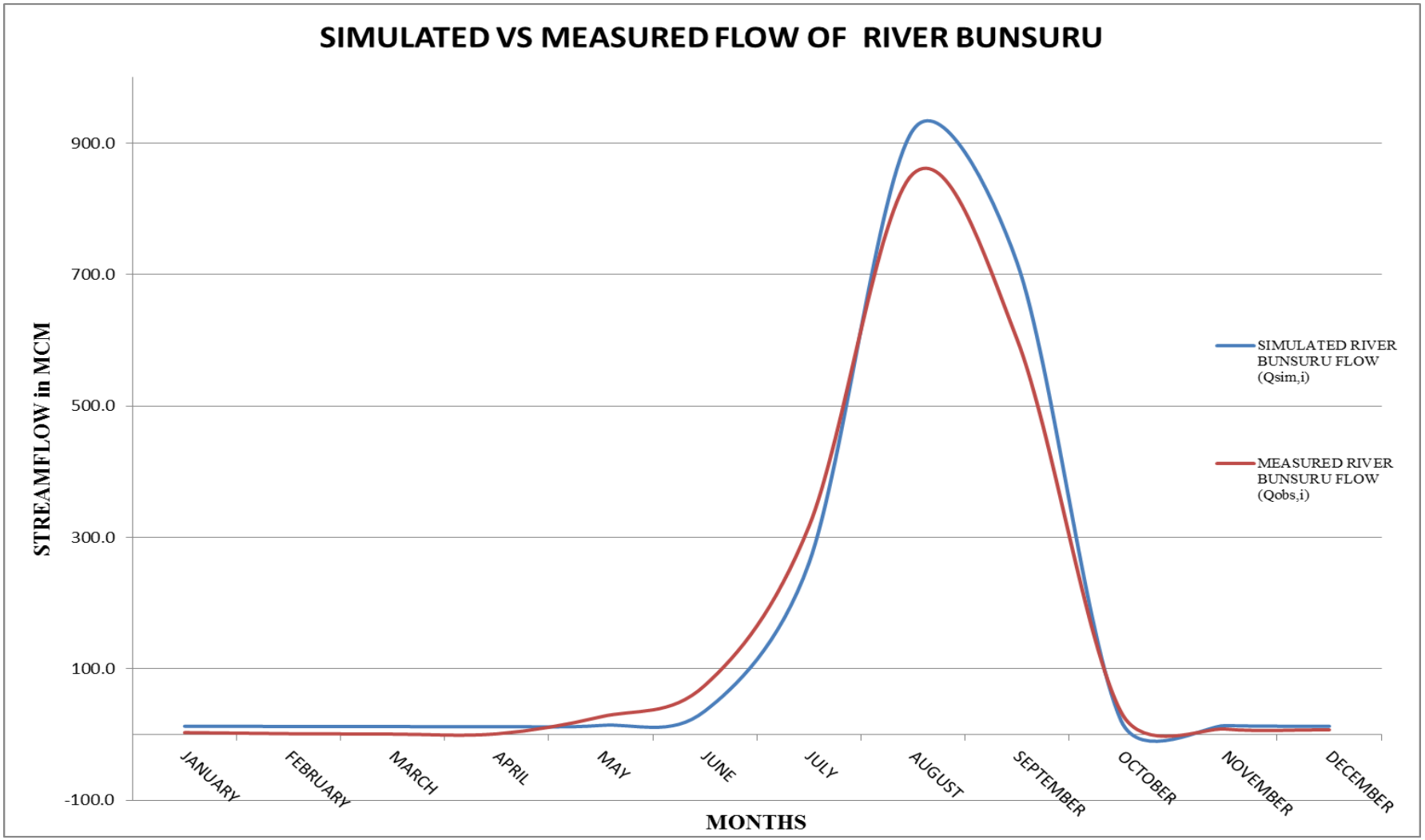


Figure 4.10: Comparison of Simulated and Measured Streamflow of River Bunsuru

Table 4.2: The Analysis of Simulated verses measured average monthly streamflow volume of River Bunsuru

			SIMULATED VS MEASURED FLOW OF RIVER BUNSURU							
MONTHS	**SIMULATED RIVER BUNSURU FLOW (Qsim,i)**	**MEASURED RIVER BUNSURU FLOW (Qobs,i)**	$Q_{sim,i}-\bar{Q}_{sim}$	$(Q_{sim,i}-\bar{Q}_{sim})^2$	$Q_{obs,i}-\bar{Q}_{obs}$	$(Q_{obs,i}-\bar{Q}_{obs})^2$	$(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})$	$Q_{obs,i}-Q_{sim,i}$	$(Q_{obs,i}-Q_{sim,i})^2$	$Q_{sim,i}-Q_{obs,i}$
JANUARY	12.6	2.9	-157.8	24900.8	-157.8	24910.0	24905.4	-9.7	94.6	9.7
FEBRUARY	12.3	1.3	-158.1	24995.6	-159.5	25425.6	25209.7	-11.1	122.1	11.1
MARCH	12.1	0.6	-158.3	25058.9	-160.1	25625.3	25340.5	-11.5	131.7	11.5
APRIL	12.0	1.0	-158.4	25090.6	-159.7	25505.4	25297.1	-11.0	121.0	11.0
MAY	13.9	27.0	-156.5	24492.3	-133.7	17876.8	20924.7	13.1	171.6	-13.1
JUNE	35.8	74.9	-134.6	18117.2	-85.8	7369.7	11555.0	39.1	1525.5	-39.1
JULY	261.0	316.9	90.6	8208.4	156.2	24383.8	14147.5	55.9	3120.0	-55.9
AUGUST	920.0	853.4	749.6	561900.2	692.7	479827.5	519244.8	-66.6	4435.6	66.6
SEPTEMBER	718.0	601.3	547.6	299865.8	440.6	194124.7	241270.3	-116.7	13618.9	116.7
OCTOBER	20.9	33.9	-149.5	22350.3	-126.8	16090.2	18963.6	13.0	167.9	-13.0
NOVEMBER	13.6	8.3	-156.8	24586.2	-152.4	23231.4	23899.2	-5.3	28.2	5.3
DECEMBER	12.6	7.1	-157.8	24900.8	-153.6	23581.1	24232.0	-5.5	29.8	5.5
Total	**2044.8**	**1928.5**	**0.0**	**1084466.9**	**0.0**	**887951.5**	**974989.9**	**-116.4**	**23566.8**	**116.4**
Mean	**170.4**	**160.7**								
			$R^2=\left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i}-\bar{Q}_{sim})^2}}\right]^2$		**0.987**		$CE=1-\frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs,i})^2}*100\%$		**97.3**	
			$VE=\frac{\sum_{i=1}^{n}(Q_{sim,i}-Q_{obs,i})}{\sum_{i=1}^{n}Q_{obs,i}}*100\%$		**6.0**		$PE=\frac{\sum_{i=1}^{m}(Q_{sim,p,i}-Q_{obs,p,i})}{\sum_{i=1}^{n}Q_{obs,p,i}}*100\%$		**3.5**	

The Correlation Coefficient for the above Table (Table 4.2) is calculated as follows:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i}-\bar{Q}_{sim})^2}}\right]^2 =$$

$$\left[\frac{Total\ of\ column\ Eight\ (974989.9)}{\sqrt{Total\ of\ column\ Seven(887951.5)}\ X\sqrt{Total\ of\ Column\ Five(1084466.9)}}\right]^2 = 0.987$$

The Nash-Sutcliffe coefficient of efficiency (*CE)* for the above Table (Table 4.2) is calculated as follows.

$$CE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs,i})^2} * 100\% =$$

$$1 - \frac{Total\ of\ column\ Ten\ (23566.8)}{Total\ of\ column\ Seven\ (887951.5)} * 100\% = 97.3\%$$

The Percentage error in peak discharge for the above Table (Table 4.2) is calculated as follows:

$$PE = \frac{\sum_{i=1}^{m}(Q_{sim,p,i}-Q_{obs,p,i})}{\sum_{i=1}^{n} Q_{obs,p,i}} * 100\% =$$

$$\frac{Difference\ in\ the\ Month\ of\ AugustValue(920-853.4)}{Total\ of\ column\ Three\ (1928.5)} * 100\% = 3.45\%$$

The Percentage error in total runoff volume for the above Table (Table 4.2) is calculated as follows:

$$VE = \frac{\sum_{i=1}^{n}(Q_{sim,i}-Q_{obs,i})}{\sum_{i=1}^{n} Q_{obs,i}} * 100\% = \frac{Total\ of\ column\ Eleven\ (116.4)}{Total\ of\ column\ Three\ (1928.5)} * 100\% = 6.03\%$$

Similarly for the remaining Tables 4.3 to 4.8.

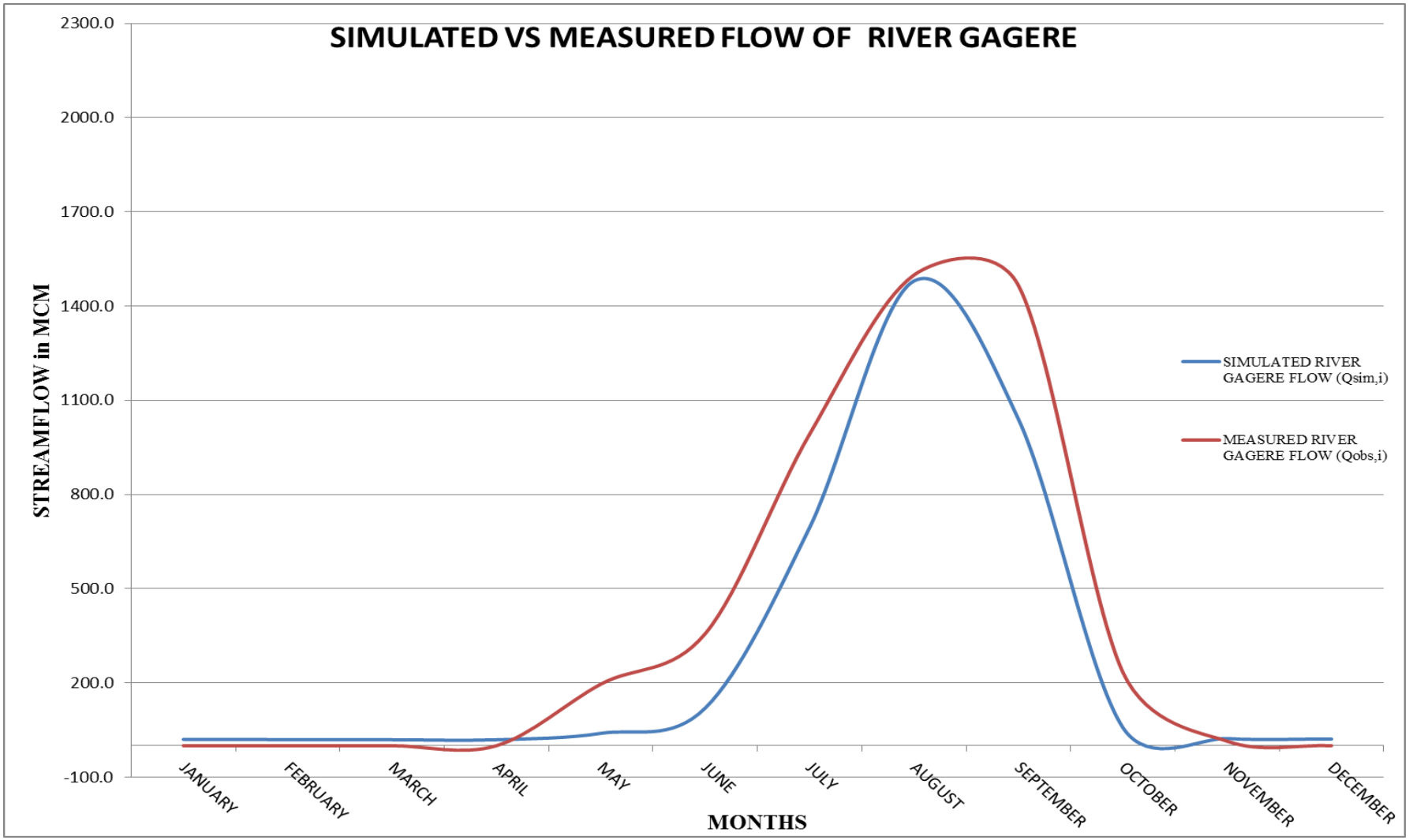


Figure 4.11: Comparison of Simulated and Measured Streamflow of River Gagere

Table 4.3: The Analysis of Simulated verses measured average monthly streamflow volume of River Gagere

			SIMULATED VS MEASURED FLOW OF RIVER GAGERE							
MONTHS	SIMULATED RIVER GAGERE FLOW (Qsim,i)	MEASURED RIVER GAGERE FLOW (Qobs,i)	$Q_{sim,i}-\bar{Q}_{sim}$	$(Q_{sim,i}-\bar{Q}_{sim})^2$	$Q_{obs,i}-\bar{Q}_{obs}$	$(Q_{obs,i}-\bar{Q}_{obs})^2$	$(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})$	$Q_{obs,i}-Q_{sim,i}$	$(Q_{obs,i}-Q_{sim,i})^2$	$Q_{sim,i}-Q_{obs,i}$
JANUARY	20.1	0.0	-276.1	76208.2	-396.6	157267.5	109476.4	-20.1	404.0	20.1
FEBRUARY	19.4	0.0	-276.8	76595.2	-396.6	157267.5	109754.0	-19.4	376.4	19.4
MARCH	18.9	0.0	-277.3	76872.2	-396.6	157267.5	109952.2	-18.9	357.2	18.9
APRIL	18.8	0.0	-277.4	76927.6	-396.6	157267.5	109991.9	-18.8	353.4	18.8
MAY	39.5	196.3	-256.7	65873.5	-200.3	40128.0	51413.7	156.8	24570.6	-156.8
JUNE	120.0	357.0	-176.2	31031.8	-39.6	1565.8	6970.5	237.0	56169.0	-237.0
JULY	695.0	992.3	398.8	159074.7	595.7	354894.7	237602.1	297.3	88387.3	-297.3
AUGUST	1480.0	1499.0	1183.8	1401481.1	1102.4	1215352.7	1305103.0	19.0	361.0	-19.0
SEPTEMBER	1040.0	1465.7	743.8	553300.4	1069.1	1143070.3	795274.3	425.7	181232.7	-425.7
OCTOBER	58.2	234.3	-238.0	56624.2	-162.3	26336.1	38616.8	176.1	31006.2	-176.1
NOVEMBER	22.9	14.3	-273.3	74670.1	-382.3	146141.0	104462.3	-8.6	74.2	8.6
DECEMBER	21.1	0.0	-275.1	75657.1	-396.6	157267.5	109079.8	-21.1	445.2	21.1
Total	**3553.9**	**4758.8**	**0.0**	**2724316.0**	**0.0**	**3713825.8**	**3087696.9**	**1204.9**	**383737.1**	**-1204.9**
Mean	**296.2**	**396.6**								
			$R^2=\left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i}-\bar{Q}_{sim})^2}}\right]^2$		**0.942**		$CE=1-\frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs,i})^2}*100\%$		**89.7**	
			$VE=\frac{\sum_{i=1}^{n}(Q_{sim,i}-Q_{obs,i})}{\sum_{i=1}^{n}Q_{obs,i}}*100\%$		**-25.3**		$PE=\frac{\sum_{i=1}^{m}(Q_{sim,p,i}-Q_{obs,p,i})}{\sum_{i=1}^{n}Q_{obs,p,i}}*100\%$		**-0.4**	

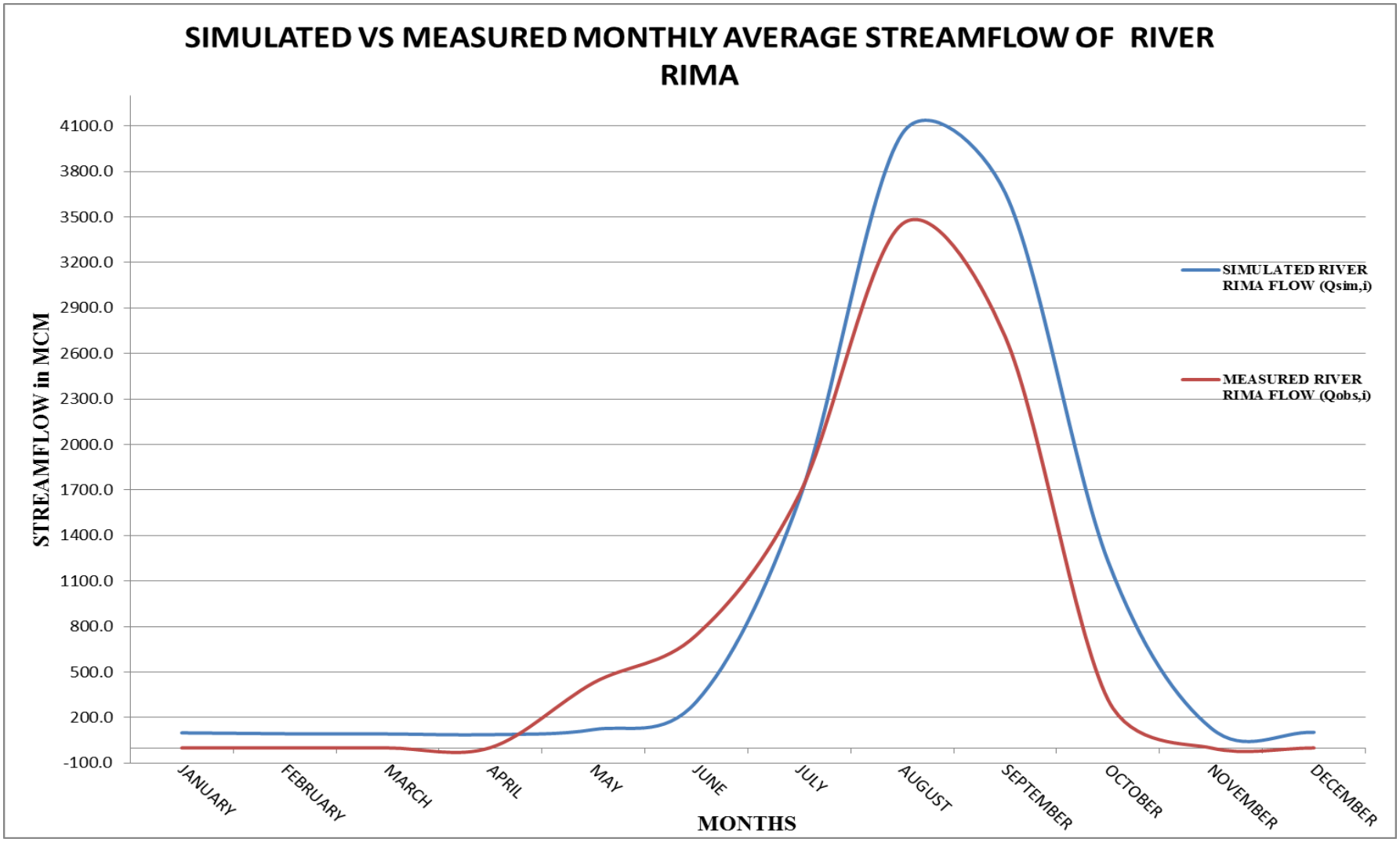


Figure 4.12: Comparison of Simulated and Measured Streamflow of River Rima

Table 4.4: The Analysis of Simulated verses measured average monthly streamflow volume of River Rima

			SIMULATED VS MEASURED FLOW OF RIVER RIMA							
MONTHS	**SIMULATED RIVER RIMA FLOW (Qsim,i)**	**MEASURED RIVER RIMA FLOW (Qobs,i)**	$Q_{sim,i}-\bar{Q}_{sim}$	$(Q_{sim,i}-\bar{Q}_{sim})^2$	$Q_{obs,i}-\bar{Q}_{obs}$	$(Q_{obs,i}-\bar{Q}_{obs})^2$	$(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})$	$Q_{obs,i}-Q_{sim,i}$	$(Q_{obs,i}-Q_{sim,i})^2$	$Q_{sim,i}-Q_{obs,i}$
JANUARY	99.5	0.0	-868.2	753843.6	-777.7	604742.8	675189.9	-99.5	9900.3	99.5
FEBRUARY	93.6	0.0	-874.1	764123.7	-777.7	604742.8	679778.1	-93.6	8761.0	93.6
MARCH	92.2	0.0	-875.5	766573.2	-777.7	604742.8	680866.8	-92.2	8500.8	92.2
APRIL	87.6	2.5	-880.1	774649.4	-775.2	600860.8	682243.6	-85.1	7242.0	85.1
MAY	121.0	429.4	-846.7	716971.5	-348.3	121296.9	294900.7	308.4	95095.1	-308.4
JUNE	305.0	744.4	-662.7	439226.5	-33.3	1107.4	22054.1	439.4	193050.4	-439.4
JULY	1640.0	1671.9	672.3	451931.3	894.2	799634.6	601148.8	31.9	1016.0	-31.9
AUGUST	4050.0	3454.5	3082.3	9500316.4	2676.8	7165514.8	8250736.8	-595.5	354620.3	595.5
SEPTEMBER	3660.0	2711.6	2692.3	7248254.9	1933.9	3740154.5	5206687.4	-948.4	899462.6	948.4
OCTOBER	1230.0	317.6	262.3	68779.4	-460.1	211647.9	-120652.5	-912.4	832473.8	912.4
NOVEMBER	131.0	0.0	-836.7	700136.6	-777.7	604742.8	650693.9	-131.0	17161.0	131.0
DECEMBER	103.0	0.0	-864.7	747778.2	-777.7	604742.8	672468.2	-103.0	10609.0	103.0
Total	**11612.9**	**9331.8**	**0.0**	**22932584.6**	**0.0**	**15663930.7**	**18296115.9**	**-2281.1**	**2437892.2**	**2281.1**
Mean	**967.7**	**777.7**								
			$R^2=\left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i}-\bar{Q}_{sim})^2}}\right]^2$		**0.932**		$CE=1-\frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs,i})^2}*100\%$		**84.4**	
			$VE=\frac{\sum_{i=1}^{n}(Q_{sim,i}-Q_{obs,i})}{\sum_{i=1}^{n}Q_{obs,i}}*100\%$		**24.4**		$PE=\frac{\sum_{i=1}^{m}(Q_{sim,p,i}-Q_{obs,p,i})}{\sum_{i=1}^{n}Q_{obs,p,i}}*100\%$		**6.4**	

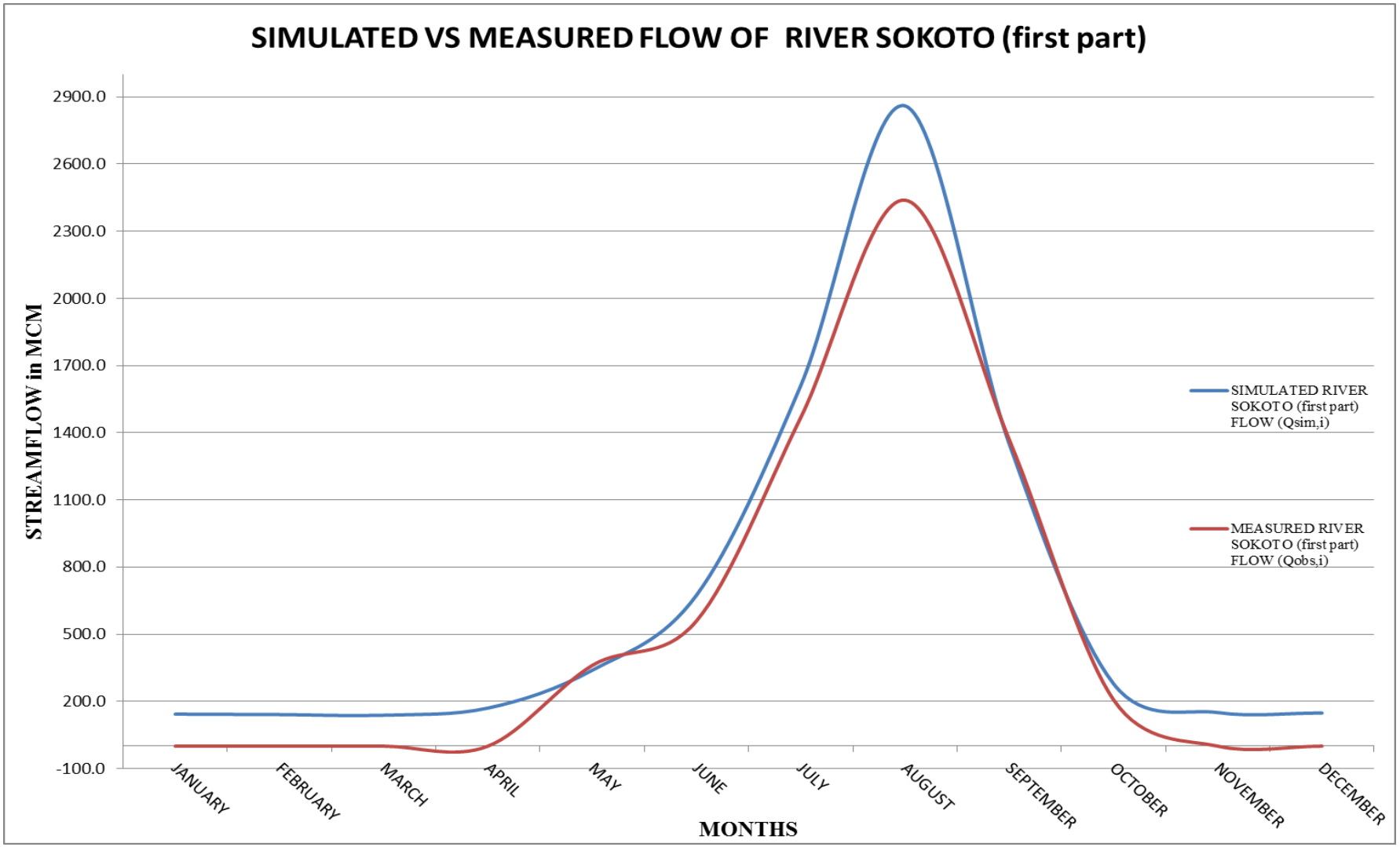


Figure 4.13: Comparison of Simulated and Measured Streamflow of River Sokoto (first part)

Table 4.5: The Analysis of Simulated verses measured average monthly streamflow volume of River Sokoto (first part)

			SIMULATED VS MEASURED FLOW OF RIVER SOKOTO (first part)							
MONTHS	**SIMULATED RIVER SOKOTO (first part) FLOW (Qsim,i)**	**MEASURED RIVER SOKOTO (first part) FLOW (Qobs,i)**	$Q_{sim,i}-\bar{Q}_{sim}$	$(Q_{sim,i}-\bar{Q}_{sim})^2$	$Q_{obs,i}-\bar{Q}_{obs}$	$(Q_{obs,i}-\bar{Q}_{obs})^2$	$(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})$	$Q_{obs,i}-Q_{sim,i}$	$(Q_{obs,i}-Q_{sim,i})^2$	$Q_{sim,i}-Q_{obs,i}$
JANUARY	143.0	0.0	-523.8	274401.4	-533.6	284677.8	279492.4	-143.0	20449.0	143.0
FEBRUARY	141.0	0.0	-525.8	276500.7	-533.6	284677.8	280559.5	-141.0	19881.0	141.0
MARCH	138.0	0.0	-528.8	279664.7	-533.6	284677.8	282160.1	-138.0	19044.0	138.0
APRIL	170.0	0.0	-496.8	246843.4	-533.6	284677.8	265086.5	-170.0	28900.0	170.0
MAY	339.0	360.5	-327.8	107474.7	-173.1	29947.0	56732.2	21.5	462.3	-21.5
JUNE	674.0	559.1	7.2	51.4	25.6	654.0	183.3	-114.9	13196.3	114.9
JULY	1610.0	1467.5	943.2	889563.4	933.9	872258.7	880868.5	-142.5	20306.3	142.5
AUGUST	2860.0	2438.8	2193.2	4809980.0	1905.2	3629779.1	4178416.6	-421.3	177451.6	421.3
SEPTEMBER	1350.0	1369.4	683.2	466716.7	835.8	698599.9	571006.4	19.4	375.4	-19.4
OCTOBER	279.0	207.4	-387.8	150414.7	-326.2	106391.5	126502.3	-71.6	5130.1	71.6
NOVEMBER	150.0	0.0	-516.8	267116.7	-533.6	284677.8	275757.5	-150.0	22500.0	150.0
DECEMBER	148.0	0.0	-518.8	269188.0	-533.6	284677.8	276824.6	-148.0	21904.0	148.0
Total	**8002.0**	**6402.6**	**0.0**	**8037915.7**	**0.0**	**7045697.2**	**7473589.9**	**-1599.4**	**349599.9**	**1599.4**
Mean	**666.8**	**533.6**								
			$R^2=\left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i}-\bar{Q}_{sim})^2}}\right]^2$		**0.986**		$CE=1-\frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs,i})^2}*100\%$		**95.0**	
			$VE=\frac{\sum_{i=1}^{n}(Q_{sim,i}-Q_{obs,i})}{\sum_{i=1}^{n}Q_{obs,i}}*100\%$		**25.0**		$PE=\frac{\sum_{i=1}^{m}(Q_{sim,p,i}-Q_{obs,p,i})}{\sum_{i=1}^{n}Q_{obs,p,i}}*100\%$		**6.6**	

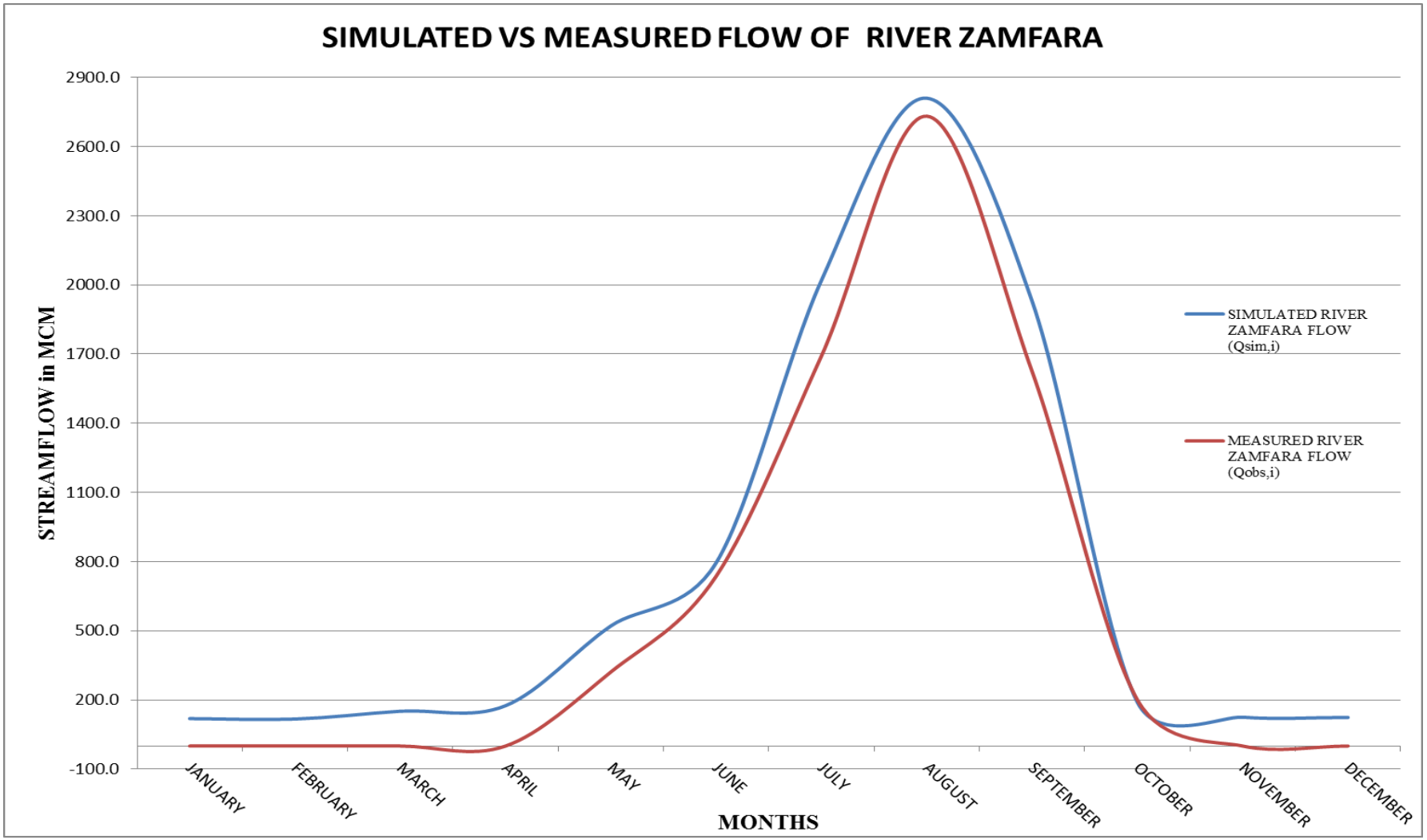


Figure 4.14: Comparison of Simulated and Measured Streamflow of River Zamfara

Table 4.6: The Analysis of Simulated verses measured average monthly streamflow volume of River Zamfara

			SIMULATED VS MEASURED FLOW OF RIVER ZAMFARA							
MONTHS	SIMULATED RIVER ZAMFARA FLOW (Qsim,i)	MEASURED RIVER ZAMFARA FLOW (Qobs,i)	$Q_{sim,i}-\bar{Q}_{sim}$	$(Q_{sim,i}-\bar{Q}_{sim})^2$	$Q_{obs,i}-\bar{Q}_{obs}$	$(Q_{obs,i}-\bar{Q}_{obs})^2$	$(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})$	$Q_{obs,i}-Q_{sim,i}$	$(Q_{obs,i}-Q_{sim,i})^2$	$Q_{sim,i}-Q_{obs,i}$
JANUARY	119.0	0.0	-637.4	406300.0	-608.9	370804.9	388146.9	-119.0	14161.0	119.0
FEBRUARY	117.0	0.0	-639.4	408853.7	-608.9	370804.9	389364.8	-117.0	13689.0	117.0
MARCH	151.0	0.0	-605.4	366529.3	-608.9	370804.9	368660.9	-151.0	22801.0	151.0
APRIL	175.0	0.0	-581.4	338045.3	-608.9	370804.9	354046.4	-175.0	30625.0	175.0
MAY	521.0	321.3	-235.4	55421.0	-287.7	82764.1	67726.4	-199.8	39900.1	199.8
JUNE	795.0	736.7	38.6	1488.7	127.7	16314.7	4928.2	-58.3	3402.8	58.3
JULY	2020.0	1692.0	1263.6	1596642.8	1083.1	1173024.4	1368539.7	-328.0	107584.0	328.0
AUGUST	2810.0	2732.0	2053.6	4217204.5	2123.1	4507394.4	4359885.8	-78.0	6084.0	78.0
SEPTEMBER	1930.0	1625.3	1173.6	1377297.8	1016.4	1033060.5	1192825.2	-304.7	92821.8	304.7
OCTOBER	190.0	200.0	-566.4	320827.8	-408.9	167229.9	231629.0	10.0	100.0	-10.0
NOVEMBER	125.0	0.0	-631.4	398687.0	-608.9	370804.9	384493.3	-125.0	15625.0	125.0
DECEMBER	124.0	0.0	-632.4	399950.8	-608.9	370804.9	385102.2	-124.0	15376.0	124.0
Total	**9077.0**	**7307.3**	**0.0**	**9887248.9**	**0.0**	**9204617.2**	**9495348.9**	**-1769.8**	**362169.6**	**1769.8**
Mean	**756.4**	**608.9**								
			$R^2=\left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i}-\bar{Q}_{sim})^2}}\right]^2$		**0.991**		$CE=1-\frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs,i})^2}*100\%$		**96.1**	
			$VE=\frac{\sum_{i=1}^{n}(Q_{sim,i}-Q_{obs,i})}{\sum_{i=1}^{n}Q_{obs,i}}*100\%$		**24.2**		$PE=\frac{\sum_{i=1}^{m}(Q_{sim,p,i}-Q_{obs,p,i})}{\sum_{i=1}^{n}Q_{obs,p,i}}*100\%$		**1.1**	

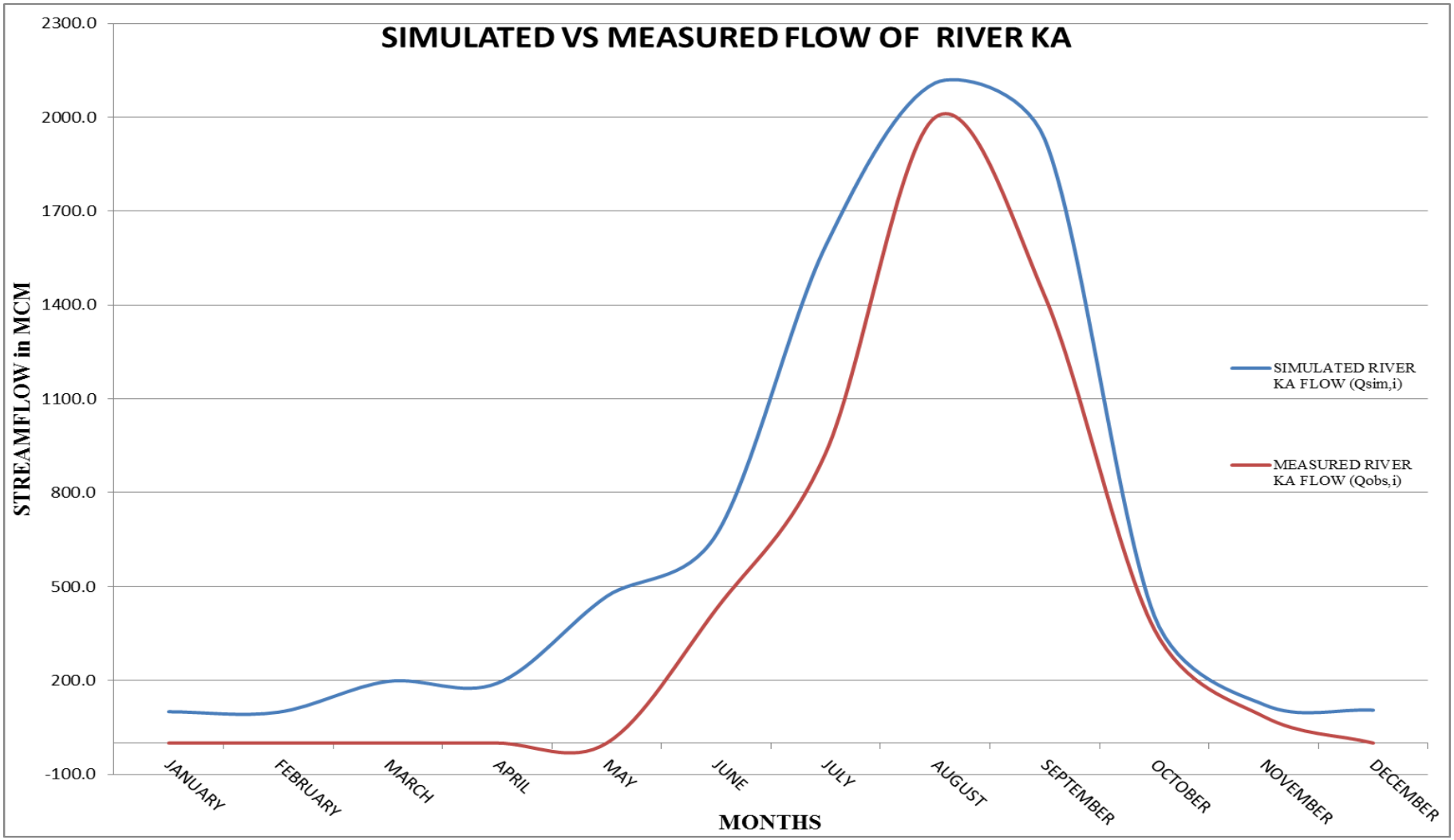


Figure 4.15: Comparison of Simulated and Measured Streamflow of River Ka

Table 4.7: The Analysis of Simulated verses measured average monthly streamflow volume of River Ka

			SIMULATED VS MEASURED FLOW OF RIVER KA							
MONTHS	**SIMULATED RIVER KA FLOW (Qsim,i)**	**MEASURED RIVER KA FLOW (Qobs,i)**	$Q_{sim,i}-\bar{Q}_{sim}$	$(Q_{sim,i}-\bar{Q}_{sim})^2$	$Q_{obs,i}-\bar{Q}_{obs}$	$(Q_{obs,i}-\bar{Q}_{obs})^2$	$(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})$	$Q_{obs,i}-Q_{sim,i}$	$(Q_{obs,i}-Q_{sim,i})^2$	$Q_{sim,i}-Q_{obs,i}$
JANUARY	100.0	0.0	-565.6	319846.8	-436.1	190207.4	246652.1	-100.0	10000.0	100.0
FEBRUARY	98.6	0.0	-567.0	321432.3	-436.1	190207.4	247262.6	-98.6	9722.0	98.6
MARCH	197.0	0.0	-468.6	219539.1	-436.1	190207.4	204347.7	-197.0	38809.0	197.0
APRIL	191.0	0.0	-474.6	225197.7	-436.1	190207.4	206964.4	-191.0	36481.0	191.0
MAY	469.0	0.0	-196.6	38631.9	-436.1	190207.4	85720.9	-469.0	219961.0	469.0
JUNE	666.0	428.4	0.4	0.2	-7.7	59.7	-3.5	-237.6	56453.8	237.6
JULY	1590.0	927.7	924.5	854607.8	491.6	241643.2	454433.9	-662.3	438641.3	662.3
AUGUST	2110.0	2000.1	1444.5	2086435.8	1564.0	2446009.1	2259079.7	-109.9	12078.0	109.9
SEPTEMBER	1930.0	1428.7	1264.5	1598833.8	992.5	985133.4	1255015.8	-501.3	251335.1	501.3
OCTOBER	407.0	364.0	-258.6	66848.1	-72.1	5202.4	18648.6	-43.0	1849.0	43.0
NOVEMBER	123.0	84.7	-542.6	294360.5	-351.5	123524.9	190685.2	-38.3	1469.4	38.3
DECEMBER	105.0	0.0	-560.6	314216.3	-436.1	190207.4	244471.4	-105.0	11025.0	105.0
Total	**7986.6**	**5233.5**	**0.0**	**6339950.3**	**0.0**	**4942817.5**	**5413279.0**	**-2753.1**	**1087824.6**	**2753.1**
Mean	**665.6**	**436.1**								
			$R^2=\left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i}-\bar{Q}_{sim})^2}}\right]^2$		**0.935**		$CE=1-\frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs,i})^2}*100\%$		**78.0**	
			$VE=\frac{\sum_{i=1}^{n}(Q_{sim,i}-Q_{obs,i})}{\sum_{i=1}^{n}Q_{obs,i}}*100\%$		**52.6**		$PE=\frac{\sum_{i=1}^{m}(Q_{sim,p,i}-Q_{obs,p,i})}{\sum_{i=1}^{n}Q_{obs,p,i}}*100\%$		**2.1**	

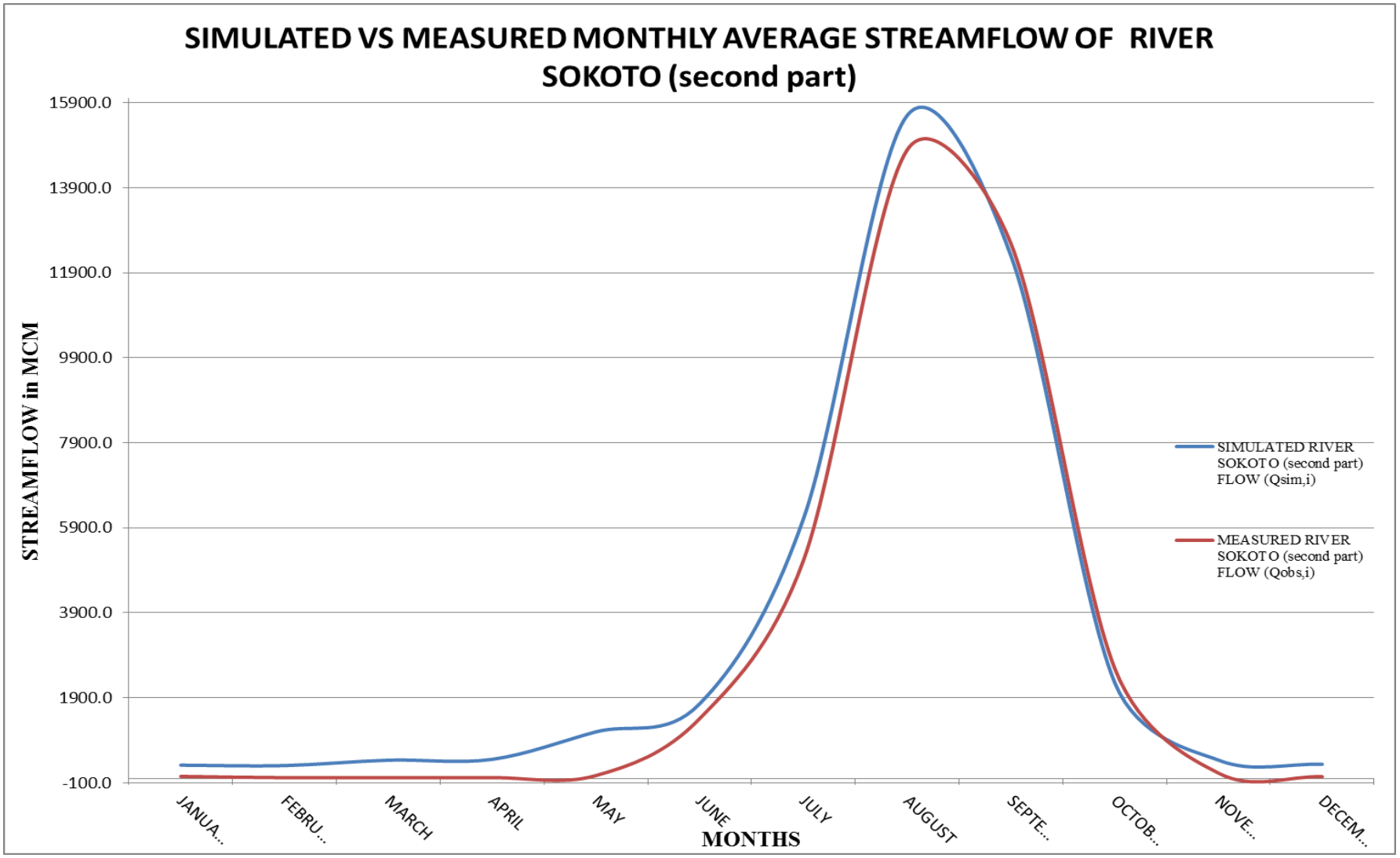


Figure 4.16: Comparison of Simulated and Measured Streamflow of River Sokoto (second part)

Table 4.8: The Analysis of Simulated verses measured average monthly streamflow volume of River Sokoto (second part)

			SIMULATED VS MEASURED FLOW OF RIVER SOKOTO (second part)							
MONTHS	**SIMULATED RIVER SOKOTO (second part) FLOW (Qsim,i)**	**MEASURED RIVER SOKOTO (second part) FLOW (Qobs,i)**	$Q_{sim,i}-\bar{Q}_{sim}$	$(Q_{sim,i}-\bar{Q}_{sim})^2$	$Q_{obs,i}-\bar{Q}_{obs}$	$(Q_{obs,i}-\bar{Q}_{obs})^2$	$(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})$	$Q_{obs,i}-Q_{sim,i}$	$(Q_{obs,i}-Q_{sim,i})^2$	$Q_{sim,i}-Q_{obs,i}$
JANUARY	317.0	52.0	-3134.3	9824045.4	-3021.5	9129462.3	9470388.2	-265.0	70225.0	265.0
FEBRUARY	307.0	22.0	-3144.3	9886832.1	-3051.5	9311652.3	9594933.2	-285.0	81225.0	285.0
MARCH	435.0	22.0	-3016.3	9098266.8	-3051.5	9311652.3	9204341.2	-413.0	170569.0	413.0
APRIL	454.0	24.0	-2997.3	8984007.1	-3049.5	9299450.3	9140368.0	-430.0	184900.0	430.0
MAY	1100.0	72.0	-2351.3	5528768.4	-3001.5	9009002.3	7057527.0	-1028.0	1056784.0	1028.0
JUNE	1760.0	1412.0	-1691.3	2860608.4	-1661.5	2760582.3	2810150.3	-348.0	121104.0	348.0
JULY	6110.0	5130.0	2658.7	7068508.4	2056.5	4229192.3	5467548.0	-980.0	960400.0	980.0
AUGUST	15600.0	14790.0	12148.7	147590101.8	11716.5	137276372.3	142339853.0	-810.0	656100.0	810.0
SEPTEMBER	12300.0	12586.0	8848.7	78298901.8	9512.5	90487656.3	84172941.7	286.0	81796.0	-286.0
OCTOBER	2260.0	2596.0	-1191.3	1419275.1	-477.5	228006.3	568861.7	336.0	112896.0	-336.0
NOVEMBER	436.0	130.0	-3015.3	9092235.1	-2943.5	8664192.3	8875633.7	-306.0	93636.0	306.0
DECEMBER	337.0	46.0	-3114.3	9699072.1	-3027.5	9165756.3	9428644.2	-291.0	84681.0	291.0
Total	**41416.0**	**36882.0**	**0.0**	**299350622.7**	**0.0**	**298872977.0**	**298131190.0**	**-4534.0**	**3674316.0**	**4534.0**
Mean	**3451.3**	**3073.5**								
			$R^2=\left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})(Q_{sim,i}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i}-\bar{Q}_{sim})^2}}\right]^2$		**0.993**		$CE=1-\frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\bar{Q}_{obs,i})^2}*100\%$		**98.8**	
			$VE=\frac{\sum_{i=1}^{n}(Q_{sim,i}-Q_{obs,i})}{\sum_{i=1}^{n}Q_{obs,i}}*100\%$		**12.3**		$PE=\frac{\sum_{i=1}^{m}(Q_{sim,p,i}-Q_{obs,p,i})}{\sum_{i=1}^{n}Q_{obs,p,i}}*100\%$		**2.2**	

Figure 4.16 shows the comparison of simulated and measured streamflow of River Sokoto (second part), which is the final section of the SRRB drainage system that link the basin to River Niger. The visual evaluation of the graph indicates similar pattern. While, Table 4.8 shows the calculation of the objective functions for efficiency parameters of River Sokoto (second part) streamflow simulation. The values obtained for R^2, CE, *VE*, and *PE* are 0.99, 98.8%, 12.3% and 2.2% respectively.

The summary of the efficiency parameter values for all rivers are shown in Table 4.9.

Table 4.9: Summary of Efficiency Parameters for all Rivers

RIVER	Coefficient of Determination (R^2)	Nash-Sutcliffe Coefficient of Efficiency (CE)	Percentage Error in Total Runoff Volume (VE)	Percentage Error in Peak Discharge (PE)
Bunsuru	0.99	97.3%	6.0%	3.5%
Gagere	0.94	89.7%	-25.3%	-0.4%
Rima	0.93	84.4%	24.4%	6.4%
Sokoto (first part)	0.99	95.0%	25.0%	6.6%
Zamfara	0.99	96.1%	24.2%	1.1%
Ka	0.94	78.0%	52.6%	2.1%
Sokoto (second part)	0.99	98.8%	12.3%	2.2%

The model objective functions for efficiency parameters the average coefficient of determination (R^2) of 0.94, Nash-Sutcliffe coefficient of efficiency (CE) of 0.73, percentage error in total runoff volume (VE) around 19% and percentage error in peak discharge (PE) of around 17%.

4.6 Impact of Climate Change on Water availability

Based on the simulation and comparison of the sreamflow within the basin for the reference scenario and scenarios 1 to 6, it was observed that the effect of the climate change is not uniform. The difference in water availability from the scenarios depends on the section of the stream observed as shown in Figure 4.19, which shows the difference in volume of available water at different section of the basin as indicated on the x-axis. The reference scenario and the Scenario 1 and 4 have almost the same value with only slight difference indicating the water loss by evaporation and evapotranspiration due to increase in temperature by 0.5^0C and 1.0^0C for scenario 2 and 4 respectively, similarly for scenario 2 and 5, and scenario 3 and 6. The difference in water volume from the reference scenario to the worst scenario (scenario 6) at River Bunsuru is not much but on reaching the River Rima the difference is around 347.1 MCM, indicating a reduction of 8.9 MCM of water annually While the difference at River Sokoto is 66.3 BCM under the same period, indicating a reduction of 1.70BCM of water from the annual flow in that river, as shown in Figure 4.17, while other rivers have less than this amount.

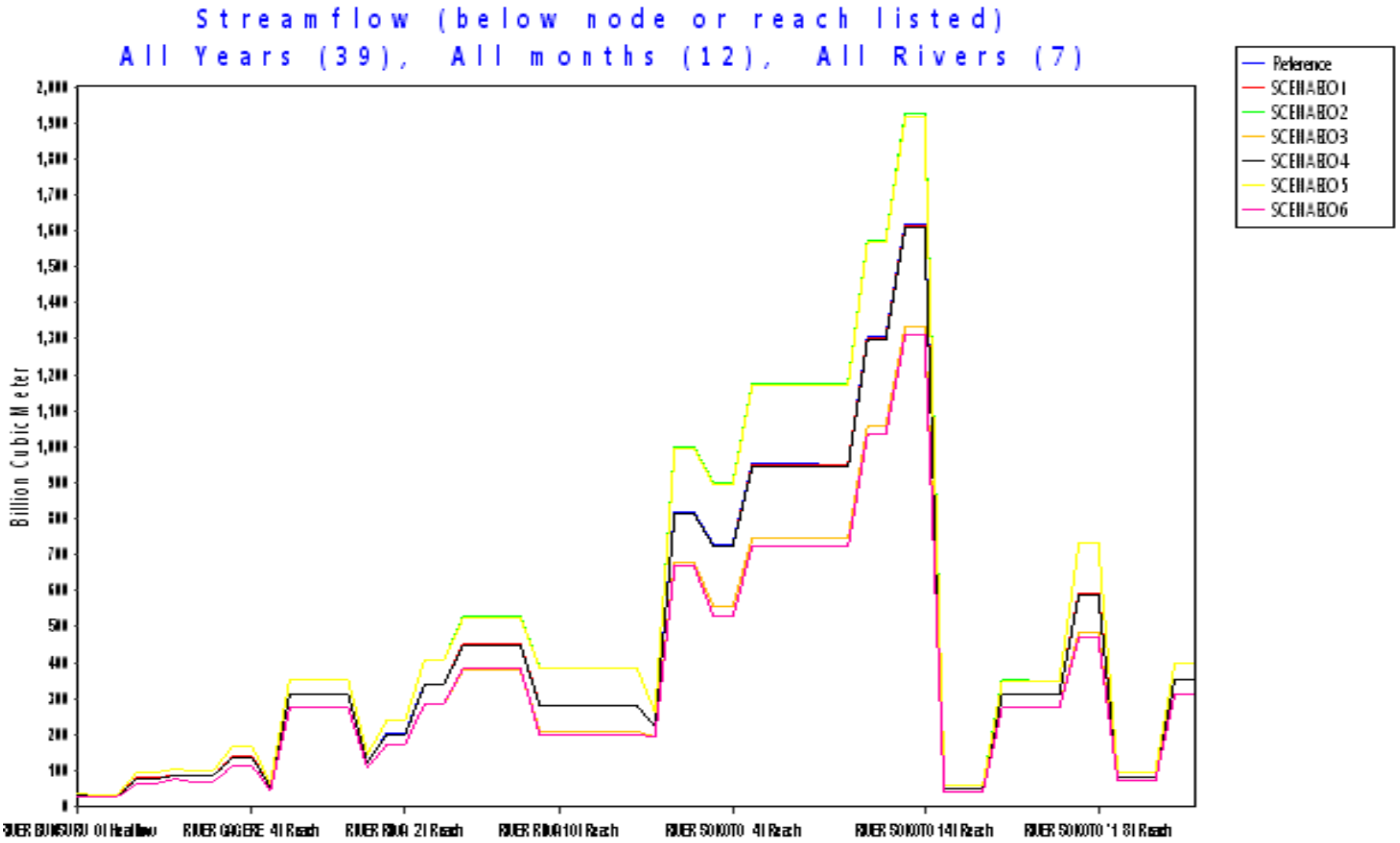


Figure 4.17: Streamflow for the basin

The different amount of water availability based on the simulation due to different prescribed climate scenarios is shown in Table 4.10. The reference scenario shows an average total available water of 83.8BCM in the basin. While the highest average available volume of 97.16BCM is from scenario 2. The maximum available water to the basin under worst scenario of $1^{o}C$ increase in temperature and 10% decrease in precipitation (i.e. scenario 6) is 64.4BCM.

Table 4.10: Effect of different climate scenarios to water availability for all rivers

Amount of Water Available in MCM							
	Reference	Scenario 1 $+0.5^{0}C$	Scenario 2 $+0.5^{0}C$, +10%P	Scenario 3 $+0.5^{0}C$, -10%P	Scenario 4 $+1.0^{0}C$,	Scenario 5 $+1.0^{0}C$, +10%P	Scenario 6 $+1.0^{0}C$, -10%P
Min	10958.9	10958.9	12545.1	4405.2	10958.9	12220.3	4405.2
Max	83768.1	83477.5	97164.4	64836.9	83190.6	95803.1	64414.4

The available flow in every node and reach for River Bunsuru is shown in Table 4.11. The maximum average volume of water from the catchment of this river is 51.21MCM, with the minimum of 29.24MCM and the mean of 40.71MCM; while the maximum average volume of water at headflow of this river is 15.15MCM, with the minimum of 11.44 MCM and the mean of 13.21MCM.

Table 4.11: Effect of different climate scenarios to water availability on average streamflow at River Bunsuru

All Scenarios, All River Bunsuru Nodes and Reaches , All Years (44), All months (12) (Million Cubic Meter)					
	River Bunsuru 0 \ Headflow	River Bunsuru 1 \ Withdrawal Node 11	River Bunsuru 2 \ Reach	River Bunsuru 3 \ Catchment Inflow Node 1	River Bunsuru 4 \ Reach
Reference	13.23	11.37	11.37	41.93	41.93
Scenario 1	13.23	11.37	11.37	41.53	41.53
Scenario 2	15.15	13.02	13.02	51.21	51.21
Scenario 3	11.44	4.41	4.41	29.56	29.56
Scenario 4	13.23	11.37	11.37	41.14	41.14
Scenario 5	14.76	12.68	12.68	50.37	50.37
Scenario 6	11.44	4.41	4.41	29.24	29.24

The available flow in every node and reach for River Gagere is shown in Table 4.12. The maximum average volume of water from the catchment of this river is 111.33MCM, with the minimum of 71.19MCM and the mean of 91.23MCM; while the maximum average volume of water at headflow of this river is 42.88MCM, with the minimum of 32.38MCM and the mean of 37.40MCM.

Table 4.12: Effect of different climate scenarios to water availability on average streamflow at River Gagere

All Scenarios, All River Gagere Nodes and Reaches, All Years (44), All months (12) (Million Cubic Meter)					
	River Gagere 0 \ Headflow	River Gagere 1 \ Withdrawal Node 10	River Gagere 2 \ Reach	River Gagere 3 \ Catchment Inflow Node 2	River Gagere 4 \ Reach
Reference	37.46	35.29	35.29	92.19	92.19
Scenario 1	37.46	35.32	35.32	91.61	91.61
Scenario 2	42.88	40.26	40.26	111.33	111.33
Scenario 3	32.38	26.33	26.33	71.64	71.64
Scenario 4	37.46	35.35	35.35	91.05	91.05
Scenario 5	41.77	39.25	39.25	109.57	109.57
Scenario 6	32.38	26.40	26.40	71.19	71.19

The available flow in every node and reach for River Ka is shown in Table 4.13 below. The maximum average volume of water from the catchment of this river is 348.89MCM, with the minimum of 273.25MCM and the mean of 311.03MCM

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Table 4.13: Effect of different climate scenarios to water availability on average streamflow (below node or reach listed) at River Ka.

All Scenarios, All River Ka Nodes and Reaches, All Years (44), All months (12) (Million Cubic Meter)					
	River Ka 0 \ Headflow	River Ka 1 \ Catchment Inflow Node 5	River Ka 2 \ Reach	River Ka 3 \ Withdrawal Node 7	River Ka 4 \ Reach
Reference	22.87	311.89	311.89	311.82	311.82
Scenario 1	22.87	311.22	311.22	311.15	311.15
Scenario 2	26.18	348.89	348.89	348.82	348.82
Scenario 3	19.77	273.91	273.91	273.84	273.84
Scenario 4	22.87	310.55	310.55	310.48	310.48
Scenario 5	25.50	347.53	347.53	347.47	347.47
Scenario 6	19.77	273.25	273.25	273.18	273.18

The available flow in every node and reach for River Rima is shown in Table 4.14.The maximum average volume of water from the catchment of this river is 332.96 MCM, with the minimum of 244.38MCM and the mean of 283.82MCM; while the maximum average volume of water along the reach of this river is 110.49MCM, with the minimum of 74.01MCM and the mean of 92.41 MCM.

The available flow in every node and reach for first part of River Sokoto is shown in Table 4.15. The maximum average volume of water from the catchment of this river is 340.28MCM, with the minimum of 269.11MCM and the mean of 304.53MCM; while the maximum average volume of water at the headflow of this river is 12.55MCM, with the minimum of 9.48MCM and the mean of 10.95MCM.

Table 4.14: Effect of different climate scenarios to water availability on average streamflow (below node or reach listed) at River Rima

All Scenarios, All RIVER RIMA Nodes and Reaches, All Years (44), All months (12) (Million Cubic Meter)															
	River Rima 0 \ Headflow	River Rima 1 \ River Bun Inflow	River Rima 2 \ Reach	River Rima 3 \ River Gagere Inflow	River Rima 4 \ Reach	River Rima 5 \ Catch Inflow Node 6	6 \ Reach 6 \ Reach	7 \ Withdrawal Node 2	8 \ Reach	9 \ Goronyo Dam	10 \ Reach	11 \ Withdrawal Node 5	12 \ Reach	13\ Withdrawal Node 1	14Reach
Reference	51.79	93.72	93.72	185.90	185.90	279.89	279.89	279.84	279.84	158.83	158.83	158.77	158.77	158.71	158.71
Scenario 1	51.79	93.32	93.32	184.93	184.93	277.53	277.53	277.48	277.48	157.68	157.68	157.62	157.62	157.56	157.56
Scenario 2	59.28	110.49	110.49	221.82	221.82	332.96	332.96	332.89	332.89	219.10	219.10	219.03	219.03	218.95	218.95
Scenario 3	44.77	74.33	74.33	145.97	145.97	247.16	247.16	247.13	247.13	51.72	51.72	51.68	51.68	51.63	51.63
Scenario 4	51.79	92.93	92.93	183.98	183.98	275.25	275.25	275.20	275.20	156.55	156.55	156.50	156.50	156.43	156.43
Scenario 5	57.75	108.12	108.12	217.69	217.69	329.59	329.59	329.53	329.53	207.33	207.33	207.26	207.26	207.18	207.18
Scenario 6	44.77	74.01	74.01	145.21	145.21	244.38	244.38	244.34	244.34	52.55	52.55	52.51	52.51	52.46	52.46

Table 4.15: Effect of different climate scenarios to water availability on average Streamflow (below node or reach listed) at First part of River Sokoto

All Scenarios, All River Sokoto Nodes and Reaches, All Years (44), All months (12) (Billion Cubic Meter)										
	River Sokoto `1 0 \ Headflow	River Sokoto `1 1 \ Withdrawal Node 9	River Sokoto `1 2 \ Reach	River Sokoto `1 3 \ Catchment Inflow Node 3	River Sokoto `1 3 \ Streamflow Gauge at Gusau	River Sokoto `1 4 \ Reach	5 \ Bakolori Dam	6 \ Reach	7 \ River Rima Inflow	8 \ Reach
Reference	10.97	10.96	10.96	304.99	43.28	304.99	304.19	304.19	462.90	462.90
Scenario 1	10.97	10.96	10.96	304.57	43.28	304.57	303.77	303.77	461.33	461.33
Scenario 2	12.55	12.55	12.55	340.28	43.28	340.28	339.48	339.48	558.43	558.43
Scenario 3	9.48	9.47	9.47	269.52	43.28	269.52	268.97	268.97	320.61	320.61
Scenario 4	10.97	10.96	10.96	304.15	43.28	304.15	303.35	303.35	459.78	459.78
Scenario 5	12.23	12.22	12.22	339.10	43.28	339.10	338.30	338.30	545.48	545.48
Scenario 6	9.48	9.47	9.47	269.11	43.28	269.11	268.66	268.66	321.12	321.12

The available flow in every node and reach of River Zamfara is shown in Table 4.16. The maximum average volume of water from the catchment of this river is 378.1MCM, with the minimum of 300.19MCM and the mean of 338.86MCM; while the maximum average volume of water at the headflow and along the reach of this river is 40.15MCM, with the minimum of 30.32MCM and the mean of 35.02MCM.

Table 4.16: Effect of different climate scenarios to water availability on average streamflow (below node or reach listed)at River Zamfara

All Scenarios, All River Zamfara Nodes and Reaches, All Years (44), All months (12) (Billion Cubic Meter)					
	River Zamfara 0 \ Headflow	River Zamfara 1 \ Withdrawal Node 8	River Zamfara 2 \ Reach	River Zamfara 3 \ Catchment Inflow Node 4	River Zamfara 4 \ Reach
reference	35.07	35.07	35.07	339.27	339.27
scenario 1	35.07	35.07	35.07	338.94	338.94
scenario 2	40.15	40.15	40.15	378.10	378.10
scenario 3	30.32	30.32	30.32	300.52	300.52
scenario 4	35.07	35.07	35.07	338.60	338.60
scenario 5	39.11	39.11	39.11	376.38	376.38
scenario 6	30.32	30.32	30.32	300.19	300.19

The available flow in every node and reach of second part of River Sokoto is shown in Table 4.17. The maximum average volume of water from the catchment of this river is 828.33MCM, with the minimum of 457.88MCM and the mean of 652.86MCM; while the maximum average volume of water at the headflow of this river is 74.44MCM, with the minimum of 56.22MCM and the mean of 64.93MCM.

Table 4.17: Effect of different climate scenarios to water availability on average streamflow (below node or reach listed) at second part of River Sokoto

All Scenarios, All River Sokoto 2 Nodes and Reaches, All Years (44), All months (12) (Million Cubic Meter)															
	0 \ Headflow	1 \ River Sokoto `1 Inflow	2 \ Reach	3 \ Withdrawal Node 6	4 \ Reach	5 \ Catchment Inflow Node 7	6 \ Reach	7 \ Withdrawal Node 3	8 \ Reach	9 \ Withdrawal Node 4	10 \ Reach	11 \ River Zamfara Inflow	12 \ Reach	13 \ River Ka Inflow	14 Rea
Reference	65.03	527.93	527.93	436.66	436.66	673.82	673.82	673.55	673.55	673.19	673.19	1,012.47	1,012.47	1,324.29	1,32
Scenario 1	65.03	526.36	526.36	435.25	435.25	670.17	670.17	669.90	669.90	669.55	669.55	1,008.48	1,008.48	1,319.64	1,31
Scenario 2	74.44	632.87	632.87	530.74	530.74	828.33	828.33	828.06	828.06	827.70	827.70	1,205.80	1,205.80	1,554.63	1,55
Scenario 3	56.22	376.83	376.83	274.81	274.81	463.65	463.65	463.38	463.38	463.03	463.03	763.54	763.54	1,037.39	1,03
Scenario 4	65.03	524.82	524.82	433.86	433.86	666.58	666.58	666.32	666.32	665.96	665.96	1,004.56	1,004.56	1,315.05	1,31
Scenario 5	72.52	618.00	618.00	517.80	517.80	809.62	809.62	809.36	809.36	809.00	809.00	1,185.38	1,185.38	1,532.85	1,53
Scenario 6	56.22	377.34	377.34	268.45	268.45	457.88	457.88	457.61	457.61	457.26	457.26	757.44	757.44	1,030.63	1,03

4.7 Evapotranspiration

Water availability is directly affected by temperature and precipitation changes in the study area as shown in section 4.6. The temperature changes affect the surface water availability by increasing the evaporation and/or evapotranspiration. The monthly average potential evapotranspiration for all catchments within the basin is shown in Figure 4.18.

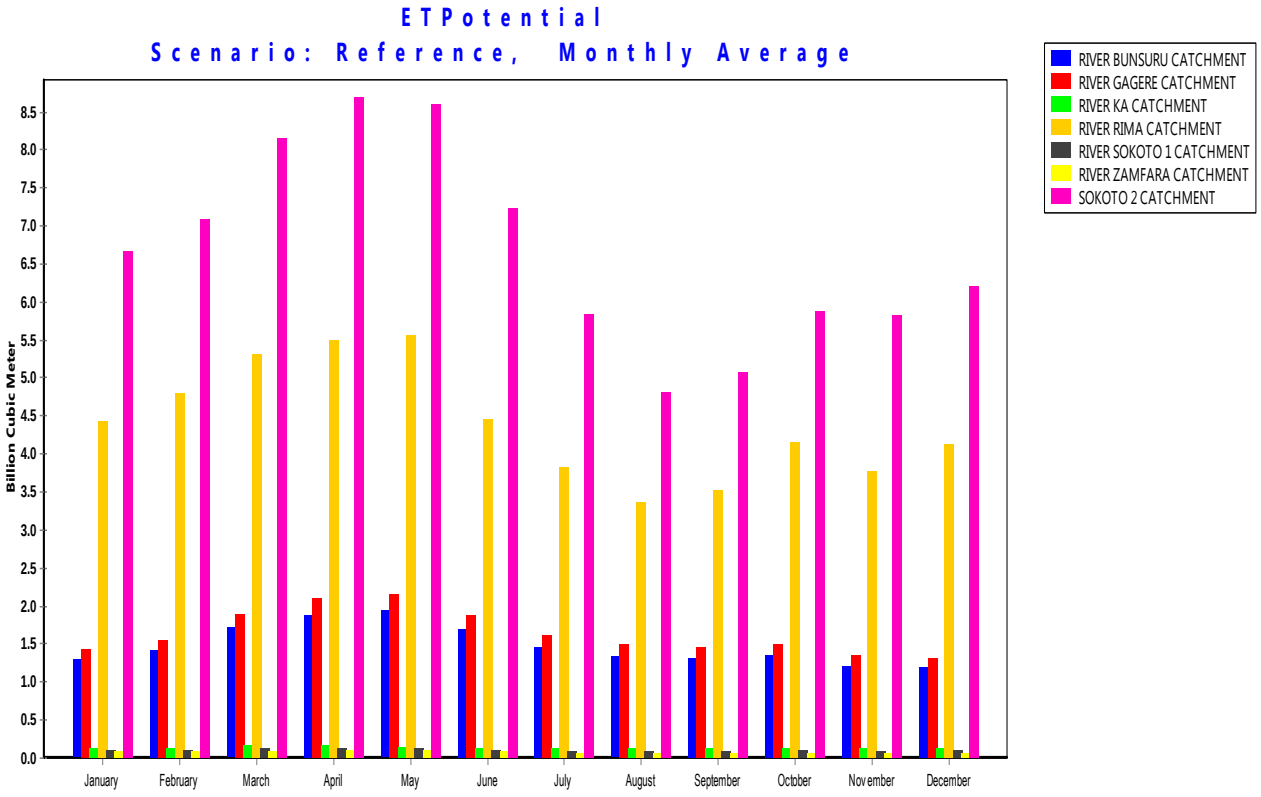


Figure 4.18: Monthly Average PET for Reference scenario

The River Rima catchment and second part of River Sokoto catchment located in the northern part of the basin show higher volume of monthly average potential evapotranspiration and actual evapotranspiration (Figure 4.19) compared with the other catchments under reference scenario and for all other scenarios (Figure 4.20).

River Zamfara and River Ka catchments appear to have lower actual evapotranspiration, probably due to their location in the southern part of the basin close to guinea savannah region.

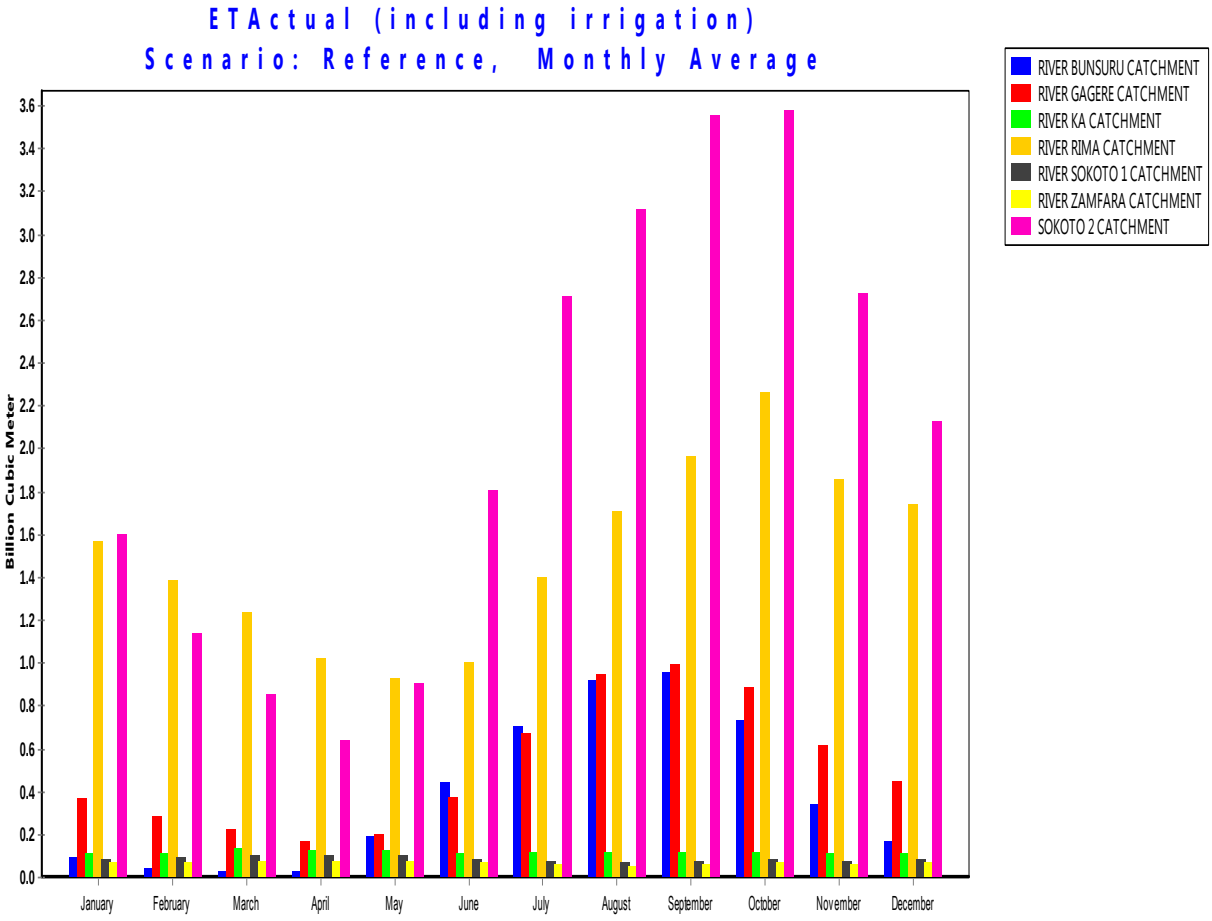


Figure 4.19: Actual ET for all catchments under reference scenarios.

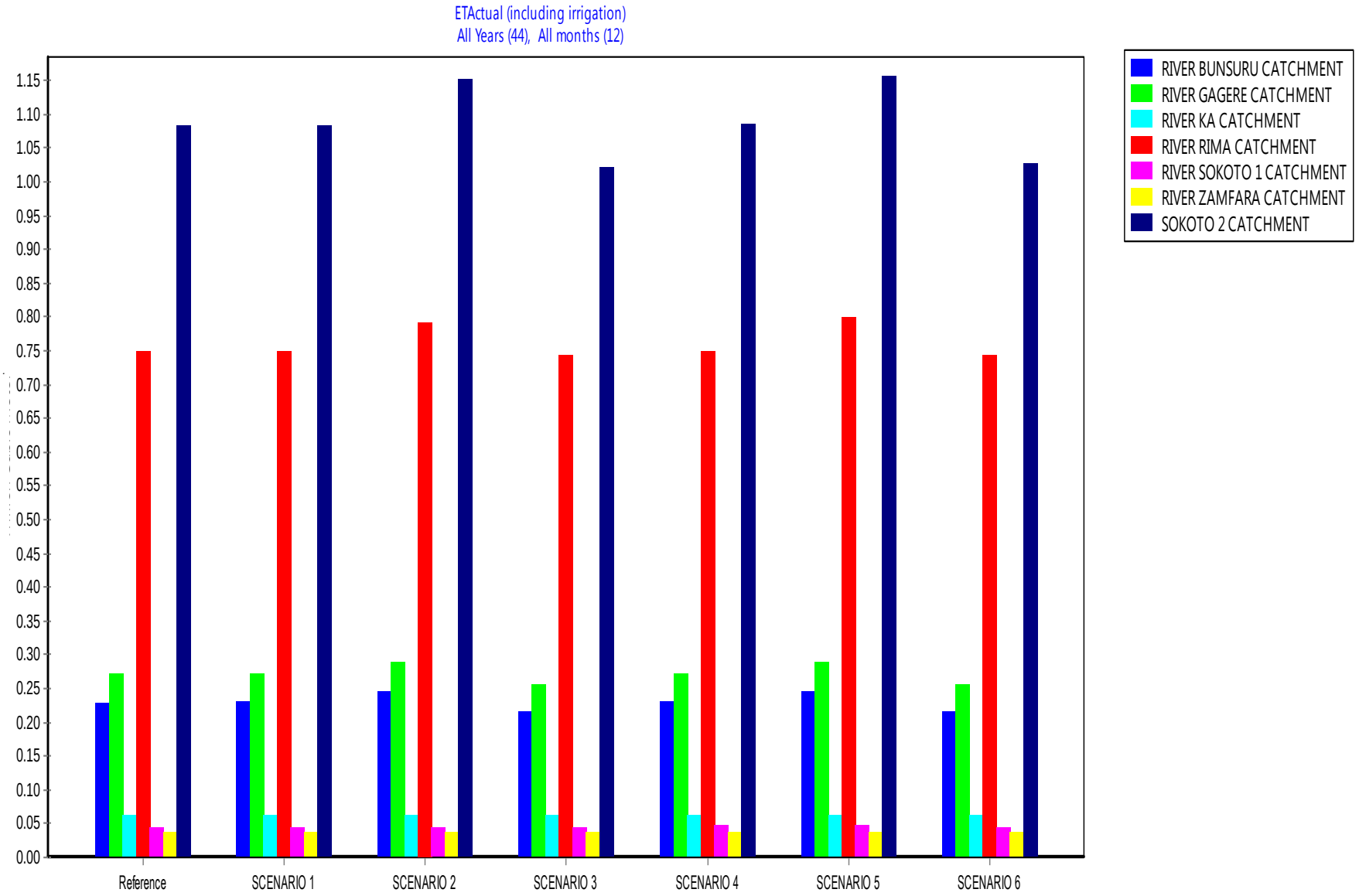


Figure 4.20: Actual ET for all catchments under all scenarios.

4.8 Demand Sites

The average annual domestic water demand of the population of 10,291,799 people living within the basin according to 1990 census of the states in the basin, was 450.84million cubic metres (MCM). While the 2006 census indicated that the population of the basin is 16,039,674 people. The monthly average domestic water demand for this population is 702.50million cubic metres. However, projecting the population to 2064 reveal that the present population of the basin will be 20,492,825 and their annual domestic water demand will be 897.60million cubic metres. The monthly average water demand for the selectected sites in the whole basin under reference scenario or actual situation is shown in Figure 4.21.

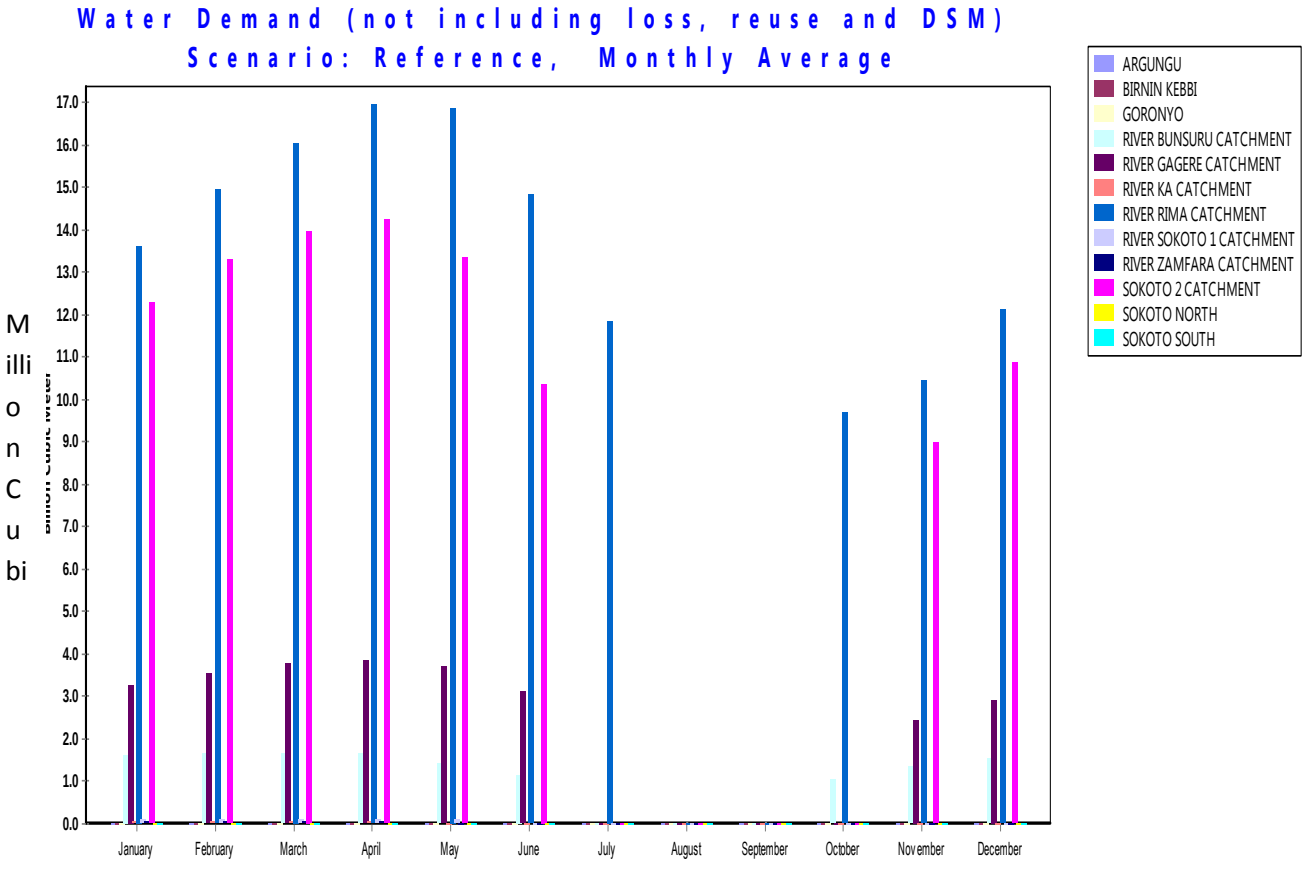


Figure 4.21: Monthly Average Water Demand for reference scenario

The monthly average water demand for different scenarios is shown in Figure 4.22. The demand varies for different months, but the months of August and September indicates very low average monthly demand.

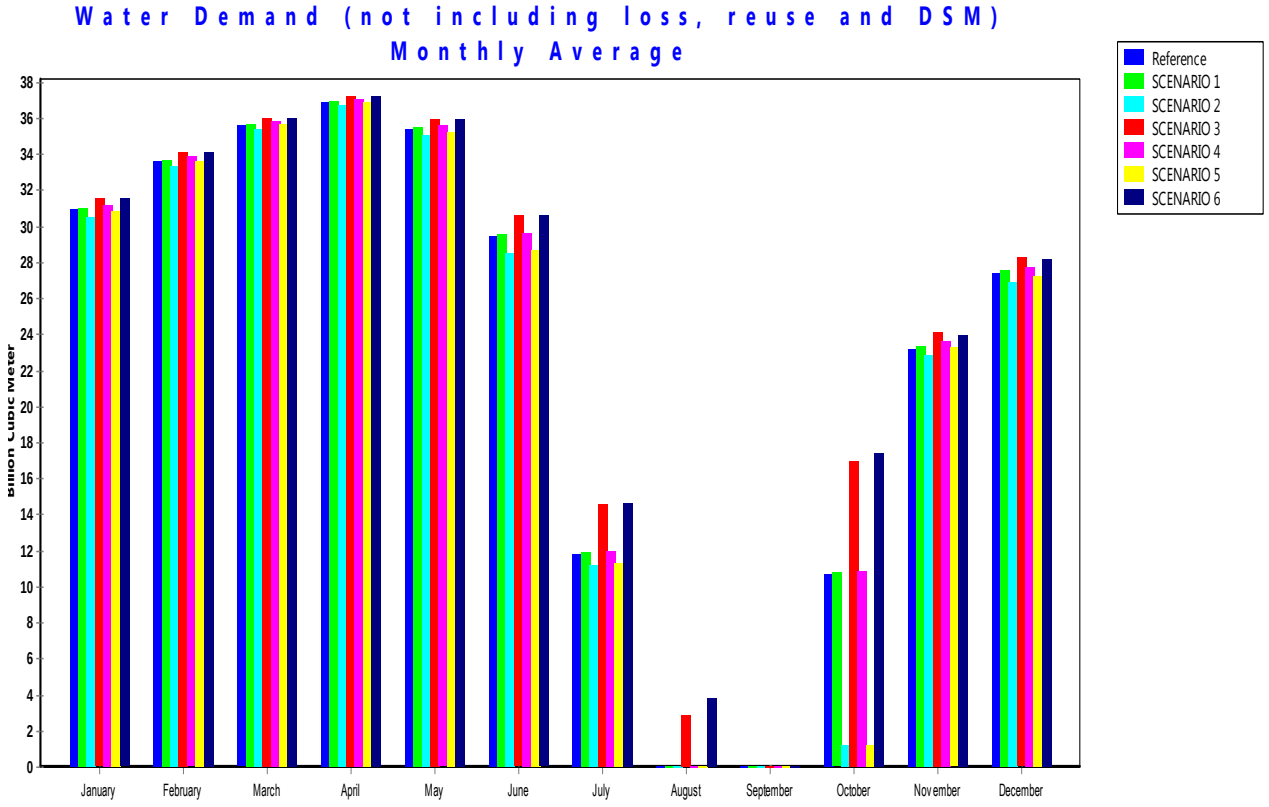


Figure 4.22: Monthly Average Water Demand for all scenarios

4.9 Reliability of selected demand sites on Water Availability

The demand site reliability of the available water for the selected sites is shown in Figure 4.23 and Table 4.18. It depicts the projected water availability reliability under all scenarios due to the impact of climate change. Some sites like Argungu, Birnin-kebbi, and River Zamfara catchment have 100% reliability under all scenarios, while for some sites like Goronyo, River Rima catchment and Sokoto the reliability ranges from 15% to 25%.

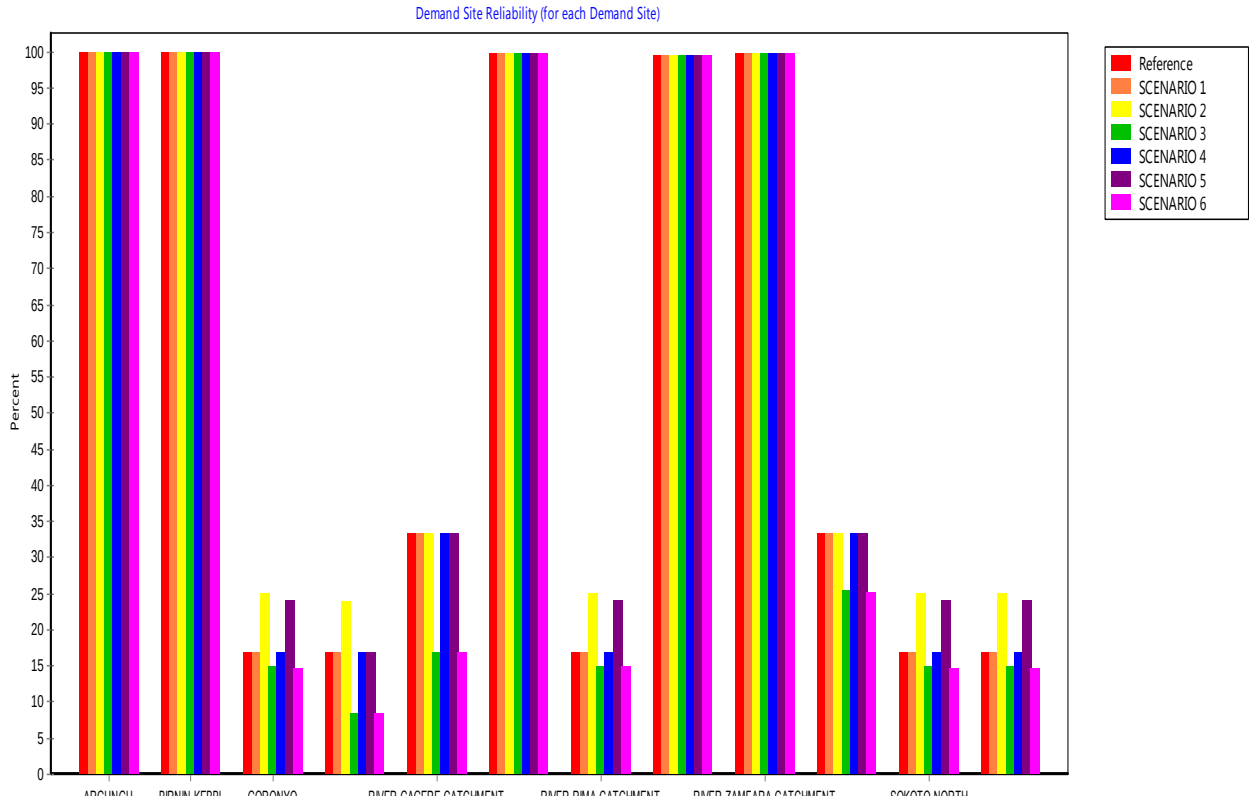


Figure 4.23: Demand sites Reliability for all scenarios.

Table 4.18: Some Selected Sites Demand Reliability for all Scenarios in percentage (%)

	Goronyo	River Bunsuru Catch.	River Gagere Catch.	River Ka Catch.	River Rima Catch.	Sokoto 2 Catch.	Sokoto South
Ref	16.67	16.67	33.33	99.24	16.67	33.33	16.67
Scen 1	16.67	16.67	33.33	99.24	16.67	33.33	16.67
Scen 2	22.54	16.67	33.33	99.24	22.54	33.33	22.54
Scen 3	8.52	8.52	17.05	99.24	8.52	27.08	8.52
Scen 4	16.67	16.67	33.33	99.24	16.67	33.33	16.67
Scen 5	19.90	16.67	33.33	99.24	19.90	33.33	19.90
Scen6	8.52	8.52	17.05	99.24	8.52	25.19	8.52
Min	8.52	8.52	17.05	99.24	8.52	25.19	8.52
Max	22.54	16.67	33.33	99.24	22.54	33.33	22.54

4.10 Comparison of Scenarios on Water Availability

The streamflow for each node and reach in the whole basin is shown in Figure 4.24. Scenario 2 and scenario 5 indicates higher volume of available water within the basin, while the reference scenario, scenarios 1 and 4 appear to have the same volume. Scenarios 3 and 6 have lower volume than all the other scenarios.

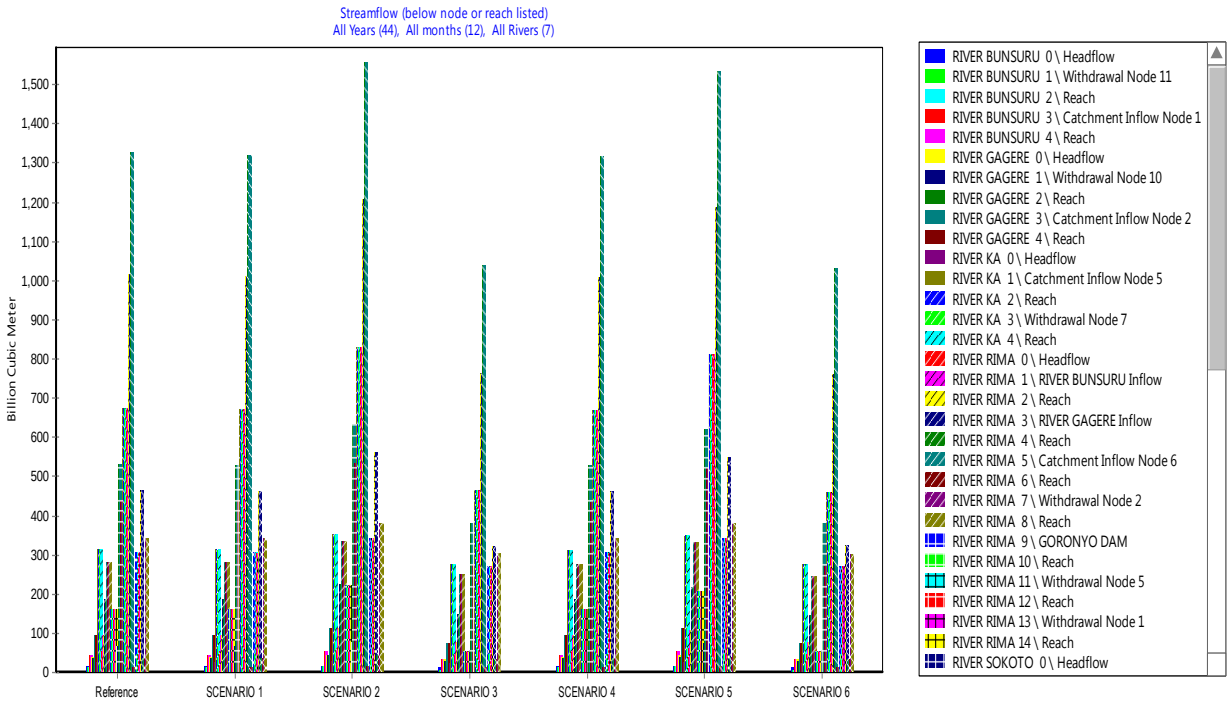


Figure 4.24: Streamflow of rivers for all scenarios.

The reference scenario was compared with all the other scenarios as shown in Figure 4.25. Table 4.19 gives the minimum and maximum monthly average volume as the summary of each scenario difference with the reference scenario shown in Figure 4.26. Scenarios 2 and 4 shows very small negative volume indicating the difference between the reference scenario and the decrease in volume that occur under 0.5^{o}C and 1.0^{o}C rise in temperature in the region respectively. Scenarios3 and 5 depict higher positive volume due to the 10% increase in

precipitation, while, scenarios 3 and 6 depict higher negative volume due to 10% reduction in precipitation.

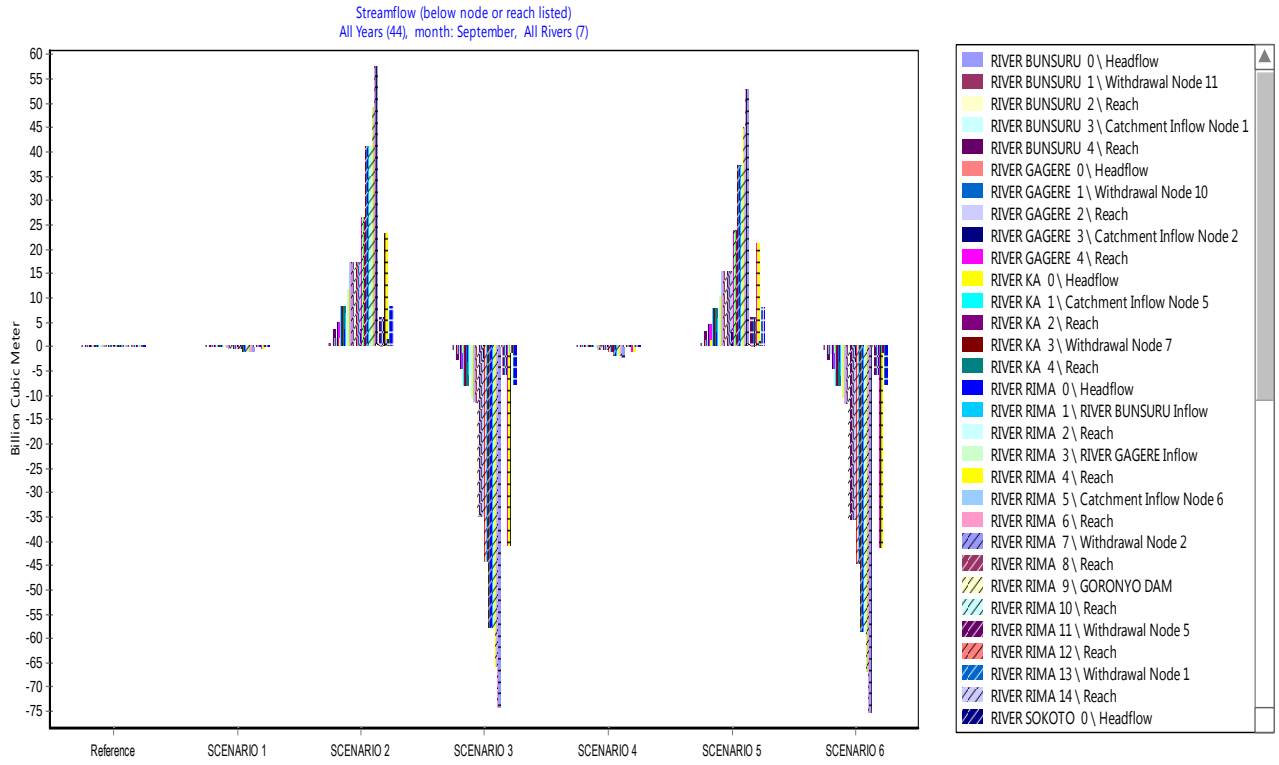


Figure 4.25: Streamflow of rivers for all scenarios compared with reference scenario.

Table 4.19: Streamflow from rivers for all scenarios compared with reference scenario.

All Nodes and Reaches, All Rivers (7), All Years (1970 to 2013), All months (12) (Million Cubic Meter)							
	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Min	0	-388	0	-23,909	-770	0	-24,472
Max	0	3	19,195	0	6	17,380	0

Graphical comparison of all other scenarios with scenario 1 is shown in Figure 4.26 and Table 4.20 gives the summary of minimum and maximum monthly average volume of each scenario difference with the scenario 1. Scenarios 2 and 5 show higher positive volume due to the 10% increase in precipitation over that scenario. The reference Scenario and scenario 4 depict, very small positive and negative volume respectively, indicating the difference between the reference scenario and the decrease in volume that occur under 1.0^{o}C rise in temperature in scenario 4. Scenarios 3 and 6 depict higher negative volume due to 10% reduction in precipitation.

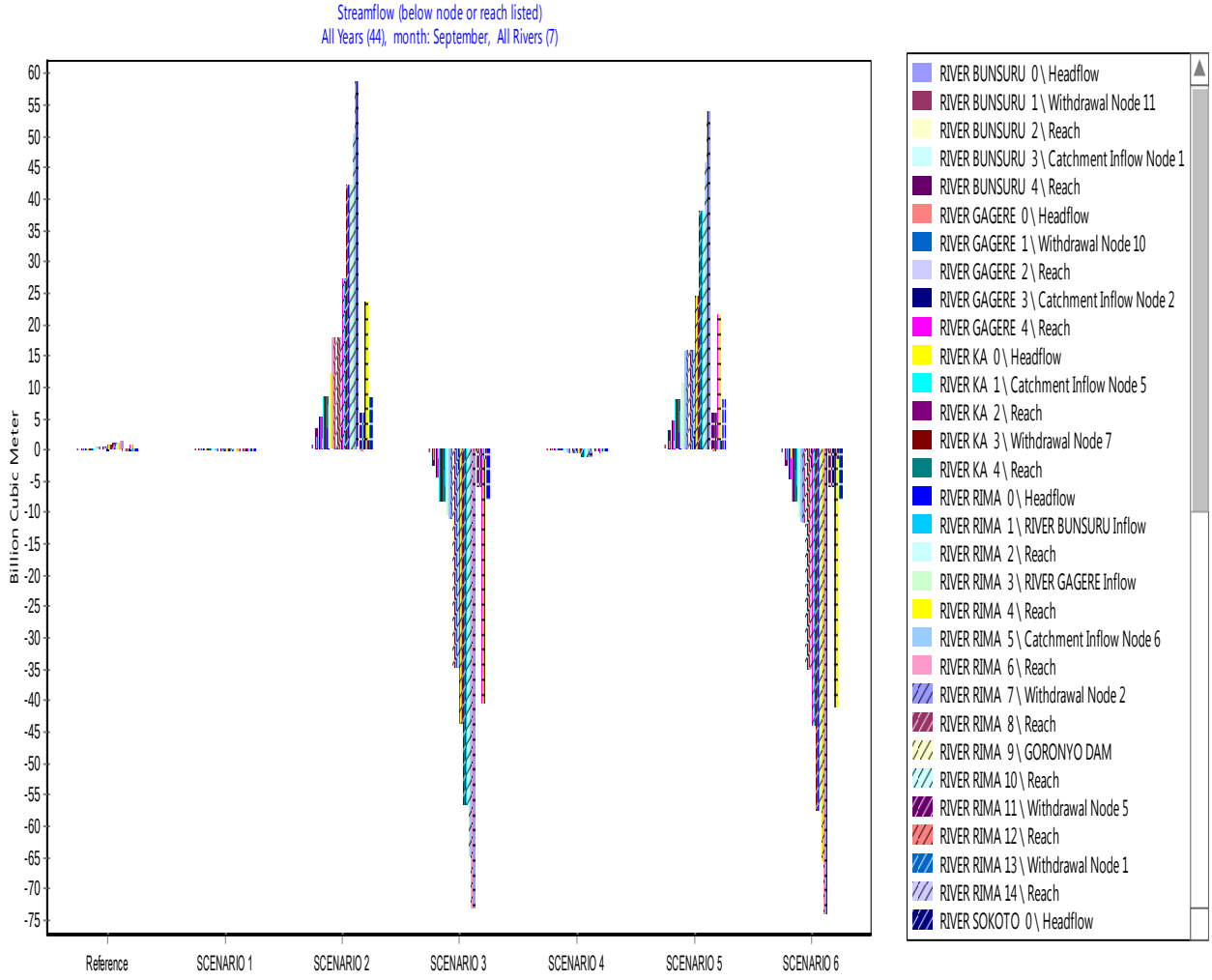


Figure 4.26: Streamflow of rivers for all scenarios compared with scenario 1.

Table 4.20: Summary of Streamflow for all Scenarios Compared with Scenario 1

All Nodes and Reaches, All Rivers (7), All Years (1970 to 2013), All months (12) (Million Cubic Meter)							
	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Min	-3	0	0	-23,521	-383	0	-24,084
Max	388	0	19,582	0	3	17,768	0

The graphical comparison of scenario 2 with all other scenarios is also shown in Figure 4.27 and summarised in Table 4.21. All the scenarios indicate negative volume difference, which shows that scenario 2 influence all other scenarios negatively. If scenario 2 was used as the reference scenario, all other scenarios will show deficit in total available water.

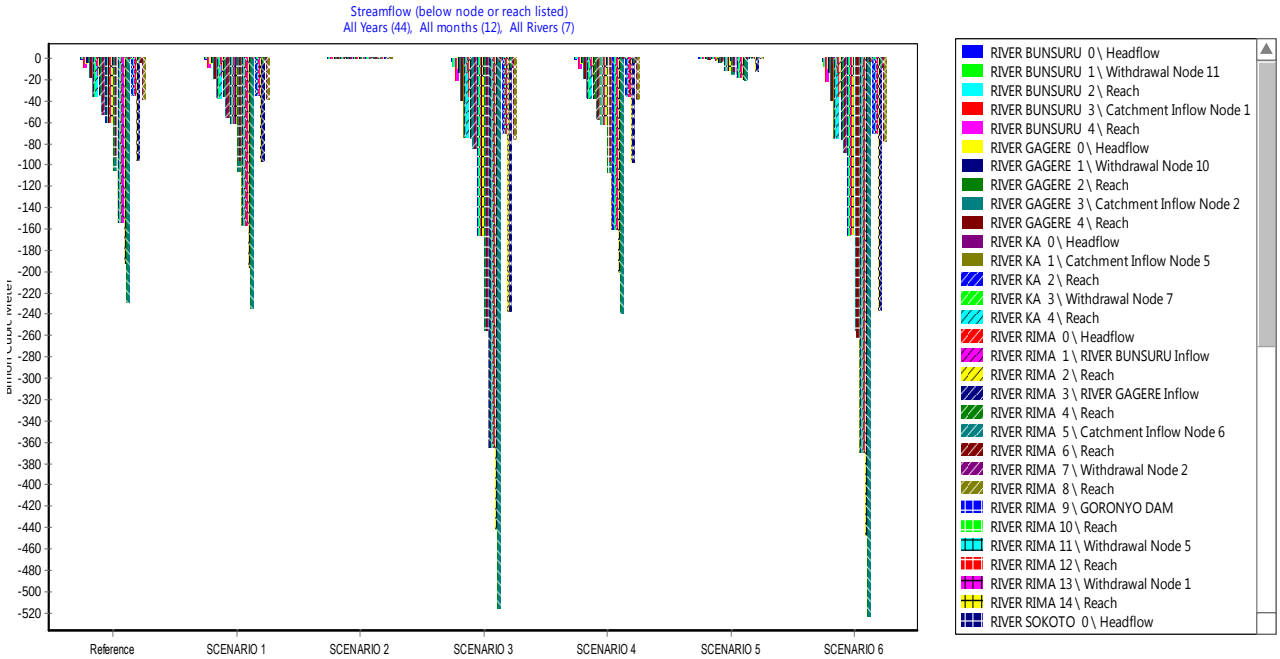


Figure 4.27: Streamflow of rivers for all scenarios compared with scenario 2.

Table 4.21: Summary of Streamflow for all scenarios compared with Scenario 2

All Nodes and Reaches, All Rivers (7), All Years (1970 to 2013), All months (12) (Million Cubic Meter)							
	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Min	-19,195	-19,582	0	-43,103	-19,965	-1,815	-43,667
Max	0	0	0	0	0	0	0

The graphical comparison of scenario 3 with all other scenarios is also shown in Figure 4.28 and summarised in Table 4.22. All the scenarios indicate positive volume difference except scenario 6, which shows that scenario 3 influence all other scenarios positively, but scenario 6 shows deficit in total available water.

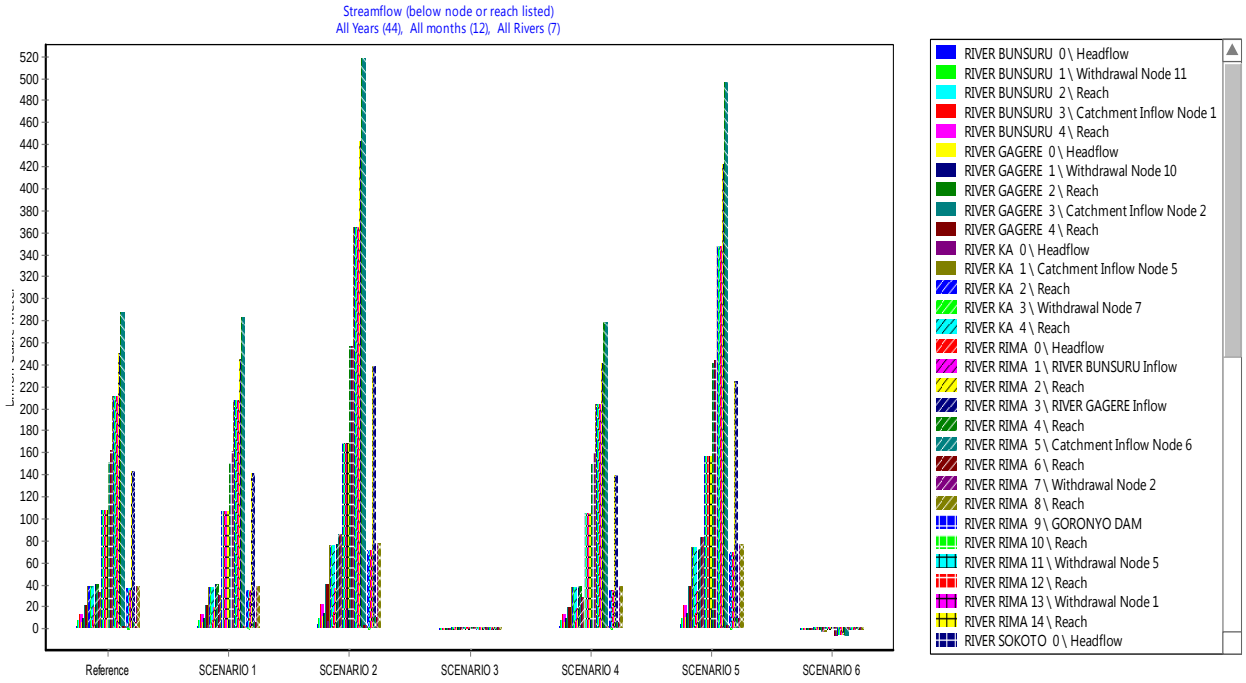


Figure 4.28: Streamflow of rivers for all scenarios compared with scenario 3.

Table 4.22: Summary of Streamflow for all Scenarios Compared with Scenario 3

All Nodes and Reaches, All Rivers (7), All Years (1970 to 2013), All months(12) (Million Cubic Meter)							
	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Min	0	0	0	0	0	0	-563
Max	23,909	23,521	43,103	0	23,139	41,289	69

Comparing scenario 4 with other scenarios shows that (Figure 4.29) Scenarios 3 and 5 depict positive volume due to the 10% increase in precipitation, while, scenarios 3 and 6 depict higher volume due to 10% reduction in precipitation. Reference scenario and Scenario 2 shows very small positive volume indicating the difference between the reference scenario and the decrease in volume that occur under 0.5^{o}C for scenario 2 and scenario 4 that has 1.0^{o}C rise in temperature, as indicated in Table 4.23.

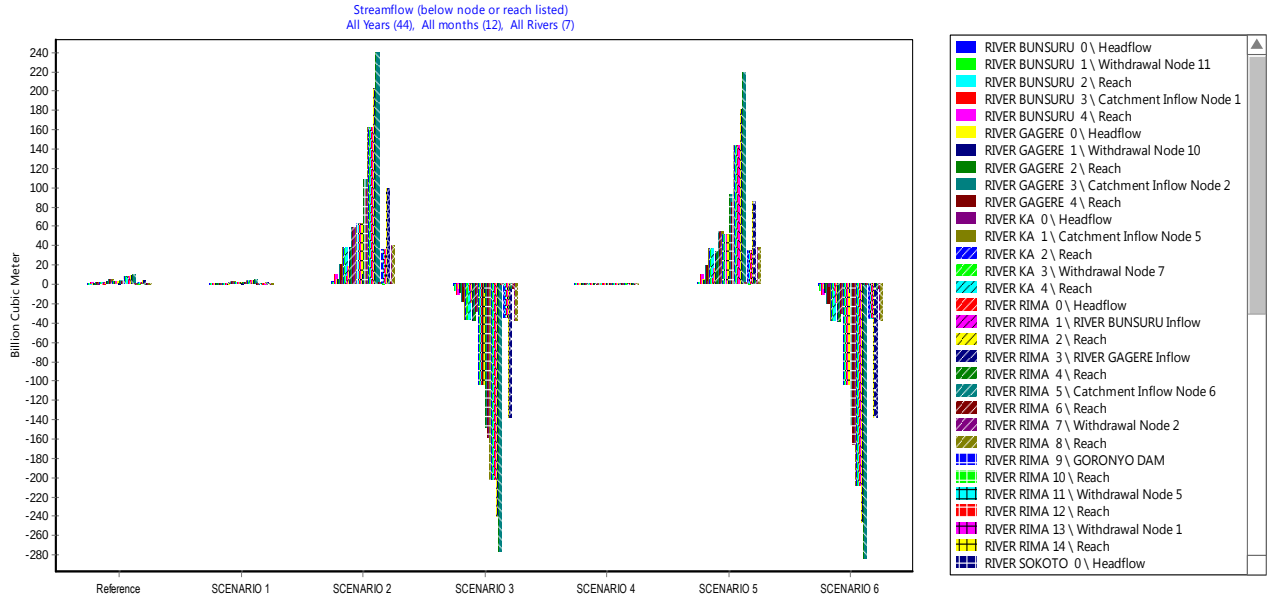


Figure 4.29: Streamflow of rivers for all scenarios compared with scenario 4.

Table 4.23: Summary of Streamflow for all Scenarios Compared with Scenario 4

All Nodes and Reaches, All Rivers (7), All Years (1970 to 2013), All months (12) (Million Cubic Meter)							
	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Min	-6	-3	0	-23,139	0	0	-23,702
Max	770	383	19,965	0	0	18,150	0

The graphical comparison of scenario 5 with all other scenarios is also shown in Figure 4.30 and summarised in Table 4.24. All the scenarios indicate negative volume difference except scenario 2, which shows that scenario 5 influence all other scenarios negatively, but scenario 2 shows increase in total available water.

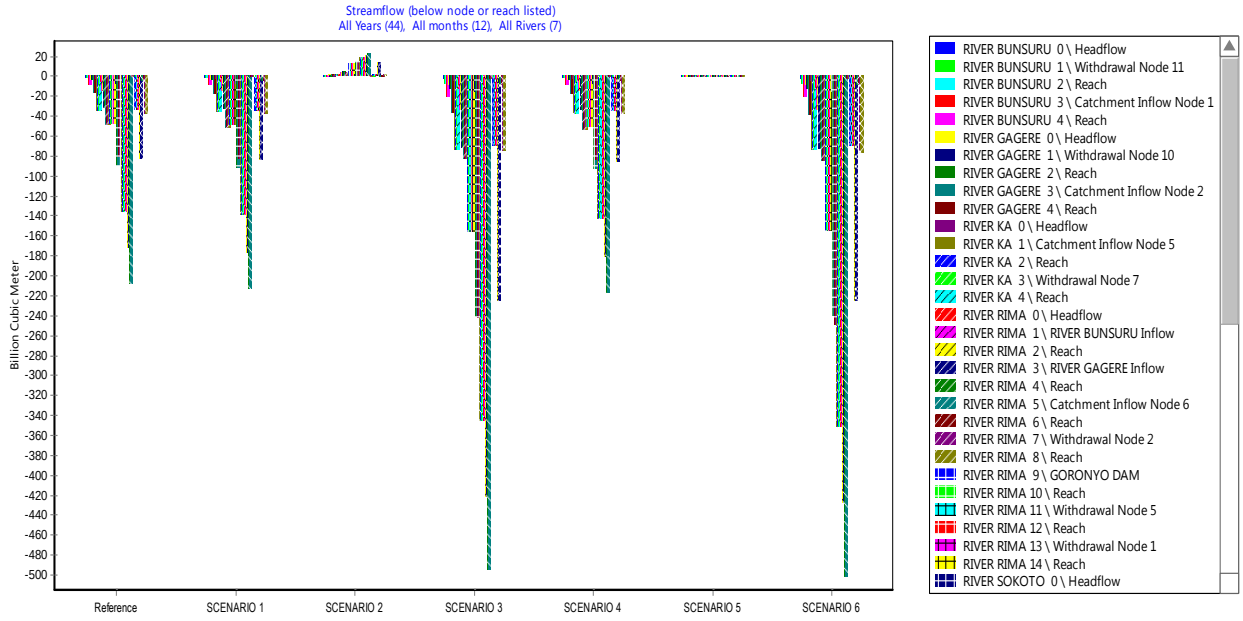


Figure 4.30: Streamflow of rivers for all scenarios compared with scenario 5.

Table 4.24: Summary of Streamflow for all Scenarios Compared with Scenario 5

All Nodes and Reaches, All Rivers (7), All Years (1970 to 2013), All months (12) (Million Cubic Meter)							
	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Min	-17,380	-17,768	0	-41,289	-18,150	0	-41,852
Max	0	0	1,815	0	0	0	0

The graphical comparison of scenario 6 with all other scenarios is also shown in Figure 4.31 and summarised in Table 4.25. All the scenarios indicate positive volume difference, which shows that scenario 6 influence all other scenarios positively. If scenario 6is used as the reference scenario, all other scenarios show increase in total available water.

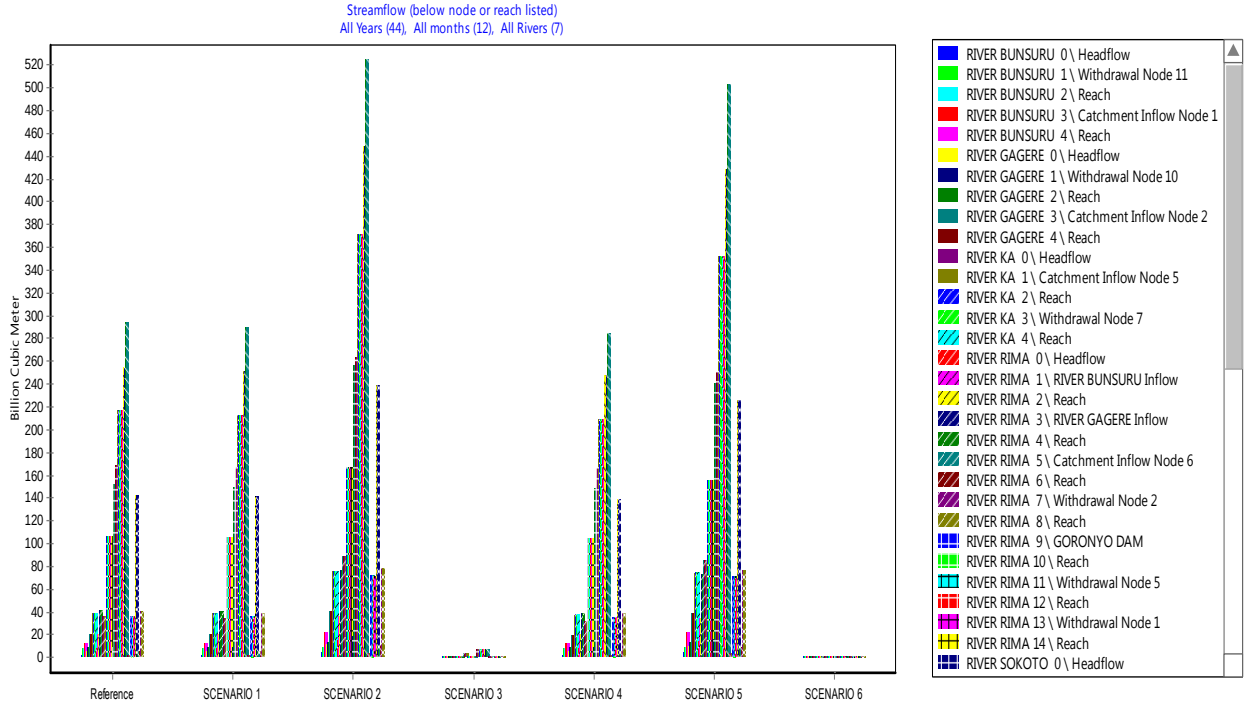


Figure 4.31: Streamflow of rivers for all scenarios compared with scenario 6.

Table 4.25: Summary of Streamflow for all Scenarios Compared with Scenario 6

All Nodes and Reaches, All Rivers (7), All Years (1970 to 2013), All months (12) (Million Cubic Meter)							
	reference	scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	scenario 6
Min	0	0	0	-69	0	0	0
Max	24,472	24,084	43,667	563	23,702	41,852	0

4.11 Modelling the Future Hydrology

The impact of climate change on future availability of surface water to meet the demand obligations was assessed for the SRRB using the seven scenario based climate dataset. Taking into consideration of the model errors, the situation was projected into the future, up to the year 2064, which is 50 years from the year 2014. The results indicate similar trend of climate change with the previous outcome as shown in Figure 4.32. It indicates higher future stream flows for the two scenarios (scenario 2 and 5) that have 10% increases in precipitation. The magnitude of peak maximum monthly stream flow increases relative to observed maximum monthly stream flow (year 1970 – 2008) for the two scenarios.

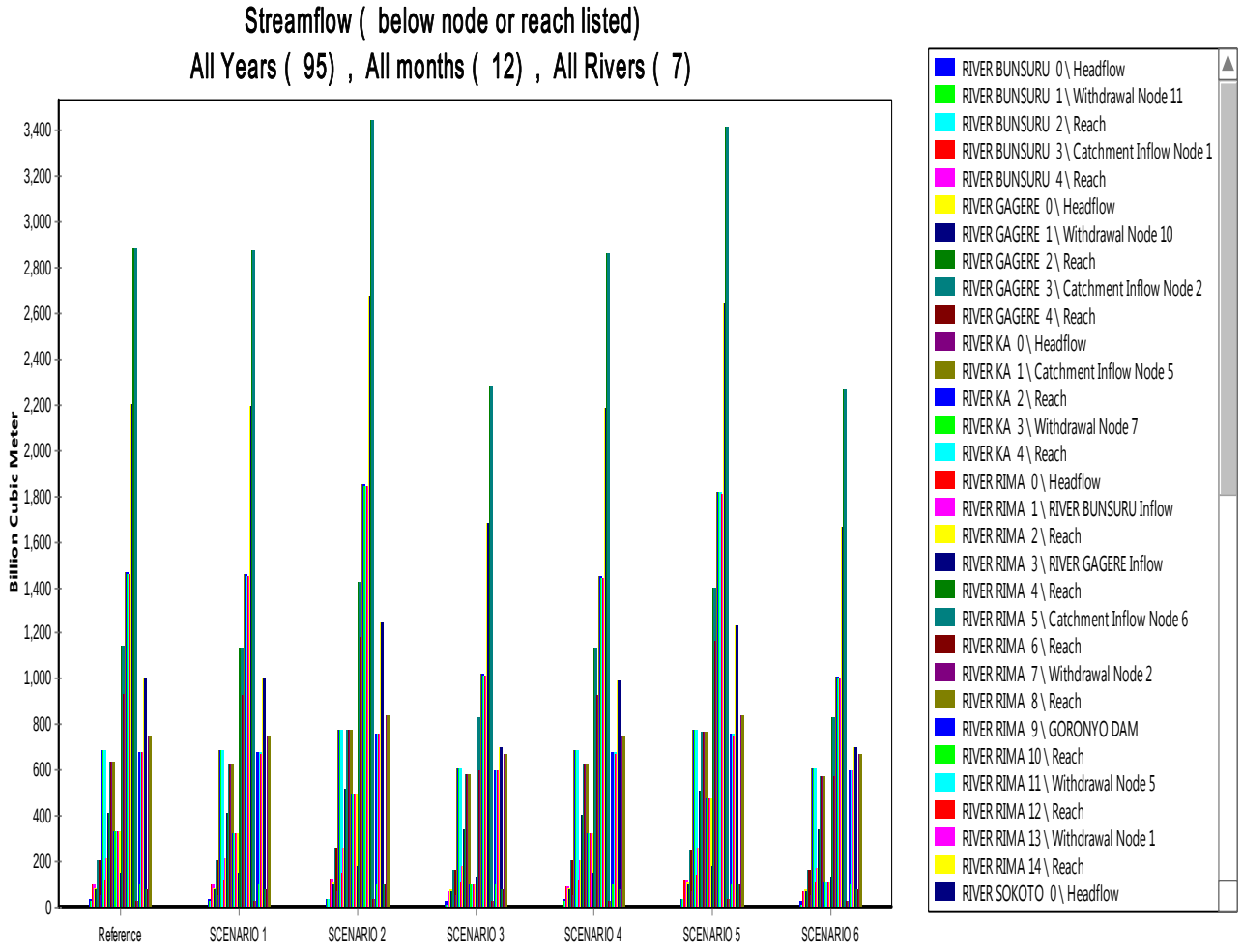


Figure 4.32: Streamflow of rivers for all scenarios projected to 2064.

The existing storage infrastructure indicates ability to buffer the deficits in meeting water demand in the basin for the future. However, the basin requires increase in storage infrastructure and improvement on using new technology in water conservation and storage.

The major domestic water demand from some selected sites in the basin was projected, as shown in Figure 4.33 indicating that the demand will more than triple in 50 years to come and that the domestic water demand and industrial requirements will only be satisfied up to the year 2030.

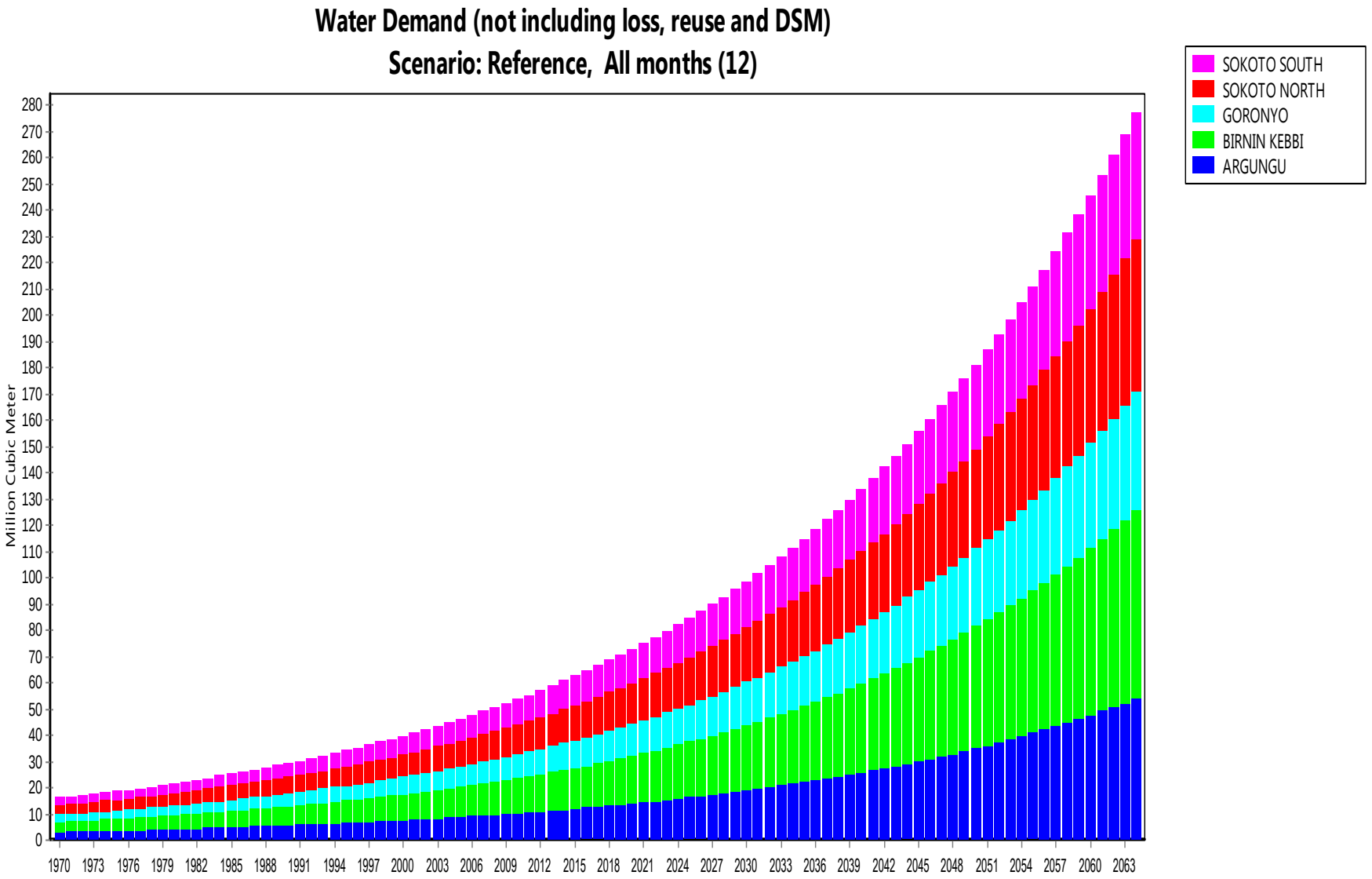


Figure 4.33: Domestic Water Demand for some selected sites projected to 2064

The unmet demand projected into future is shown in Figure 4.34. It indicates that all the scenarios have similar trend of not satisfying the domestic demand. However, demands for some towns namely Sokoto North, Gusau and Goronyo which are not satisfied in the future more especially during the dry seasons can depend on alternative sources of water like groundwater. The model set up only assigned the respective demands to rivers and alternative water supplies to towns was not considered. Therefore, it is assumed that the deficits in these towns can be met from alternative sources like groundwater.

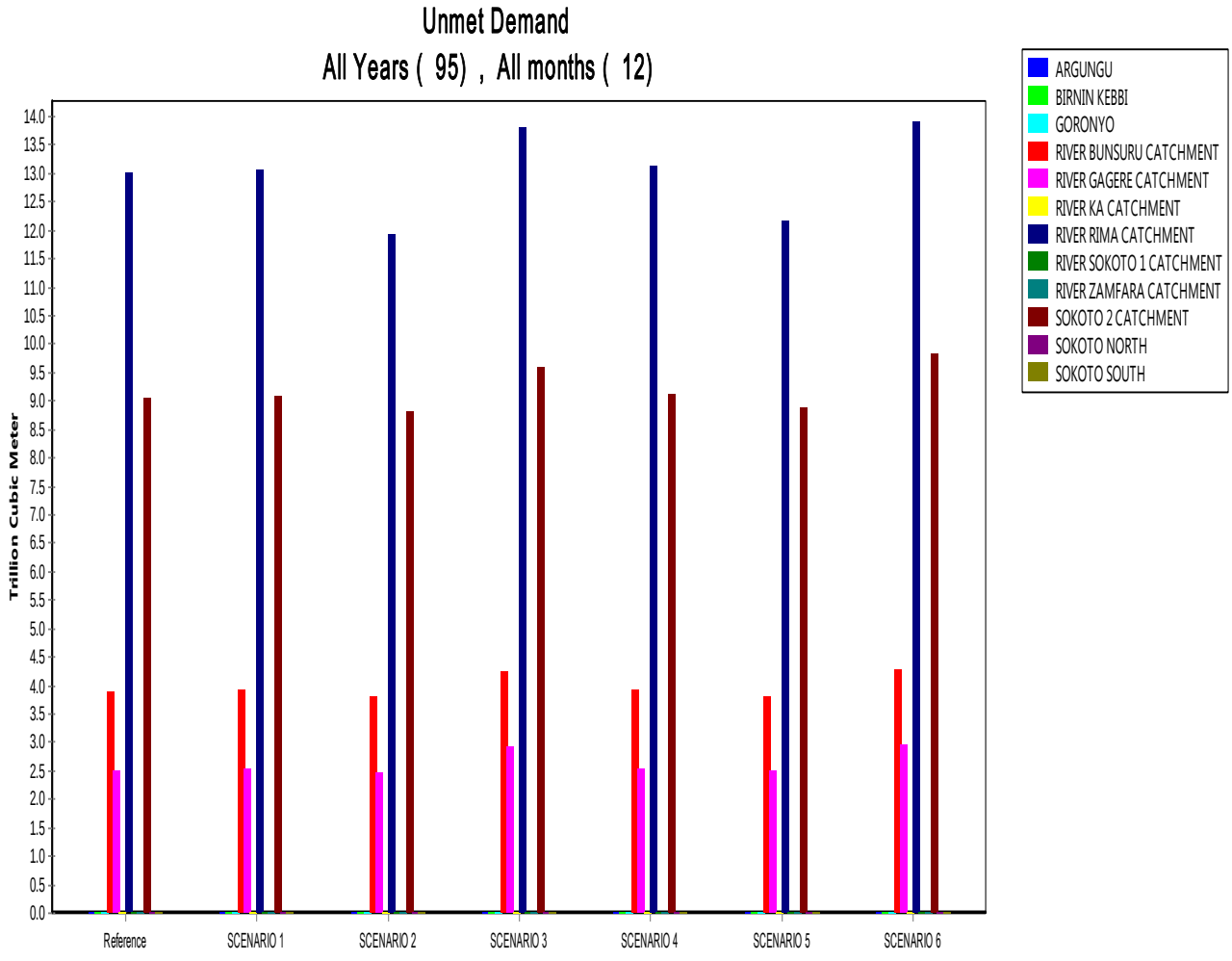


Figure 4.34: Unmet Demand for all scenarios projected to 2064

On the other hand, irrigation demands constantly experience deficits during the dry season in the range of 10 – 13% in some river reaches.

The demand sites reliability for all scenarios projected to 2064 is shown in Figure 4.35. Scenarios 3 and 6 appear to have very low reliability at many demand points and catchments compared with the other scenarios.

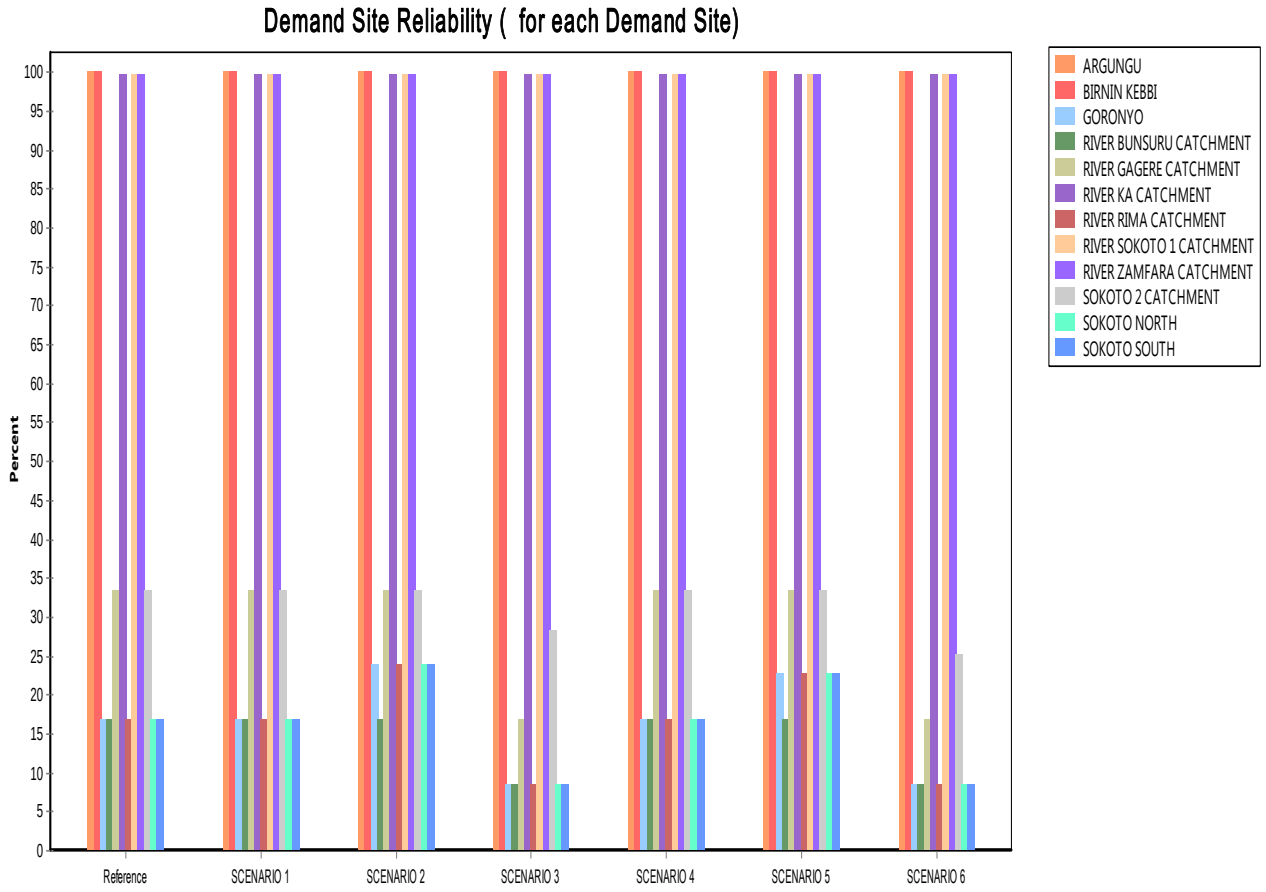


Figure 4.35: Demand sites reliability for all scenarios projected to 2064

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this study, an effort has been made to evaluate climate change impacts on the surface water resources in the Sokoto Rima River Basin (SRRB) using the WEAP model. A statistical analysis was performed in order to verify the presence of trends in the temperature and precipitation data. Consistent trend was detected over the basin, using annual data for the analysis. Increasing trend is found over annual temperature data, which assist in coming up with 0.5^0C and 1.0^0C used in the hypothetical scenarios. Annual rainfall variation data indicate that the whole basin receive negative and positive precipitation at different years. This leads to the use of 10% increase and 10% decrease in the hypothetical Scenarios, Which is in agreement with the values provided by the IPCC (2014).

The existing hydrological condition (streamflow) of the entire SRRB was estimated using available data. The calibration was carried out using observed and simulated data. The WEAP modelling indicates that the entire basin have a maximum monthly average Streamflow of 83768.1Million Cubic Meter (MCM) and minimum of 10958.9MCM of surface water under reference scenario. WEAP model estimated water balance components reasonably well with the observed data. However, under scenarios 1, 3, 4 and 6 used to analyse climate change there was reduction of monthly average stream flow by 388MCM, 3909MCM, 770MCM, and 24472MCM respectively. But scenarios 2 and 5 indicate an increase of monthly average stream flow by 19,195MCM and 17,380MCM respectively.

Therefore, the strong ability of WEAP in modelling complex water systems thus providing an opportunity for rapid assessment of the state of existing water resources was presented. Approximate streamflow information of the six major rivers within the basin was obtained from the model. This confirmed that WEAP model can be used effectively to analyse what happens if climate changes and the analysis can be extended to other River Basins.

The WEAP model was applied to simulate surface water availability of SRRB and the impact of climate change under six hypothetical climate change scenarios was estimated using water balance concept. The impact of climate change on current and future water availability was assessed. The water demand from some selected sites in the basin indicates that the demand will more than triple in 50 years to come and that the domestic water demand, Agricultural and industrial requirements will only be satisfied up to the year 2030. This explicates the reliability of the basin in meeting the projected water demand of some selected places.

The available average streamflow in every node and reach of all the major rivers in the basin was determined. The maximum average volume of water from all the sub-catchment of these major rivers was estimated by considering the values of Runoff Resistance Factor of the land cover and the relative storage of the root zone water capacity as watershed characteristics. The monthly average municipal and agricultural water demand for different scenarios was determined using demographic trends and irrigation areas.

The impact of climate change on future availability of surface water was assessed for the SRRB the situation was simulated and projected into the future, up to the year 2064. The water demand projected into future indicates that all the scenarios have similar trend of not satisfying the domestic demand.

However, the comparison of the water availability with and without the effect of climate change in the study area indicate an annual reduction in the total available water of about 1.70billion cubic metre (BCM) under 10% reduction in the actual rainfall within the basin and increase in evapotranspiration under 1^{o}C increase in temperature, which is scenario 6. This indicates reduction of the surface water in the future for the basin.

However, demands for some towns that are not satisfied in the future more especially during the dry seasons can depend on alternative sources of water like groundwater.

In addition, the dependency of the basin on surface water sources make it imperative to apply some methods of efficient use of water resources to ensure future sustainability. However, the reliability estimates described in this study inform anticipatory adaptation actions such as investment in increased water use efficiency, the use of water efficient crop, and other measures.

5.2 Recommendations

The recommendations on adaptation measures to mitigate the observed impacts, on ways to improve the results of this research by using all the model capabilities of WEAP and further studies are as follows:

1. Increase in water use efficiency and storage by using new improved Water-saving technologies that are traditional, household-based, and community-based and methods of irrigation like drip and intermittent irrigation by the farmers in the basin.
2. Using new improved varieties of different crops species seeds of highly productive crop varieties known as hybrids, which have revolutionized food production elsewhere in the world that does not require plenty of water in their production.

3. Increasing the forested area and reducing the impervious area by planting more trees to help in percolating more water in to the soil and entrapping it.
4. Making a proper plan for the existing reservoirs to maintain adequate flow in to downstream throughout the year by adjusting the runoff outlet value of the rainy season.
5. Creating more underground storage facilities (i.e underground reservoirs) by using new technology. This is achieved by excavating a very large area, lining it with an impermeable material and arranging the filling materials systematically to allow accumulation of water within the pores.
6. Organising collaborative planning in using the surface water among the stakeholders within the basin to provide complete control over water use, water budgeting and forecasting flood to avoid disaster or a natural catastrophe that causes great damage or loss of life.
7. To include minor rivers in the model of the basin that drain part of water to other sections. This will improve the result and give the exact quantity of water for each remote section of the basin
8. To use video images as an alternative to numbers and charts in communicating the climate change impacts, to show the stakeholders how climate change will affect specific areas or resources.
9. To incorporate groundwater and water quality analysis in to the model. This can improve the outcome and allow exploitations of other water management strategies like considering an alternative water supply in case of deficit and wastewater re-use and recycling.
10. To make the model automatic and interactive, by creating a simple graphic user interface that allow simple input of location within the basin to obtain all the hydrological information of that point.

11. To include energy and economic analysis in to the model. This can allow assessing the hydropower capability of the basin and possible economic benefits and options.

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APPENDIX A

DATA

The required data for the analysis of impact of climate change on water resources are the hydro meteorological data, water demand in all sector and land cover or land use within the basin.

Rainfall Data

The rainfall data obtained from some stations within and around the basin are the historical rainfall data of 1970 to 2013 and the historical stream flow of different gauging stations within the basin. The average rainfall patterns for some sub-catchments within the basin are shown in Figure 1A

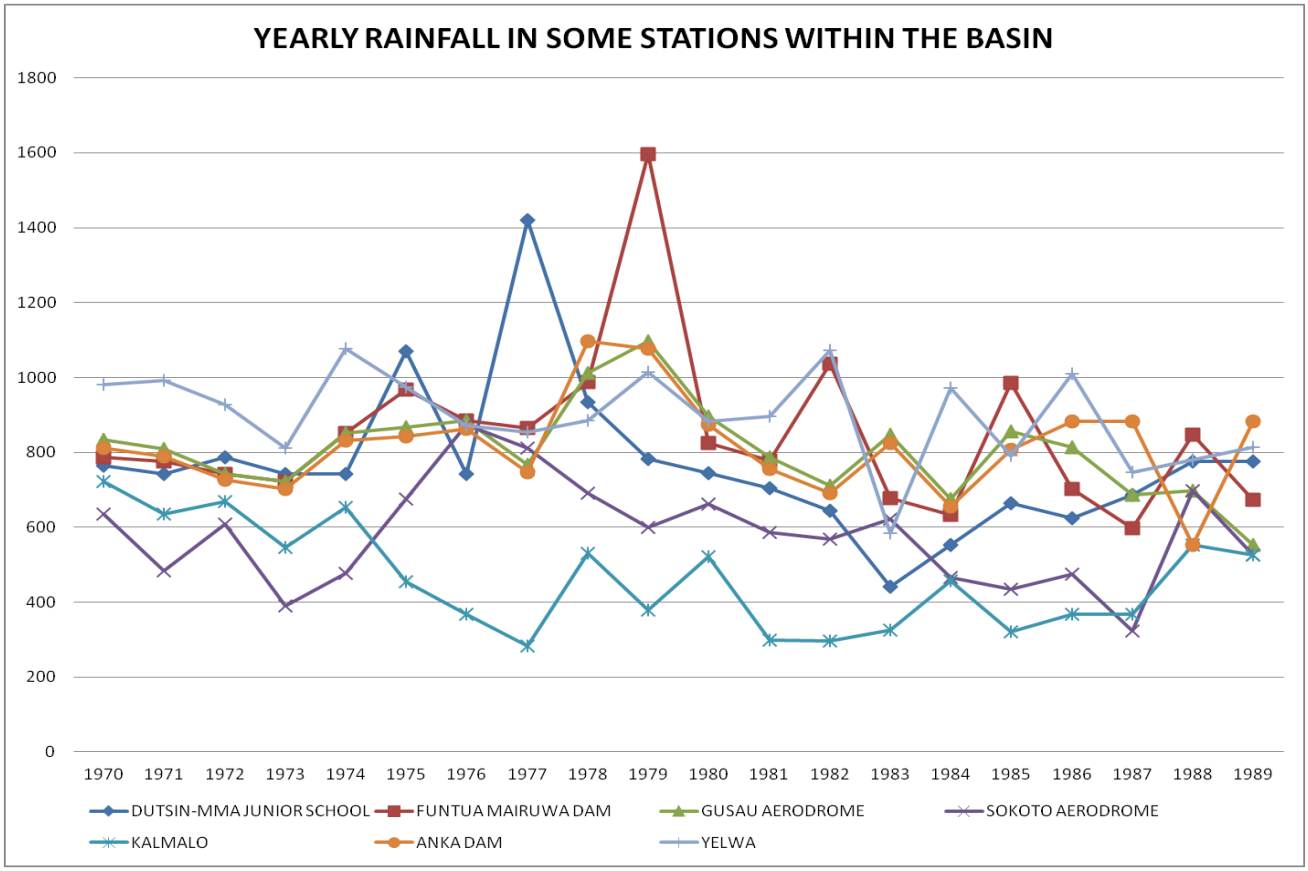


Figure 1A: Observed yearly Rainfall in some stations within the basin

Impact of Climate Change on Water availability

Based on the simulation of the sreamflow within the basin for the different scenarios. The streamflow of the year 2014 is shown in Figure 2A.

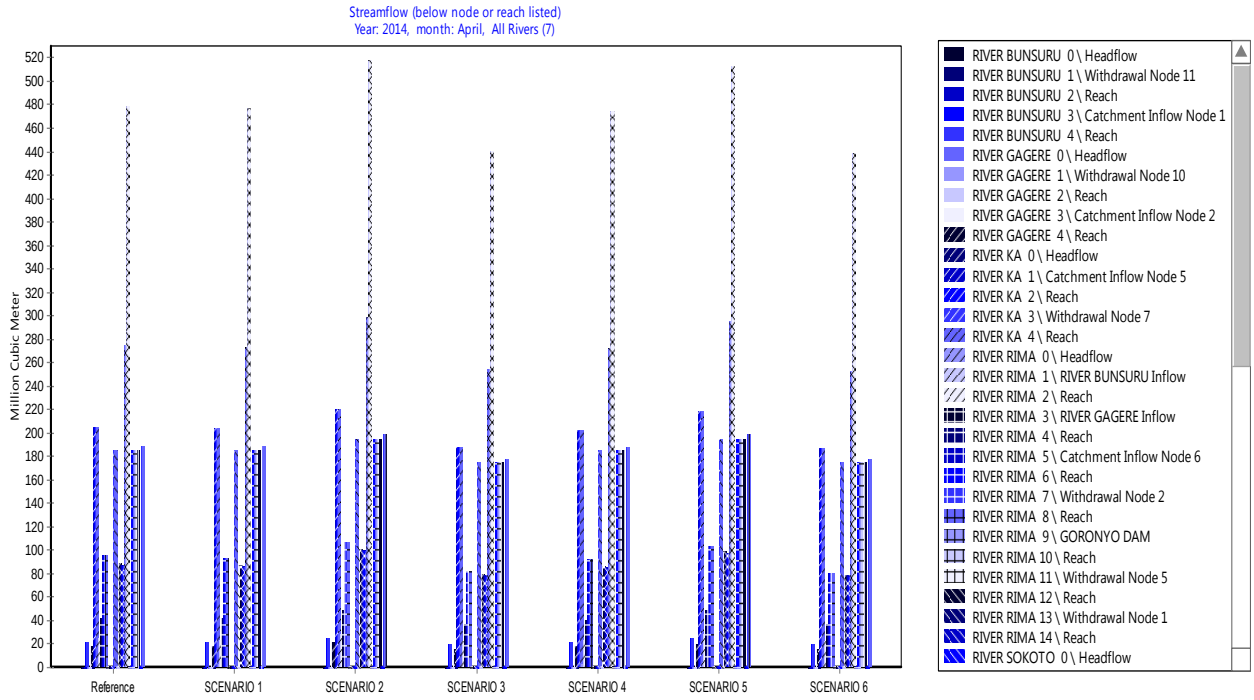


Figure 2A: Streamflow from rivers for all scenarios at the current year 2014.

APPENDIX B:

Water resources are inextricably linked with climate, so the prospect of global climate change has serious implications for water resources and regional development. The graph in Figure 1B shows water availability per capita in cubic metres for selected countries in Africa in 1990, with projected data for 2025. It also shows which countries were affected by water stress, water scarcity and water vulnerability in 1990, with projected data for 2025. This resource also includes a graphic showing which African countries are expected to be affected by freshwater stress and by freshwater scarcity in 2025.

Many countries will shift from water surplus to water scarcity as a result of population changes alone between 1990 and 2025, using a per capita water-scarcity limit of 1,000 m^3 yr^{-1}. Long-term precipitation records from the Sahara give a clear indication of declining precipitation in that region. These declines in precipitation register as reduced hydrological discharges in major river basins in the sub humid zones. It is apparent that several countries will face water availability restrictions by the middle of the 21st century, if current consumption trends persist. The combination of demographic trends and climate change is likely to cause economically significant constraints in some parts of Africa.

http://www.grida.no/publications/vg/africa/page/3116.aspx

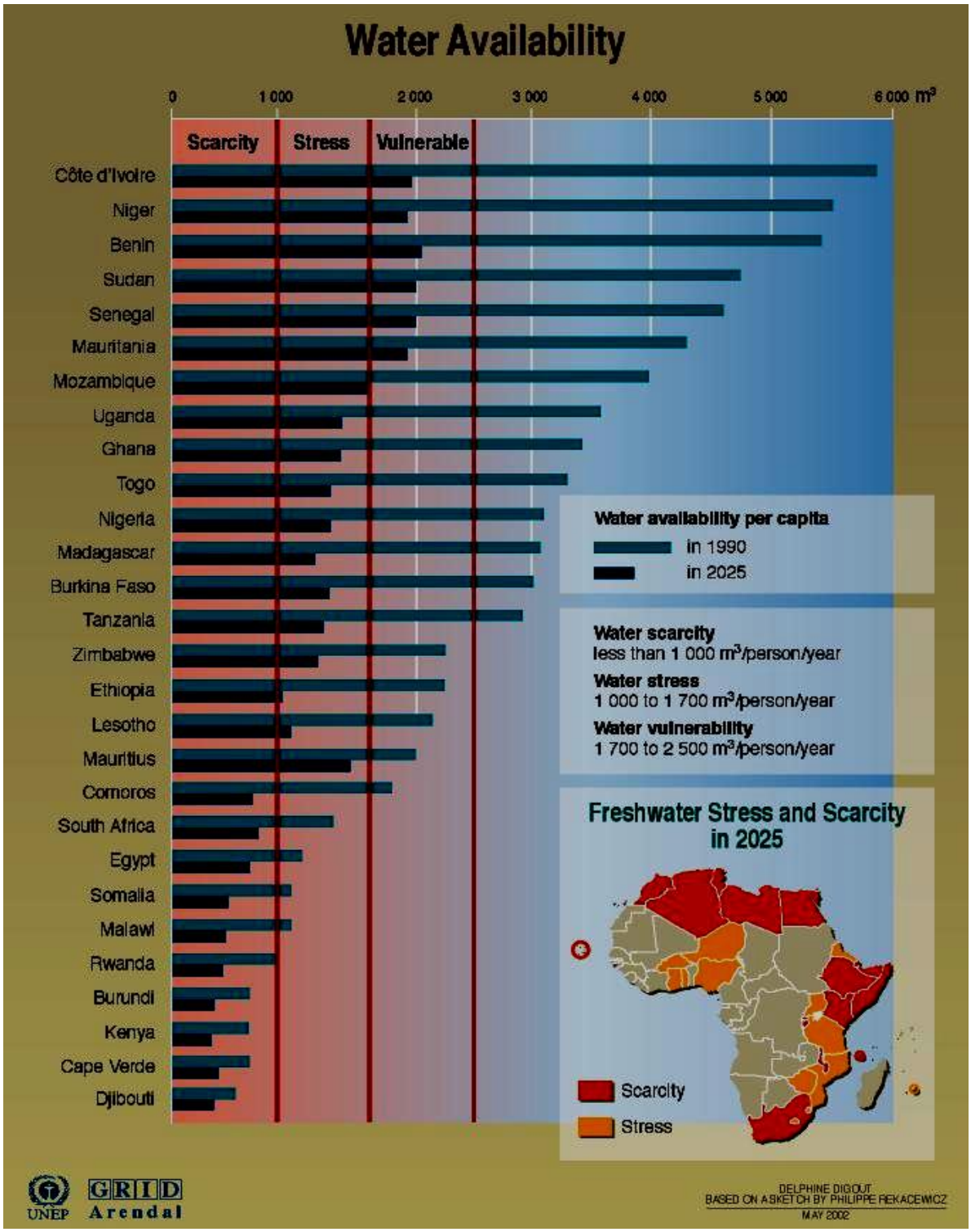


Figure 1B: Water availability per capita in cubic metres for selected countries in Africa in 1990, with projected data for 2025 (Source:http://www.grida.no/graphicslib/detail/water-availability-in-africa_3368)