Preface

This thesis work with a topic “Improved management of the water and energy resources in the Volta Basin” is submitted as a requirement for partial fulfilment of Master of Science degree in Hydropower Development course 2019-2021, to the department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. The work mainly involves analyzing how planned future dams and increase in water use will affect the inflow into the Volta lake. The effect of climate change on the water on the water resources in the Volta basin was also analyzed with the WEAP model. The effect of large-scale floating solar panel was also analyzed.

The work was started on January 15th and was submitted on June 25th, 2021 under the supervision of Tor Haakon Bakken. This work is purely for academic purpose and doesn't mean to oppose or harm any individual, group or organization. I hereby witness that the work is mine and all sources of information are referenced.

Acknowledgement

I thank God for providing me with this opportunity and for how far I have come in life.

I am highly indebted to my supervisor, Professor Tor Haakon BAKKEN of the Civil Engineering Department at the Norwegian University of Science and Technology (NTNU) for his constant guidance as well as providing the necessary information regarding this thesis.

His kind advise, valuable supervision and encouragement on research work has helped cultivate a desire within me for Research. I would also want to take this opportunity to thank all Professors who taught me in NTNU, the knowledge I have gained has really shaped me in so many ways.

I also want to acknowledge all my colleagues; I appreciate studying with you all.

I would like to extend my special thanks to NORAD for financing my master's degree program.

Lastly, but very importantly, I would like to appreciate my wife Selina Amankwah and my Kids, Jaden, Jason And Brian for being the pillar around me.

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Abstract

Integrated water management, energy and food nexus has been a major discussion due to the sustainable development goals (SDG's), especially SDG2, SDG6, SDG7 and SDG13. The population in the Volta river basin is mainly dependent on rainfed agriculture and therefore, the basin is vulnerable due to the variability in rainfall and climate change. Development of Dams has become of high priority in the basin for irrigating, municipal water supply, flood protection and livestock watering. The effect of future dams in the sub- basins are vital to the inflows into the Volta lake.

The main objectives of this study were to analyze how planned future dams and increase in water use will affect the inflow into the Volta lake. The effect of climate change on the water on the water resources in the Volta basin was also analyzed. The effect of large-scale floating solar panel was also analyzed.

A hydrological model of the three sub basins in the Volta basin was established using the Water Evaluation and Planning tool (WEAP). The percentage bias (PBIAS) statistical criterion was used to assess the calibration which shows an acceptable model for the White, Black and Oti basins.

The model simulated historical streamflow, current and future dams, irrigation, municipal and domestic water use for the three sub basins.

Future climate data (rainfall and temperature for the period 2020-2039 and 2080-2099 was generated from the World Bank Group climate change portal with ensemble mean model and RCP 4.5 scenario. Three scenarios were analyzed, i.e. the present scenario (1960-2010) and future scenarios from 2020-2039 and 2080-2099.

The result of the study indicates that streamflow in the volta basin with future planned dams will not influence the streamflow. However, there is an overall increase of 0.89%. in monthly average streamflow for the White Volta basin.

On the other hand, the Volta basin will experience temperature rise and low precipitation due to climate change which has a drastic effect in the period 2020-2039 and 2080-2099.

The introduction of a 35km^2 large-scale floating solar panel of is vital in conserving water during droughts in the basin due to climate change. It will save water of about 6.7 x 10^7 m^3/year which is quite significant to the municipality.

M.Sc. Thesis in
Water Resources Modelling and Engineering
Candidate: Maxwell Mishio

Title: Improved management of the water and energy resources in the Volta Basin

BACKGROUND

Integrated management of water, energy and food across sectors and scales is often denoted as the WEF nexus. A WEF nexus approach is key to coherent implementation of the UN Sustainable Development Goals (SDGs), SDG 2 (Zero Hunger), SDG 6 (Clean water & sanitation), SDG 7 (Clean energy) and SDG 13 (Climate action). Such an approach is not only essential to ensure availability, access, and sustainable management of the resources, but also to contribute to climate mitigation and adaptation. This master thesis will analyze the relationships between water availability, energy protection (hydropower and solar power) and sustainable releases of water from reservoirs for human needs and ecosystems.

The Volta River basin is a transboundary basin shared by six riparian countries in West Africa (Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali and Togo) with a size of around 400 000 km^2. The current estimated population of the Basin is 19 million (70% of which are rural) and it is projected to reach 35 million by 2035. Rural and peri-urban people pursue a wide variety of livelihood strategies, including rainfed crop farming, pastoralism, rice production in lowlands and on government-built irrigation schemes, small scale irrigation based on small reservoirs and pumping from rivers and groundwater, fishing, and agro-forestry.

Lake Volta is the largest artificial reservoir in the world based on surface area, i.e. 8500 km^2 and a length of approximately 400 kms, located in the far downstream end of the basin. The reservoir is dammed by Akosombo Dam which built for hydropower production and generates a substantial amount of Ghana's electricity with an installed capacity of 1020 MW (6 x 170 MW Francis turbines). The reservoir stores water from both White Volta River and the Black Volta River, which formerly converged where the middle of the reservoir now lies. Volta River is controlled by the reservoir releasing water to downstream users and flows into the Atlantic Ocean in southern Ghana. The construction of the dam introduced a large number of impacts to the ecosystem and downstream water users, of which some can be related to the absence of floods (e.g. eutrophication, aquatic weed invasion, deposition of nutrients).

2 MAIN QUESTIONS FOR THE THESIS

Key questions to be addressed in the thesis are:

- The effect on the water resources/availability in the Lake Volta region from planned new reservoir developments
- The effect of climate change on the water resources/availability in the region

<u>These questions can be addressed by carrying out the following steps:</u>

1. Compile data on climate, hydrology, water-related infrastructure and water use in Volta Basin
2. Configure/calibrate a hydrological and water allocation model (e.g. WEAP or similar)

for the selected study area (Volta Basin)

3. Compile information about new possible reservoir developments in the basin. Represent new reservoirs (presently not built) in the modelling tool, and assess the effect of such reservoirs on the water resources
4. Assess the effect of large-scale development of floating solar panel in selected reservoirs on the water resources and estimate the possible renewable energy from these installations.
5. Simulate the effect of climate change on the water resources in Volta basin

3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Tor Haakon Bakken will be the main supervisor of the thesis work. Discussion with and input from colleagues and other research or engineering staff at NTNU, power companies, consultants and research institutes are recommended, if considered relevant. Significant inputs from others shall, however, be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in a contract research or a professional engineering context.

4 REPORT FORMAT AND REFERENCE STATEMENT

The report shall be typed by a standard word processor and figures, tables, photos etc. shall be of good report quality, following the NTNU style. The report shall include a summary, a table of content, lists of figures and tables, a list of literature and other relevant references. All figures, maps and other included graphical elements shall have a legend, have axis clearly labelled and generally be of good quality.

The report shall have a professional structure and aimed at professional senior engineers and decision makers as the main target group, alternatively written as a scientific article. The decision regarding report or scientific article shall be agreed upon with the supervisor. The thesis shall include a signed statement where the candidate states that the presented work is his/her own and that significant outside input is identified.
This text shall be included in the report submitted. Data that is collected during the work with the thesis, as well as results and models setups, shall be documented and submitted in electronic format together with the thesis.

The thesis shall be submitted no later than 11th of June, 2021.

Trondheim 15th of January 2021

Tor Haakon Bakken

Tor Haakon Bakken, Professor

1.0 Introduction

1.1 Water, Energy, and food (WEF) Nexus

This section provides a concept of Water, Energy and Food (WEF). 'Nexus' refers to the linkages and connections between various elements (World Economic Forum, 2011). Water, Energy and Food is very important in our daily activities. The Water, Energy and Food security nexus are very much linked to one another, meaning, they are interdependent on each other for human benefit. (FAO,2014).

WEF interactions are complicated issues which cannot be tackled in isolation. The United Nations (UN) Sustainable Development Goals (SDG's), specifically, SDG2 (Zero hunger), SDG 6(Clean water and sanitation), SDG 7 (Clean energy) and SDG 13 (Climate action) will require a nexus approach for successful implementation.

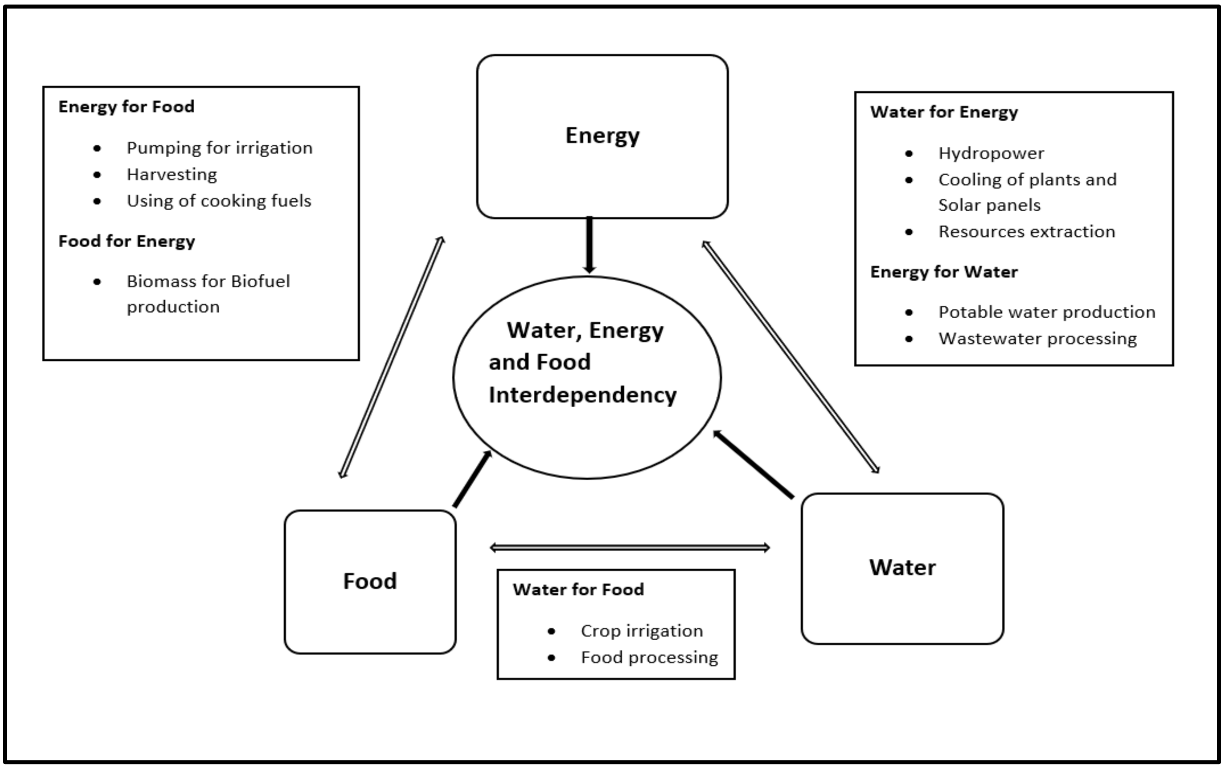

Figure 1 Water, Energy and Food (WEF) Nexus (Adapted from Nieber et. al)

Agriculture is the key in achieving the objectives and aspirations articulated in the sustainable development goals, especially SDG 2. It is crucial to the livelihoods of hundreds of millions of smallholder farmers and rural communities (FAO, 2015). For the world to ensure global food security, 60% more food needs to be produced by 2050. This must be done while conserving the natural resource base. Water is therefore, considered a major input in providing food to the world.

The (United Nations, 2014) makes it clear that, to realize zero hunger, it is important to achieve food security and improved nutrition and the promotion of sustainable agriculture. Ghana, a country located in the Volta river basin depends on agriculture for about 60% of gross national product and it also provides jobs for about 80% of the population (Source: ADAPT PROJECT). The northern part of Ghana and Burkina Faso usually experience droughts and erratic rainfalls, due to this, development of dams have become crucial in holding water for future use. Irrigation is, therefore, the way forward in agriculture to help solve the food security problem in the volta river basin. Agriculture in the volta basin is mostly rainfed with less than 1% of cultivated land being irrigated. Farmers in southern Ghana which is in the lower volta basin can grow more food since they have two rainy seasons. (World Food Program).

Water is an essential commodity in sustaining life and livelihoods. Clean water and sanitation (SDG 6) and clean energy (SDG 7 e.g. hydropower) are very important since they both depend on the supply of fresh water. They are considered not be two inseparable resources for sustaining human life on earth. (Michel Jarraud, the chair of UN- Water, January, 2014) makes it clear that the world needs to provide adequate and sustainable access to more than 1.3 billion people who still lack electricity and to more than 700 million people who lack an improved water supply. Water is vital to large hydroelectric and thermoelectric power generators. The efficiency of a photovoltaic is also increased by cooling with water.

(Avellan et al and Liu et. al) argue that, in water scarce areas like sub- Saharan Africa, there is a huge competition over water used for irrigation and water used for energy generation. This is a key example of the Water, Energy and Food (WEF) nexus as shown in figure. 1 above. There is, therefore, a need for innovative ideas to manage the interdependency between water, energy, and food.

Climate action (SDG13) has become an important factor which cannot be left out in the nexus. This is because it is gradually worsening the cases of food and water scarcity due to changes in precipitation. This can have wide ranging effects on human well-being and the ecosystems. The timing of rainfall and snowmelt can affect the amount of surface water and groundwater available for drinking, irrigation, and Energy generation (www.epa.gov/climate-indicators-us-and global precipitation).

There is some evidence that climate change has already caused more intense and more prolonged droughts in some regions globally, including Europe and West Africa. Projections indicate more frequent and more severe (even more severe than the worst droughts in the period (1981-2010) over vast parts of the world (GAR special report on drought, 2021).

1.2 Roles of reservoir in terms of water management

To adequately describe the role of a reservoir in managing water resources, it is essential to consider the level of water scarcity in the study region. In the United Nations report 2007, sub-Saharan Africa was considered the region with most countries facing water scarcity, mostly economic scarcity.

The UN-water defines *water scarcity* as the lack of water due to physical shortage or the failure of institutions to ensure regular supply or inadequate infrastructure.

The water project defines *Economic water scarcity* as the high cost of investment in the water infrastructure or insufficient human capacity to satisfy the water demand. On the other hand, physical scarcity is when the water within a particular region is not enough.

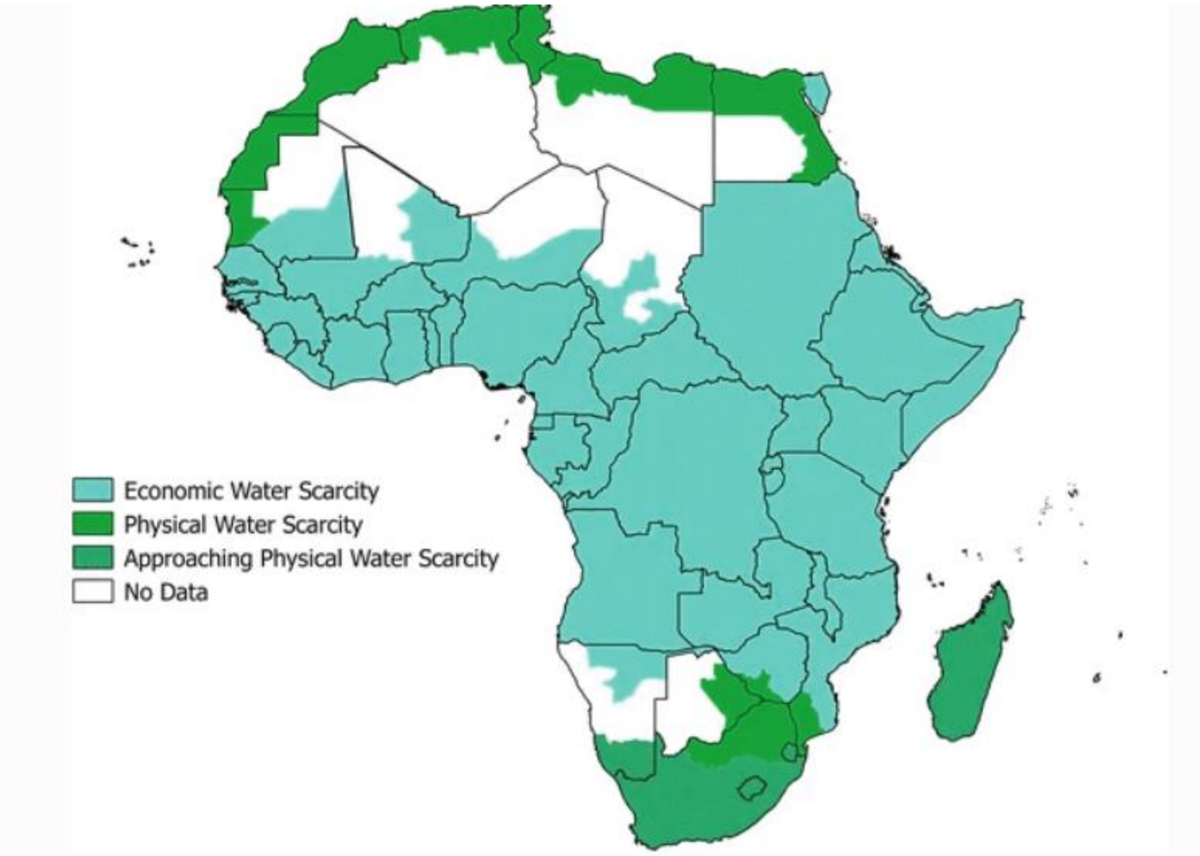

Figure 2 Map of physical and Economic water scarcity adapted in 2007 across the African continent

The United Nations Economic Commission for Africa has stressed on the need to invest in prospective water resources to reduce unnecessary economic water scarcity. These investments will be in the form of construction of dams for flood mitigation, supply of drinking and domestic water, storage for irrigation and livestock watering and for hydroelectric generation. Other storage infrastructures will be rainwater catchment systems, clean water storage tanks and boreholes for the storage of groundwater. When these infrastructures are put in place, it is obvious that most countries with economic water scarcity will no longer be water stressed if all things remain equal. Dams have long served to cope with seasonal changes in water availability and provide water for different sectors when most needed (United Nations World Water Development Report, 2019). (Chen et al., 2016), affirms that reservoirs have served human population growth and development by improving capabilities of managing water resources and thus helped to sustain food and energy security.

Beck et al., (2012) argues that, though reservoirs may have great economic and social benefits, they may be accompanied by negative biophysical, socio-economic and geopolitical impacts which have widely documented in various regions of the world and are not unique to a specific location or ecosystem. Also, since evaporation on reservoirs constitute the largest percentage of the water balance (Kebede et al.), rise in evaporation losses due to an increase in water surface area is usually expected.

1.3 Roles of hydropower

Access to electricity is the mainstay of every modern economy (Africa Development Forum, 2019). According to (Grone Wold, 2009), one third of the world's population covering 50 countries lack access to electricity while 2.1 billion are short of safely managed services. Unfortunately, about 33% of these countries are in sub- Saharan Africa. Hydropower is a source of renewable energy that satisfies the modern energy attributes that are largely untapped in sub-Saharan (Ebhota and Tabakov, 2019). To achieve the UN- SDG's position on clean energy, hydropower plays a vital role since it provides affordable, reliable, and low Greenhouse Gas (GHG) emissions.

Hydropower helps to curb climate change. The International Renewable Energy Agency (IRENA), confirms that, the world's existing hydropower will need to grow about 60% by 2050 to reach 2150GW to help limit the rise in global temperature to below 2 degrees Celsius.

Hydropower continues to be the main renewable resource in Africa with over 37GW of installed capacity (International Hydropower Association, Africa). This means that it plays a major role in the economic development of the continent. IEA (2021) states that by 2050, the main dispatchable renewable will be hydropower

The World bank stresses that, the riparian countries in the volta basin have not fully utilized the hydropower potential in the basin to meet their poverty alleviation demand. Hydropower is an important energy source that fuels the economy in some of the riparian countries yet there are some potentials which remains underdeveloped (World Bank 2015 under Global Water Practice). Currently, 70% of the electricity generation in Ghana is from hydropower. This is generated from three different hydroelectric plants in the Volta river basin, with current installed capacities of 1020 MW, 400MW and 160MW at the Akosombo, Bui and Kpong generating stations respectively (Volta River Authority, 2012). This power generated supports many industries in Ghana (e.g. mining industries, Aluminum smelting, etc.)

Though hydropower is considered a renewable energy resource, it is important to note that large scale hydropower development can result in environmental damage as well as social conflict, particularly in the case of storage-based hydropower. These dams are also known to emit GHG's especially methane (CH_4) and Carbon dioxide (CO_2) (Kaunda et. al 2012)

2.0 MATERIALS AND METHODS

2.1 Description of Study Area

-Overview of the Volta River Basin

The study was carried out in the volta river basin located in Sub-Saharan Africa. The basin lies approximately between latitude 5° 30’ N in Ghana and 14° 30’ N in Mali. It also stretches longitudinally between 5° 30’ W in Côte d’Ivoire and 2° 00’ E in Benin.

Around 23 million people live in the Volta basin, which has a heavy reliance on its natural resources for their livelihood. More than 70 percent of the population in the basin reside in rural areas(reference). There is an estimated population growth of 2.5-3.0% annually, which could reach 35 million by 2035 (ADAPT project).

There are four main sub-basins of the Volta River Bain, namely: The Black Volta, the White Volta, the Oti-Pendjari River and the Lower Volta basin. Akosombo Dam in 1964 created the Volta lake that is fed by the Black Volta, the White Volta, and the Oti-Pendjari tributaries. It is by far the most significant infrastructure in the basin. By surface area, this is the largest man-made reservoir in the world. It feeds the Lower Volta and empties into the Gulf of Guinea. The total length of the Volta river is about 1500km.

The Volta River basin is a transboundary shared by six riparian countries in West Africa (Benin, Burkina Faso, Côte d’Ivoire, Ghana, Mali, and Togo. The basin has a drainage area of about 400,000Km^2.

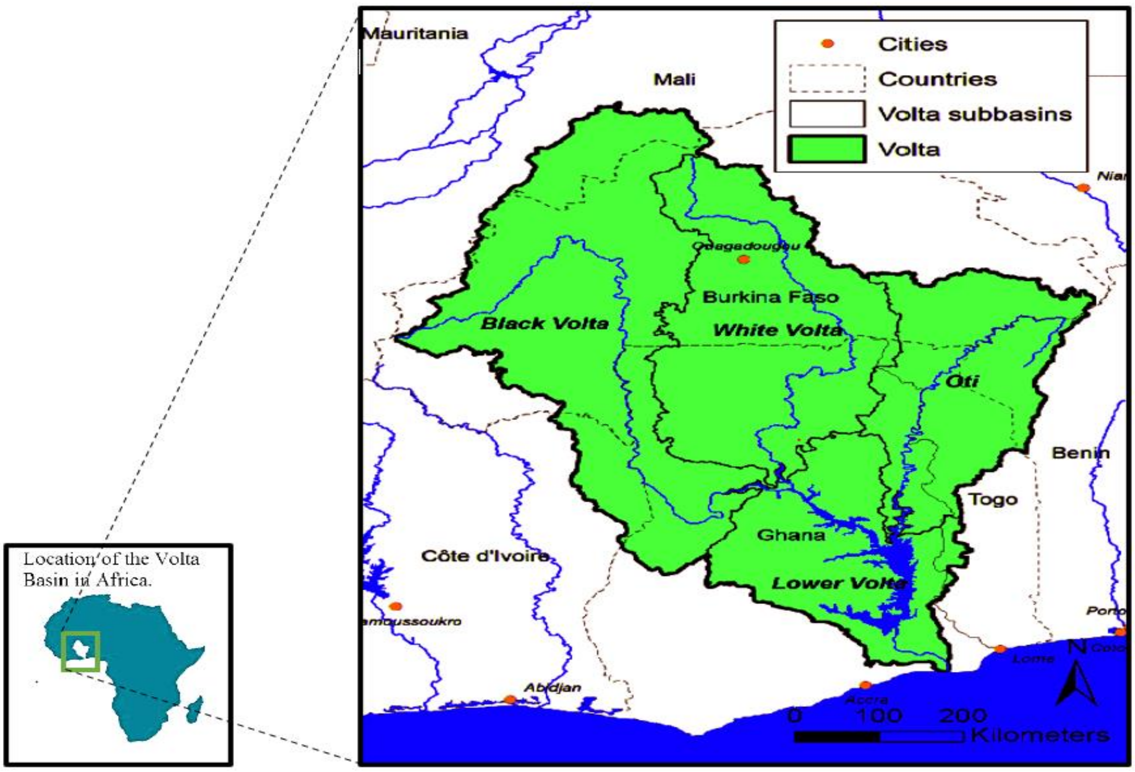

Figure 3 Volta River Basin showing sub basins

The land area distribution among the six riparian countries is shown in table 1.

Table 1 Land area distribution of Volta basin among riparian countries. Source: Volta Basin Authority (VBA, 2009) and FAO

Country	**Total area of the country (Km^2)**	**Area of Volta River Basin (Km^2)**	**% of basin in the country**	**% of country in the basin**
Benin	112,620	13,590	3.41	12.10
Burkina Faso	274,000	171,105	42.95	62.40
Côte d'Ivoire	322,462	9,890	2.48	3.07
Ghana	238,540	165,830	41.61	70.10
Mali	1,240,190	12,430	3.12	1.00
Togo	56,785	25,545	6.41	45.00
Total	**398,390**		**100**	

Approximately 28 % of West Africa is covered by the Volta Basin, according to Andreini et al (2000). The basin is generally flat, with altitudes ranging from 1m to 920m. The basin has an average altitude of approximately 257m, with over half of the area ranging between 200-300m. The Black Volta originates from the southwest of Burkina Faso and flows south-eastwards into Ghana where it ends up in the Volta lake with a flux of $6 \times 10^9 m^3$ The White Volta stem in the north of Burkina Faso and flows south-eastwards to the border with Ghana. The total annual discharge leaving Burkina Faso through the Red and White Volta Rivers is estimated at $3.7 \times 10^9 m^3$(FAO 1997, Volta Basin). The FAO also reports that, the Pendjari river springs from the north-west of Benin and flows north-east where it turns sharply to the west between Burkina Faso and Benin. It then crosses Togo in the north where it known as the Oti river. The Oti river enters Ghana further south with an estimated annual flux of $11 \times 10^9 m^3$.

The area distribution of the sub-basins as described in Barry et al is shown in table 2 below.

Table 2 Area distribution of Volta sub-basins. Source: Barry et al (2005)

Volta River Sub-basins	**Area (Km^2)**
Black Volta	149,015
White Volta	104,752
Oti River basin	72,778
Lower Volta (main Volta)	62,651
Total	**389,196**

2.1.1 Effect of inflow into Akosombo reservoir

The Akosombo reservoir has experienced variability in its water levels and its surface area due to excessive water abstractions and climate change (Ghansah et al, 2016). Despite the perception that Akosombo's per capita water supply is adequate, human activities such as deforestation and land degradation coupled with a growing population will likely exacerbate the growing water shortage (Kasei, 2009). River systems may be affected by temperature changes which could affect hydroelectric power (Markoff & Cullen, 2008). The

Akosombo reservoir is fed by several tributaries, all of which are rain-fed. Volta basin sees unpredictable precipitation in all ecological zones.

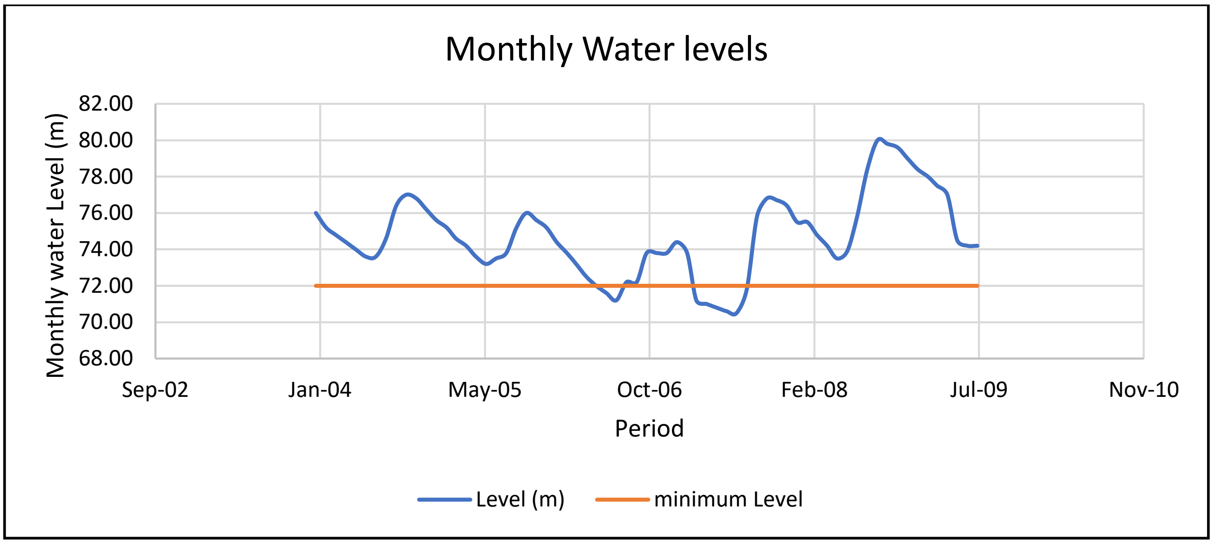

Figure 4 *Graph of Monthly water levels of Akosombo Dam (source: Volta River Authority)*

The generation of hydroelectricity is highly dependent on water availability since large amount of water is required through the turbines to generate power. The amount of inflow into the Akosombo reservoir is affected by seasonal flows (high flows in the rainy season and low flows in the dry season). As a result of the peak rainfall period in August, the reservoir receives a large influx of water, and reaches its maximum level in August/September. The overall flow may also be affected by increased evaporation due to increase in temperature (Bakken et al, 2013; Mekonnen &Hoekstra, 2012). Furthermore, the prevalent water abstraction activities upstream could determine the inflow into the Akosombo reservoir.

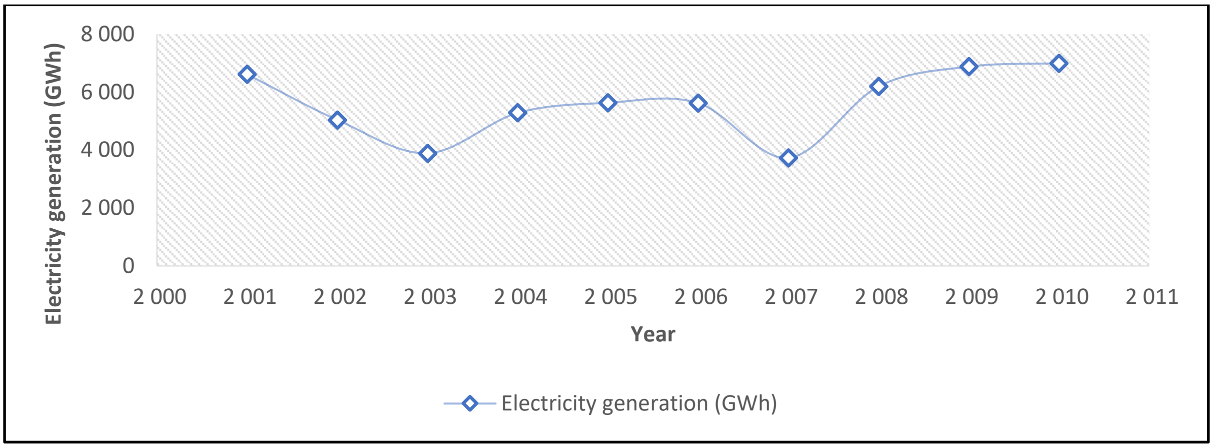

Figure 5 *Annual Hydropower generation for Akosombo dam (IRENA, 2021)*

In 2006/2007, there was very severe power rationing in Ghana due to reduced power supply to industries and households. There were six turbines in operation, but only two were operational, generating 400 MW out of the 1180MW (Obeng & Logah, 2013). In figure 3, we can tell that the water level in 2007 was deficient, which reflects the amount of power generated that year, as shown in figure 4. The low power generation was the consequence of low inflows into the

Akosombo reservoir. Therefore, there have been significant concerns about the changes in the water level since upstream activities may result in negative consequences in power production. According to Ghansah et al., 2016, upstream regulations (construction of dams) lead to reduced inflows into the Akosombo reservoir.

Any abstractions made upstream of the Volta lake - particularly those made for irrigation due to their potential magnitude - will affect the inflow into the lake and reduce the output from the Akosombo and Kpong power stations. Volta River Authority lacks reliable real-time information on inflows into the Volta lake, resulting in difficulty managing storage and hydropower output (World Bank, Global Water Practice, 2015). Therefore, it is evident that in the future, it is crucial to strike a balance between further development of irrigated based agro-industry upstream and the contribution of sub-basins water resources into the volta lake for the generation of hydropower.

2.1.2 The Falkenmark Indicator

The Falkenmark indicator (Falkenmark et al., 1989) is a widely used method for calculating water scarcity. The Falkenmark indicator is categorized as shown in the table below.

Table.1 Falkenmark Categories

Category	**m^3/capita/year**
No stress	> 1700
Stress	1000 - 1700
Scarcity	500 - 1000
Absolute scarcity	< 500

The Falkenmark indicator calculates water scarcity as the total renewable water resources divided by the total population in a particular year. A value of 1700m^3/cap/year defines the threshold of water scarcity as seen in table 1. An example of this calculation was done for Ghana to determine its category using the Falkenmark indicator.

$$Water\ Availability\ per\ capita\ in\ 2017$$

$$= \frac{Total\ renewable\ water\ resources\ (FAO, aquastat\ statistics)}{Total\ population}$$

$$= \frac{56.2 \times 10^9}{29{,}121{,}464}$$

$$= \mathbf{1930}\boldsymbol{m^3/cap/year}$$

The same calculation was done for Burkina Faso and it gave water availability per capita in 2017 to be $\mathbf{703.4}\boldsymbol{m^3/cap/year}$**.** This means there is water scarcity in Burkina Faso as indicated by Falkenmark.

A great deal of Ghana's other rivers in the volta basin originates within the country, but most of these water courses run almost completely dry after the rains, especially in the northern savannah region. There is a low yield of groundwater here, so extensive irrigation is not practical. It is estimated by (Andreini et al, 2000) that significant flux occurs only when $3.40 \times 10^{11} m^3$ of rainfall has been received by the basin and once the threshold is reached, almost half of the precipitation is determined to be runoff. An estimated $3.8 \times 10^{10} m^3$ of water flows into the sea on average per year (FAO, 1997).

2.2 BLACK VOLTA SUB-BASIN

The Black Volta basin lies between latitude 7° 00' 00''N and 14° 30' 00''N and longitude 5°30' 00''W and 1°30' 00''W and covers an estimated area of roughly 149,015 Km^2.The Ghana portion of the basin covers an area of 18,384 Km^2 comprising 14% of the entire basin and has six sub catchments including Lerinord, Nwokuy, Bui, Dapola, Noumbiel and Bamboi (Water Resources Commission, Ghana).

Most of the lands in the Black Volta basin are used for agriculture. There are mainly rain-fed crops such as rice, millet, sorghum, and maize, and yam, cassava, groundnuts, and beans. During the dry season, farmers grow vegetables such as tomatoes, peppers, okro, lettuce, cabbage, and pumpkins, especially in Lawra district.

According to the land use map prepared for the Black Volta basin, most of the land in Burkina Faso is agriculturally developed (rainfed and irrigated) while in Ghana, most of the land is covered with forest and grassland.

2.2.1 Hydrology in the Black Volta Sub basin

In this sub-basin, annual rainfall is between about 1,150 mm in the north and about 1,380 mm in the south, with pan evaporation estimated at about 2,540 mm per year and an average annual runoff of about 88.9 mm. An annual runoff of $243 m^3/s$ occurs in the sub-catchment. During the rainy season, the sub-basin produces about $623 m^3/s$ of runoff; during the dry season, approximately $2 m^3/s$ of runoff are generated (Opoku-Ankomah, 1998). Barry et al, 2005 confirms that the contribution of the black volta basin to the annual total flow of the lake volta is roughly 18%.

Table 3 Black volta basin surface water flow in Ghana. Source: Barry et al. 2005

	Catchment area (Km^2)	**Annual discharge (m^3/s)**	**Annual dry season discharge (m^3/s)**	**Annual wet season discharge (m^3/s)**
Lawra (Inflow)	90,658	103.75	34.75	172.13
Bamboi	128,759	218.97	62.83	373.79
Catchment outflow		243.30	69.81	415.32
Flows from within Ghana		139.55	35.06	243.19
% contribution to lake Volta		42.64	49.70	41.45

An evaluation of the average monthly discharges at Bui by the Volta River Authority (VRA) shows that 94% of the total discharges in a year occur between June and November peaking in September as shown in figure 6.

Nick Van de Giesen et al (2001) explains that, there is a strong correlation between yearly rainfall and river flow in the basin. In the dry season, when the volatility of the black volta is dramatically reduced, disconnected pools form along the river course, separated by stretches of sand depositions and rock boulders. Sudden rises in water level occur during the rainy season and rivers and streams often overflow their banks, suggesting that there is a considerable surface runoff within the black volta basin during heavy rainfall.

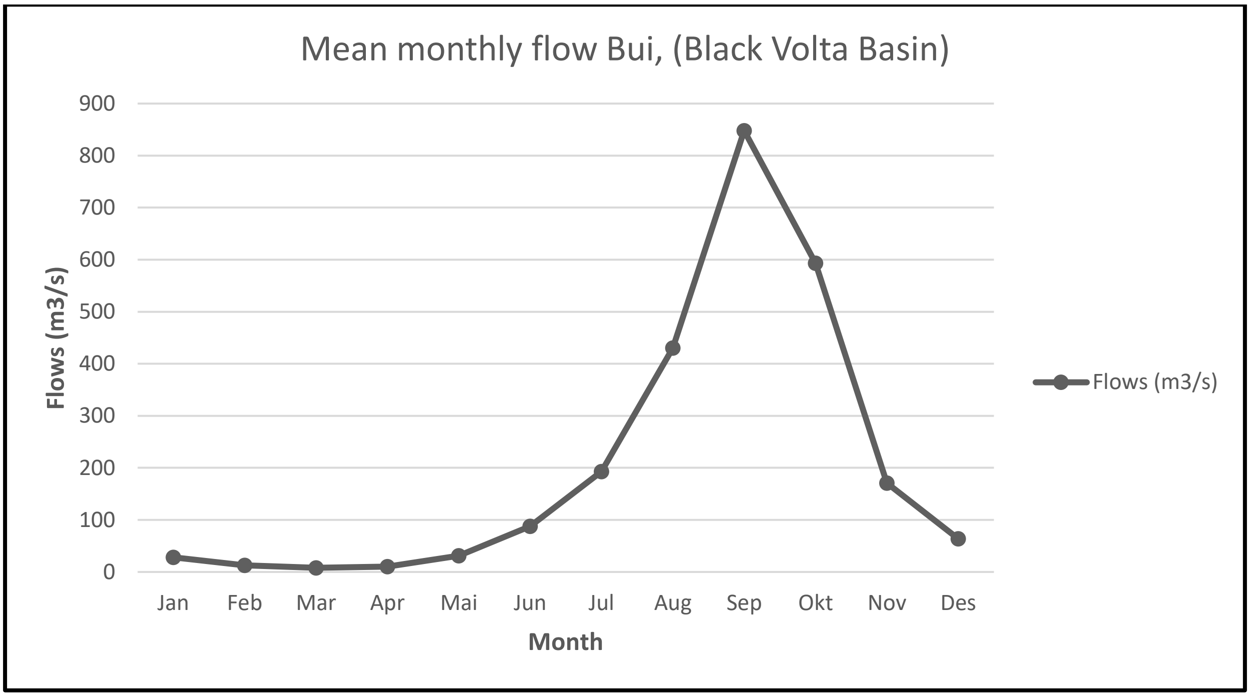

Figure 6 *Mean Monthly flows of the Black Volta at Bui, 1954-2005, source, VRA.*

2.3 WHITE VOLTA SUB- BASIN

As the second largest catchment within the Volta Basin, the White Volta Basin covers approximately 104,752 km^2 and represents 46% of the entire Volta catchment territory. Geographically, the region lies within the Interior Savannah Ecological Zone, underlain by voltarian and granite rock formations (Opoku-Ankomah, 1998). Morago and Tamne rivers are the main tributaries of the white volta. Morago has a total area of 1608 km^2 of which 596 km^2 is in Ghana, 912 km^2 is in Togo and 100 km^2 is in Burkina Faso. A total of 855 km^2 lies within Ghana's Tamne tributary. Barry et al., 2005 implies that the white volta lies mainly in the north-central part of Ghana. The white Volta sub-basin is noted for its high irrigation potential of about 48,000ha (FAO, 1997)

2.3.1 Hydrology in the sub basin

The annual rainfall in this sub-basin according to (Opoku-Ankomah, 1998) varies from 685 mm in the north (Mali) to 1,300 mm in the south (Ghana). It is estimated that the pan evaporation ranges from 1,400 mm to 3000 mm per year, with an average rainfall runoff of

96.5 mm. According to Barry et al. (2005), the peak annual flow of runoff is about 1,200 m^3/s in the rainy season and about 0.11 m^3/s in the dry season.

Stream gauges are installed at different locations in the sub basin to record periodic stream flows throughout the year. Flows generated within Burkina Faso as well as flows from inside Ghana are the primary sources of surface water in the basin. According to Barry et al. (2005), the mean annual flow of the White Volta is about 300 m3/s, 36.5% of which comes from Burkina Faso. Burkina Faso's estimated flows are measured at gauge stations along the borders with the country. These include the gauging station at Nangodi in the Red Volta and Yarugu. These stations measure average flows of 30 m3/s and 80 m3/s, respectively (Opoku-Ankomah and Amissigo, 1997). The White Volta basin flows contribute 20% of the annual total inflow into the Volta Lake (Water Resources Commission, Ghana).

Table 4 *Mean annual flux, white Volta river system (runoff generated only in Ghana)*

Sub-basin/Locality	**Area of sub-basin (km^2)**	**Mean annual flux (million m^3)**
White Volta at Pwalugu	4,130	420
White Volta at Nawuni	34,500	3,520
White Volta at Daboya	38,900	3,970
Red Volta sub-basin	420	43
Nasia Sub-basin	5,400	550
Nabogo sub-basin	2,730	280
Kulpawn sub-basin	9,310	950
Sissili sub-basin	5,220	530
Mole sub-basin	6020	610
Total White Volta River Basin	**50,000**	**5,100**

It is apparent that the flow regime of the white volta river exhibits a marked variation in both the seasonal runoff within a year and the annual flow. These features are shown in **figure 7** below using streamflow data collected from the Daboya gauge station in the downstream section of the White Volta River. The discharge record represents the pattern of flow following the construction of the Bagré Dam in Burkina Faso in 1995 (WRC, Ghana).

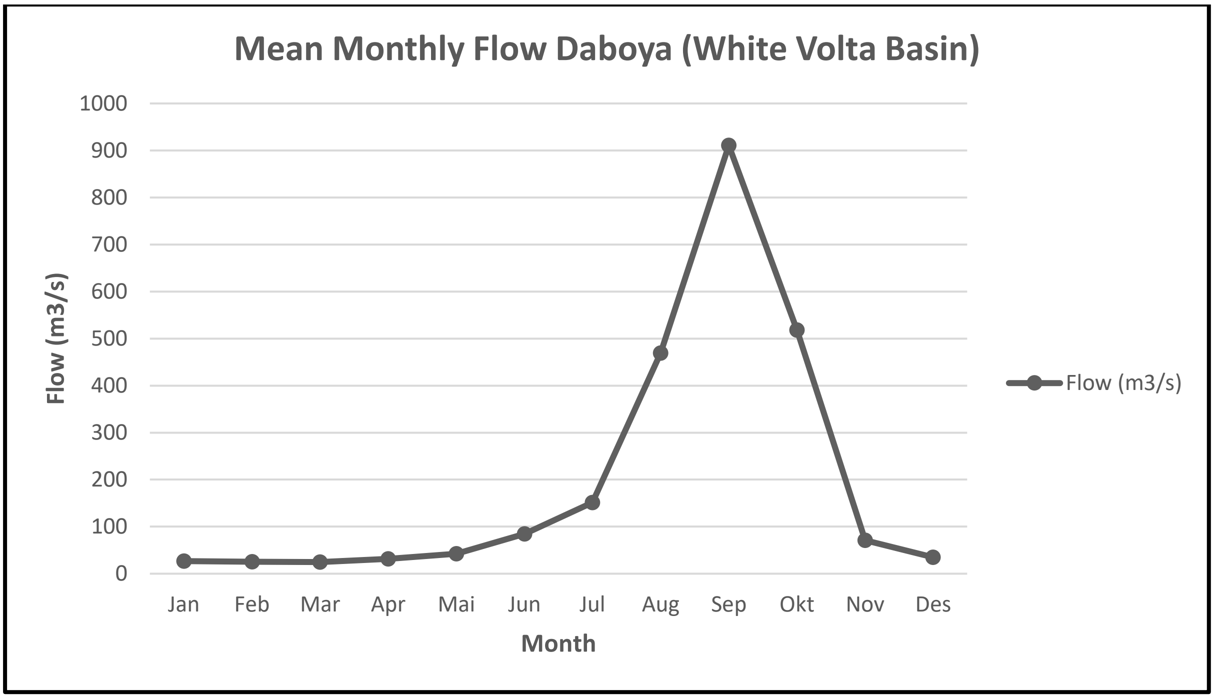

Figure 7 *White Volta river mean monthly flows at Daboya gauge station (1997-2007). Source: Hydrological Services Department, Ghana.*

2.4 Oti Sub-Basin

The Oti River Basin is among the smallest of the sub-basins, has a surface area of about 7300 km2, and lies primarily in northeastern Ghana. The basin includes parts of the Northern and Volta Region in Ghana, and it covers more than 40% of Togo's land. The northern portion of the subbasin receives about 1,000mm of rainfall each year, while the southern portion receives 1,400mm. There is 2,540mm of evaporation and about 254mm of runoff. According to the Nathan Consortium (1970), the average annual runoff into the Oti Basin is between 849 m3/s during the rainy season and 1.1 m3/s in the dry, and 12.6 km3/year is the mean flow. This catchment has steep topography and receives relatively high rainfall, facilitating surface runoff and contributing about 30-40 per cent of annual total flow contributions into Volta Lake though it is only about 18% of the entire Volta basin.

2.4.1 Climate Variability in the Volta River Basin

A major feature of the study area is the Intertropical Convergence Zone (ITCZ) movement, which is the area where northern hot, dry, and dusty harmattan air mass meets the south Atlantic cool, moist monsoon air mass. The harmattan wind blows from November to March when a north-easterly airflow from the Saharan desert replaces the south-western monsoon winds. During that time, storms in the Chad basin raise large quantities of dust into the atmosphere, which is then carried southwestward by the predominant winds (Kalu, 1979; McTainsh, 1980; McTainsh and Walker, 1982). During the wet season, moist equatorial air masses originating from the Atlantic Ocean bring annual monsoon rains (Nicholson, 2013).

2.5 Humidity and Temperature

The average temperature in the basin never falls below 25ºC due to its proximity to the equator. March-April is the hottest month, with temperatures reaching 44ºC, and August is the coolest. The temperature varies between 5-6ºC in the south and 7-9ºC in the north. This makes evaporation rates very high, ranging from 1500mm/year in the south to more than 2500mm/year in the north. The southern part of the basin is more humid than the northern part. There is 95-100% relative humidity in the morning and 75% relative humidity in the afternoon in the coastal area of Ghana. During the harmattan period, values can be as low as 20-30%, while during the rainy season, they can be as high as 70-80%.

2.6 Precipitation

In the Volta basin, rainfall is highly variable, both spatially and temporally. The Sahelian zone, located in the northern part of the basin, receives less than 500 mm/year. The Sudano-Sahelian Zone, which covers the more significant part of Burkina Faso, receives between 500 and 900 mm/year. The Sudanian zone comprises the northern part of Ghana and some parts of Côte d'Ivoire, Benin and Togo and receives rainfall between 900 and 1,100 mm/year. The Guinean Zone covers the southern part of Ghana and receives rainfall between 1,000 and 1,300 mm/year (Kranjac-Berisavljevic et al. 1999). The rainy season lasts about three months; in the Sudano-Sahelian Zone it lasts four to five months; and in the southern part of the Sudan and Guinean Zone it lasts six to seven months (Barry et al., 2005). Most of the basin's annual rainfall occurs between July, August, and September, with little or no rainfall between November and March.

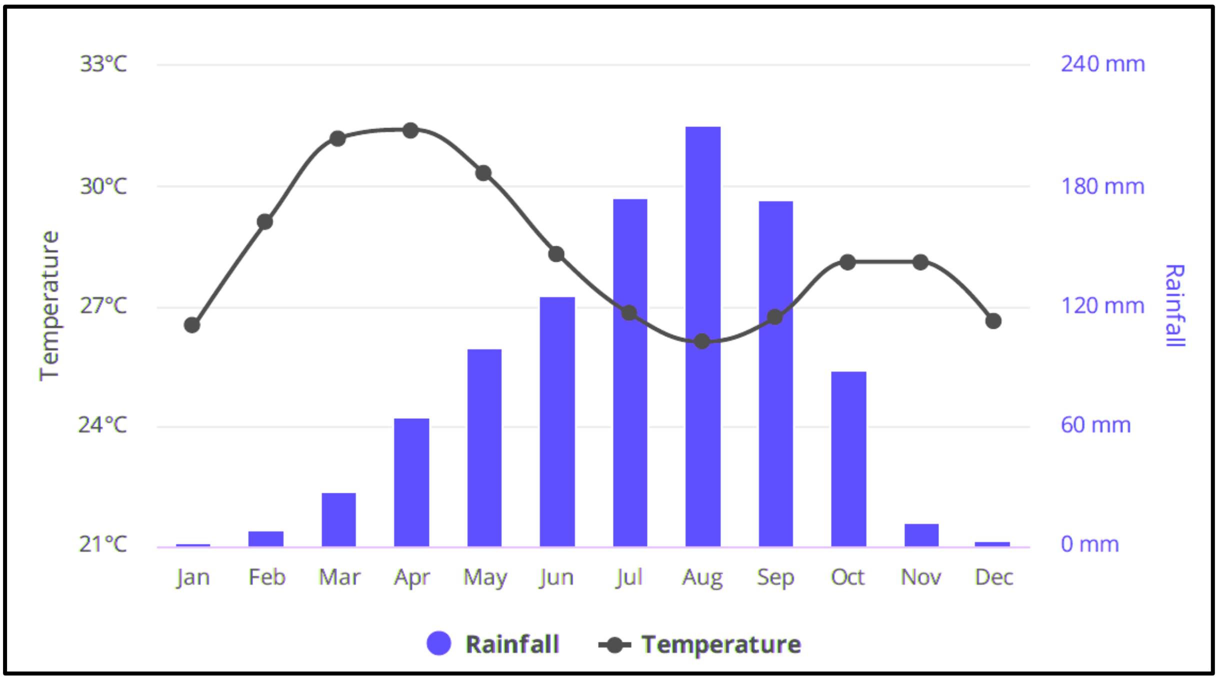

Figure 8 Mean monthly temperature and precipitation for the Volta Basin, (1991-2020) source: World bank climate change knowledge portal.

2.7 Land use and cover

A dominant land cover in the Volta Basin is savannah, characterized by grassland interspersed with shrubs and trees. Savannahs, grasslands, and shrubs cover 89.9% of the basin. Other types of land cover include wetland and water bodies (3.0%), forest cover (3.4%), and bare land/settlements (3.7%). The tree cover in the basin is generally low due to extensive farming, wood extraction, and overgrazing (Abubakari et al., 2012). In the savannah, both the density and quality of trees decrease in a south-to-north direction (i.e., according to the rainfall pattern).

The basin has several national parks, wildlife reserves, and other protected areas. The vegetation in these areas is green throughout the year, although some species shed their leaves in the dry season (MLNR 2012). Common trees associated with the forest are Cynometra Ananta, LOPHIRA ALATA, Tarrietia utilis, Antiaris africana and Chlorophora excelsa. Some of these trees have a higher regeneration rate and are more resistant to bush fires (MOFA 2011). Croplands are gradually replacing forest areas. Fallow periods have also reduced significantly. This is mainly due to increasing population growth. According to Landmann et al. (2007), land cover change within the Volta Basin between 1990 and 2000/2001 was investigated by comparing Landsat tiles for 1990 and 2000/2001 and adding 250-meter MODIS time-series observations for the year 2000. According to the resulting land cover map, 37% of the total area was converted from woodland with other shrubs to managed herbaceous vegetation; 6% was modified (change in tree cover density) from closed woodland (40-95% tree cover density [TC]) to open woody vegetation (15-40% TC); and 3% was transformed from closed woodland (40-95% TC) to herbaceous vegetation. Pressure from the increasing population was one of the important factors explaining the expansion of cropland areas and thinning of the tree cover.

2.8 Hydraulic Infrastructures and Water Use

Dams and reservoirs have been built throughout the Volta basin to mobilize water for agricultural, industrial use and produce energy. The number of large and small dams continues to increase as population pressure grows. As urbanization continues to rise, agriculture remains a strong economic force with upward trends for growth, particularly rice production. Increasing water use and decreasing precipitation due to climate change in the region threatens the management of the water and the multiple benefits drawn from the resource. Irrigation and other consumptive water use in the mid and upper reaches of the basin compete with hydropower production. The total irrigation potential in the basin is estimated to be 1,487,000 ha, and the annual water requirement for this potential is 28.590 km^3 (FAO, 1997). Despite considerable hydropower potential, the basin has only been partially exploited. Apart from the Akosombo, Kpong, Bagre and Kompienga, additional sites within the basin have been identified and constitute a combined potential of 1115MW (World Bank Global Water Practice, 2015). The list of major reservoirs both current and planned has been listed in table 5.

Table 5 Existing infrastructures in the Volta basin

Sub-basins ***Existing***	**Reservoir Name**	**Location**	**Purpose**	**Year completed**	**Storage Capacity (million m^3)**	**Installed Capacity (MW)**
Lower Volta	Akosombo	Ghana	H	1964	148000	1020
Lower Volta	Kpong	Ghana	H, WS	1981	200	160
Oti basin	Kompienga	Burkina Faso	H	1988	2025	14
White Volta	Bagré	Burkina Faso	H, I	1992	7000	16
White Volta	Vea	Ghana	I	1980	17.3	-
White Volta	Tono	Ghana	I	1985	93.0	-

The coding for the 'Purpose' of the dam is defined for this particular study where **H** is hydropower, **I** is irrigation, **WS** is water supply, and **C** is for flood control.

2.9 Flood and Drought in the Volta Basin

Flooding resulting from extreme rainfall events was in the past made worse by uncontrolled dam releases from the upper part of the basin, such as from Burkina Faso to Ghana on the White Volta. The construction of the Akosombo Dam in Ghana in the 1960s led to the inundation of over 8500km^2 resulting in the creation of Lake Volta. Drought is a common occurrence in the upper and mid part of the basin, where climatic conditions are harsher than in the south.

Ghana has the highest risk of weather-related hazards among the riparian countries, including urban flooding, farmland flooding, and dry spells. Flood and drought events are of concern, particularly in the northern part of the country. Most of the farmlands in Ghana are in the white volta basin, so decreased rainfall leading to drought affects crop production and increases hunger since most populace in the white volta basin depends on agriculture for their livelihoods. The decreasing level of lake volta in early 2006/2007, as shown in figure 3, resulted from low rainfall in the basin. August and September of 2007, after the severe drought, the basin saw a widespread of devastating floods due to extreme rainfall from July to September. These floods displaced hundreds of thousands of people, particularly in the three northern regions with resettlement. Furthermore, due to increased rainfall since 2007, possibly due to climate change, the Bagré reservoir exceeds its maximum capacity, which compels its managers to spill the excess water to protect the dam. The spill has devastating effects downstream of the reservoir.

2.9.1 Input Data

Runoff Data

Observed runoff data used for the calibration of the model is from Global Runoff Data Center (GRDC). In this study, runoff data from three stations in the sub- basins were used. These stations are Bamboi, Nawuni and Sabari in the Black, White and Oti basin respectively. Monthly runoff data was used for each of the stations due to data availability. The data from GRDC was from 1961-2006 but there were some missing data which were taken out. The GRDC data was converted to CSV format (Comma Separated Excel File) before it was uploaded into WEAP as an observed data.

Table 6 *Overview of measuring stations for runoff data*

Stations	**Bamboi**	**Nawuni**	**Oti**
Observation Period	1961-2006	1961-2006	1961-2006
Number of years	31[1]	43[1]	22[1]
Highest flow (m^3/s)	554.53(1991)	492.49(1999)	576.70(1963)
Average flow(m^3/s)	233.71	228.65	339.82
Lowest flow (m^3/s)	47.35(1990)	55.38 (1981)	110.16 (1999)
Median (m^3/s)	211.17	222.42	344.46

[1] There were some missing observed data in in the GRDC database, so those years were excluded for calibration purpose.

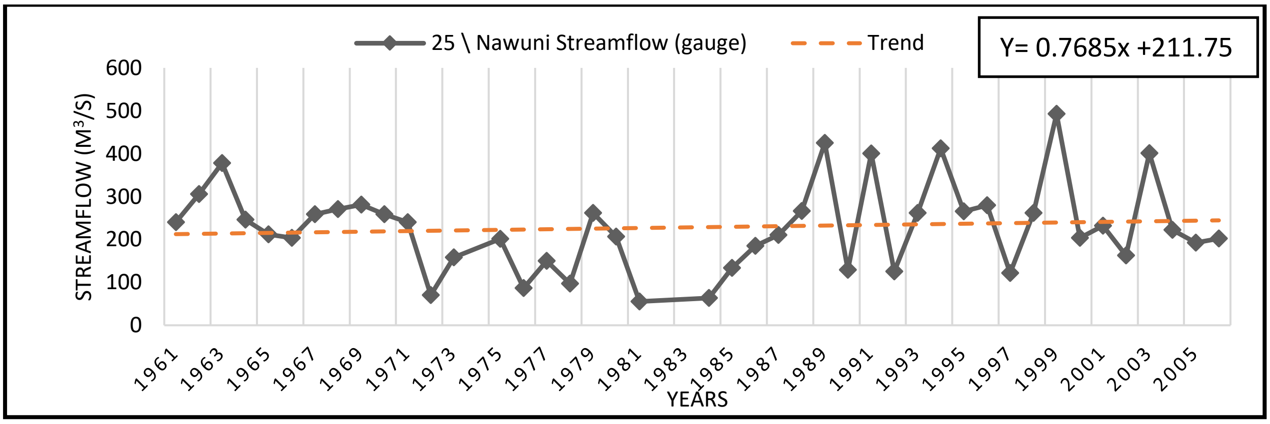

Figure 9 *Nawuni annual streamflow in the White basin.*

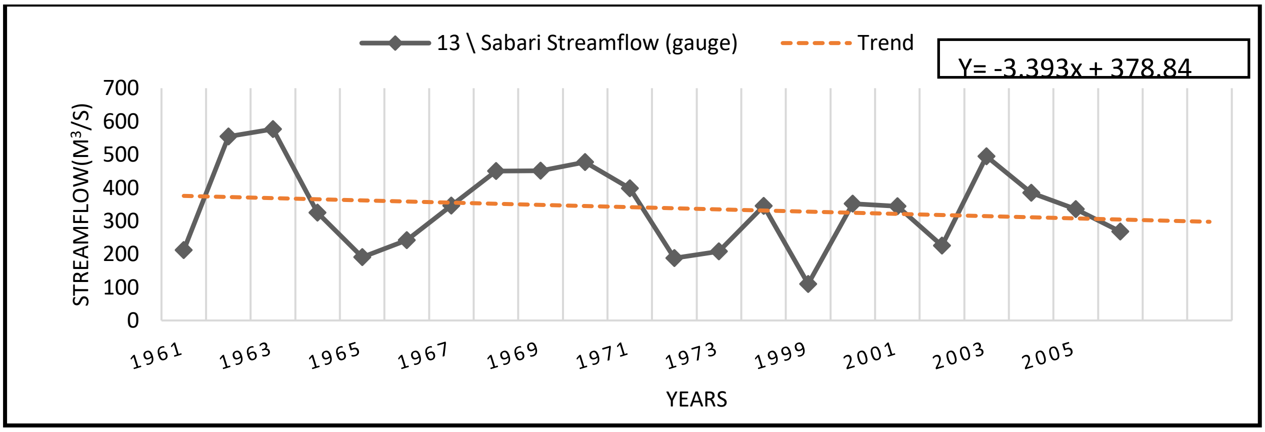

Figure 10 Sabari annual streamflow in the Oti basin

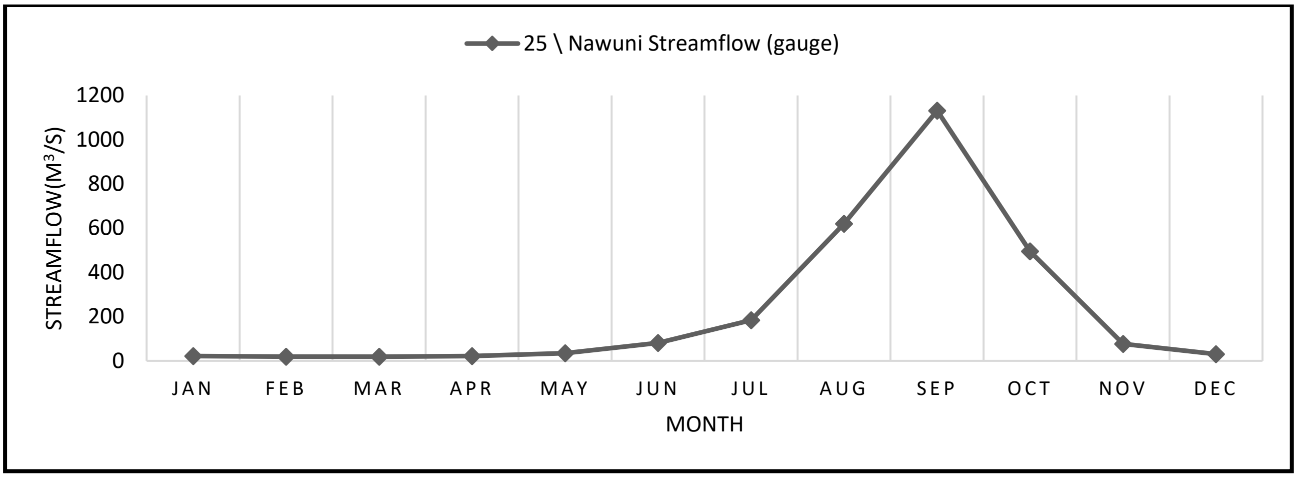

Figure 11 Nawuni monthly average streamflow from 1961-2006.

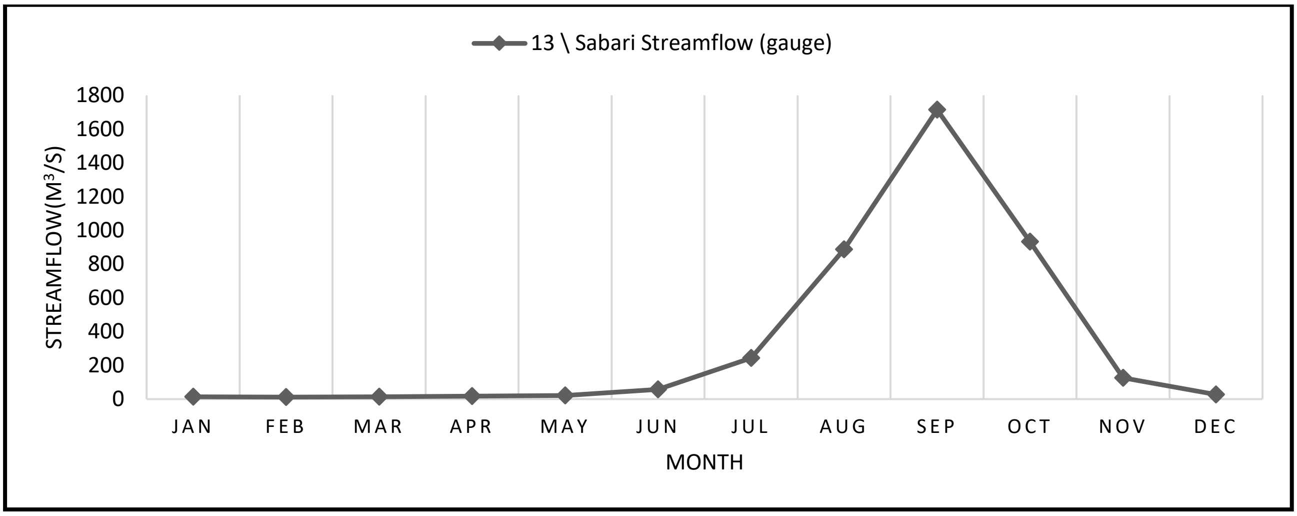

Figure 12 Sabari monthly average streamflow from 1961-2006.

The annual streamflow hydrographs in figure 9-11 show an increasing trend for the Nawuni streamflow gauge and a declining trend for Sabari and Bamboi gauges (appendix 4X). For Nawuni, the trend increases by $0.77m^3/s$. However, the trend cannot be predicted over a long period because it does not show a regular annual trend. Bamboi and Sabari gauges show a declining trend of $0.86m^3/s$ and $3.4m^3/s$, respectively. The most significant change is seen at the Sabari gauge. It is not clear whether the declining trend is due to an increase in upstream abstractions or more evaporation in the Oti basin. The hydrographs also show that streamflow through the gauges varies annually, making predictions difficult. The hydrographs for Bamboi on the Black volta basin have been attached in appendix 4.

The runoff is usually very high during the rainy season in July, August, and September, with a peak in September for all sub-basins. As shown in figure 12-14, it is evident in all the sub-basins that the flux is less in the dry season when there is low or no rainfall with high water abstraction and high evaporation in the basin.

Local reservoirs in this study are the Vea, Tono and Kompienga. They were modelled independently of river streamflow. Monthly inflows to local reservoirs were estimated using the surface water balance equation.

$$P = Q + E_T \pm \Delta S$$

Where P is the precipitation in the reservoir's catchment, Q is the Inflow into the reservoir, E_T is the Evapotranspiration in the catchment and ΔS is the change in groundwater storage, which was assumed to be zero.

2.9.2 CLIMATE DATA

The climate data in this report is from the Princeton data centre. Since climate data have been incorporated into WEAP, the study did not require downloading of climate data. These data were available for the three sub-basins. The time resolution for the dataset is monthly, where precipitation is taken as total precipitation (mm) per month and temperature is taken as the average temperature in degrees Celsius. The dataset is in CSV (Comma Separated Excel file) format. Excel has been used in the study for processing data and graphical representation for easy analysis. Climate data used for modelling is presented in this chapter.

Table 7 Overview of climate Stations in the Volta basin

Sub-basins	Elevation (m.a.s.l)	Period	Number of years	Latitude	Average precipitation (mm/year)	Average temperature (ºC)
Black Volta	0-500	1960-2010	51	11.48	862	28
	500-1000	1960-2010	51	12.203	841	27
White Volta	0-500	1960-2010	51	9.444	1069	28
Oti Basin	0-500	1960-2010	51	8.694	1240	27
	500-1000	1960-2010	51	8.613	1266	26

From the climate data provided by the Princeton data centre, there is no missing data for the period used for this study.

The historical precipitation records in the sub-basins are based on the elevation of the sub-basins; thus, 0-500 and 500-1000m, except for the White basin, whose elevation lies mainly within 0-500m. The sub-basins show significant differences in precipitation every year, and the trends show a decline in annual total precipitation in each sub-basin, as shown in figures 15-19. The trend for annual precipitation declines for the Oti sub-basin is about 2.7mm/year for the entire sub-basin considering both elevations, i.e. 0-500m and 500-1000m. The declining trend for the White Volta basin is 0.5mm/year, while the Black Volta basin declines by about 1.0mm/year. The most notable precipitation decline is in the Oti basin. The low precipitation reflects the steep decline in the runoff at the Sabari gauge, as shown in figure 11. Historically, precipitation has been very high in the Oti basin, with 1963 recording the highest precipitation of about 1800mm and the lowest of about 820mm was recorded in 1983, as shown in figure 16.

Even though figure 19 shows a decreasing trend of precipitation in the white volta basin, it is observed from figure 9 that runoff instead increases in the sub-basin. The opposite trends could be attributed to erratic rainfalls and climate change in the sub-basin (Owusu et al., 2008). On the other hand, the Black Volta basin shows a corresponding decline trend in precipitation and runoff from figures (10, 17 and 18).

The historical annual temperature data shows an increasing trend in all the sub-basins, with the temperature rising by 0.02^{o}C/year. Since the entire basin falls within the same climatic zone, the monthly variation in temperature is almost the same. In the basin, March and April are the warmest months, with a monthly average temperature of about 31^{o}C. The basin records its highest evaporation around this period, as seen in appendix.1A. The coldest months in the basin are July, August, and September, with a monthly average temperature of about 26^{o}C. This is shown in figures 26-28.

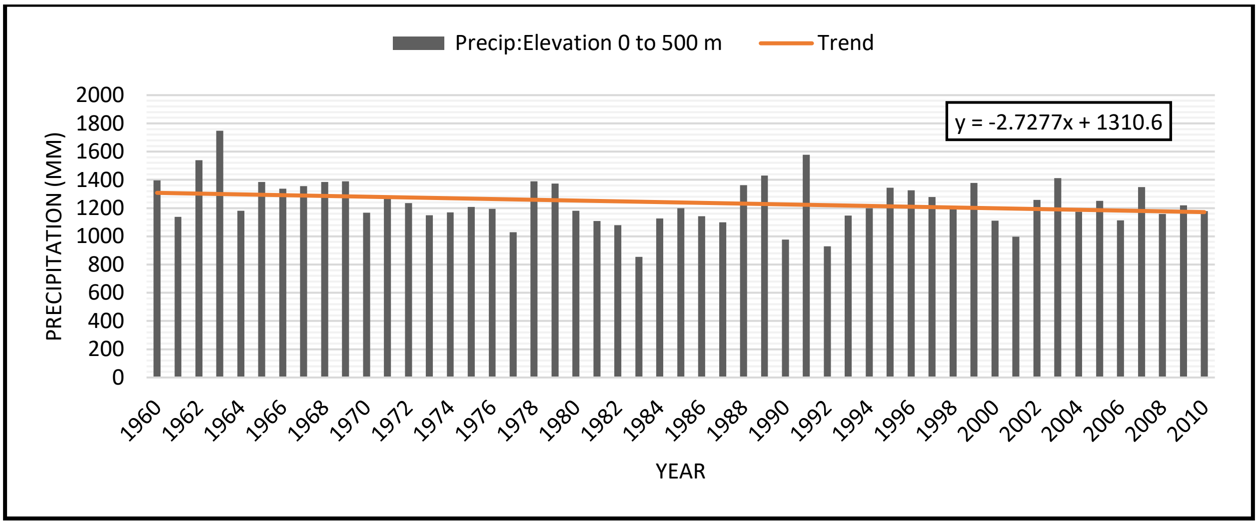

Figure 13 Annual precipitation in the Oti basin at an elevation of 0-500m

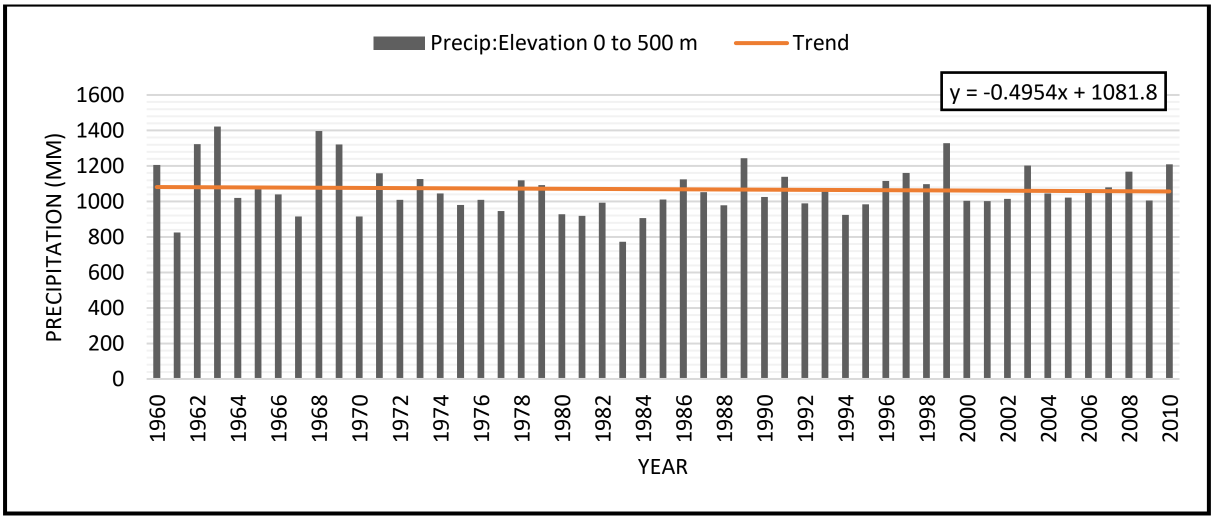

Figure 14 Annual precipitation in the White volta basin at an elevation of 0-500m

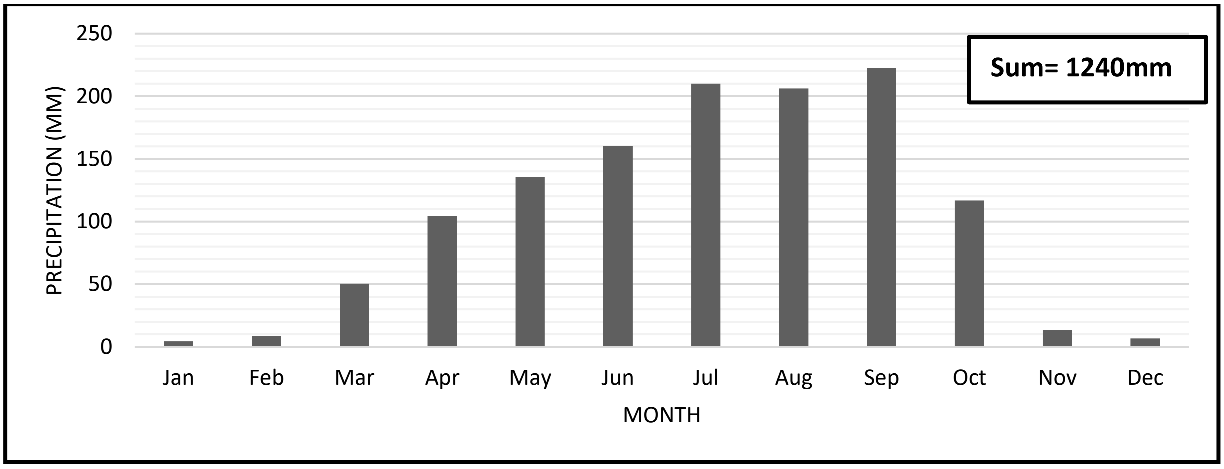

Figure 15 *Average monthly precipitation in Oti basin (1960-2010)*

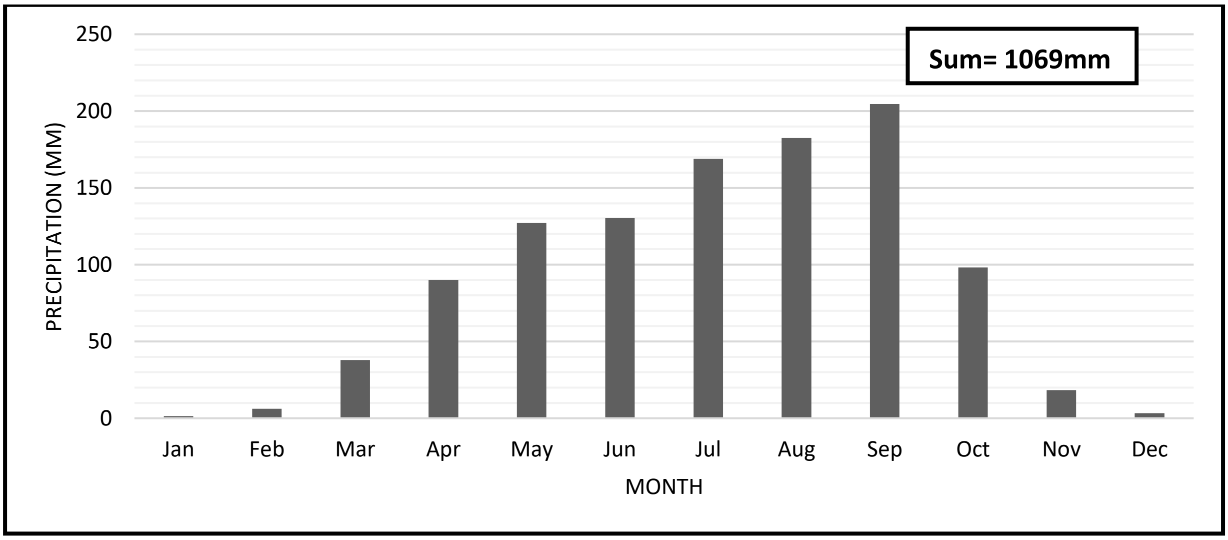

Figure 16 *Average monthly precipitation in White Volta basin (1960-2010)*

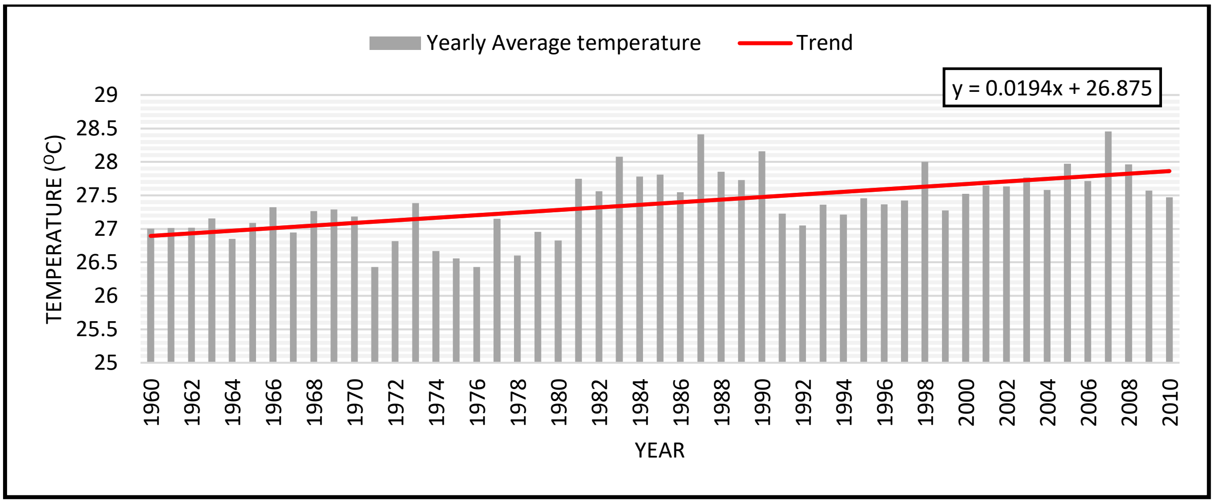

Figure 17 *Yearly average temperature for Oti basin*

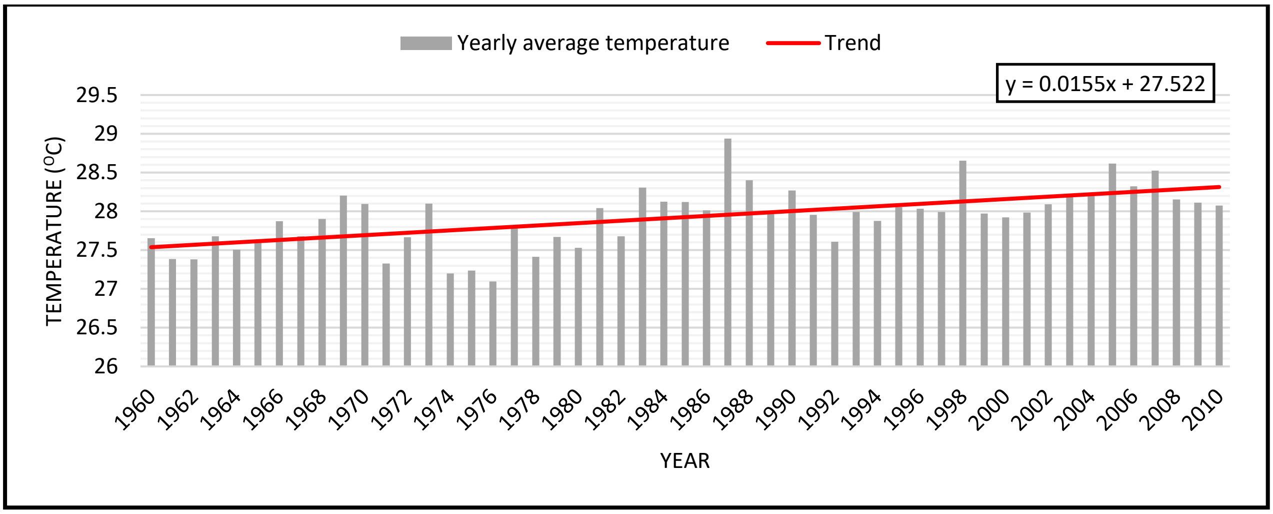

Figure 18 Yearly average temperature for White volta basin.

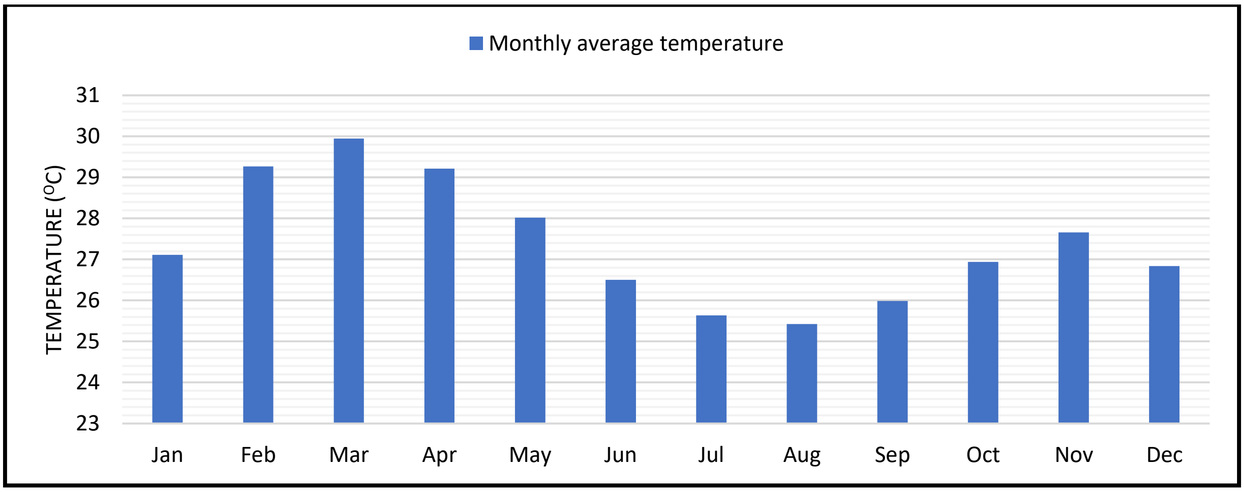

Figure 19 Monthly average temperature for Oti basin (1960-2010).

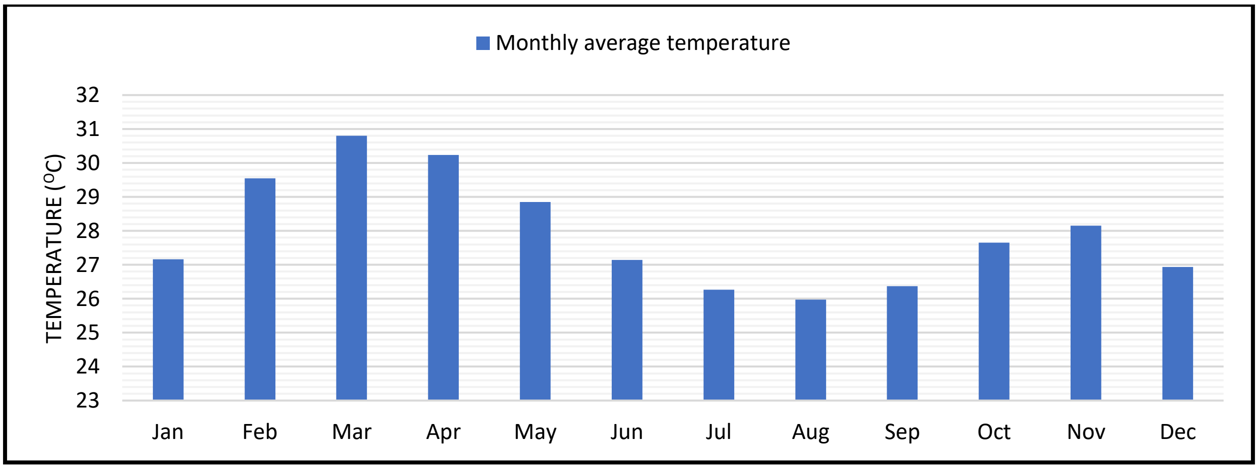

Figure 20 Monthly average temperature for White Volta basin (1960-2010).

2.9.3 Water Demand in WEAP

There is limited water demand information available, but the data used for this study represent the highest abstractions in the basin. The demands have been categorized into three parts, i.e. Irrigation demand, Water supply (domestic and industrial) and livestock demand. The water demand data is taken from the Water Resources Commission of Ghana (WRC) report, 2008; Ministry of Works and Housing, 1998; Boubacar et al., 2005; Nii Consult, 2007; Allwaters consult report on Black volta, 2012 and the Community Water and Sanitation Agency (CWSA). The population data was obtained from Ghana Statistical Service (GSS). The water demand has been summarized for the sub-basins in Table 8. For the sake of simplicity, the water demand for irrigation in the black volta and Oti basin were lumped before setting in WEAP as irrigation demand.

Table 8 *Water demands in the Volta basin.*

Sub-basin	**Irrigation Demand (Mm^3/year)**	**Water Supply (Mm^3/year)**	**Livestock demand (Mm^3/year)**
Black Volta	192.92	158.35	1.7
Oti basin	70	32.8	Unknown
White Volta basin	96	33.43	11.3

The existing irrigation information used in this study has been reported in table 9.

Table 9 *Irrigation water use data*

Existing Irrigation	**Startup year**	**Priority in WEAP**	**Irrigated area (Ha)**	**Annual water use rate (m^3/ha)**	**Percentage share of annual volumes (%)**											
					January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Vea	1980	1	1000	8000	26	23	0.1	0	0	0	0	0	0	0.1	25	26
Bagré	1992	1	2100	19048	26	23	0.1	0	0	0	0	0	0	0.1	25	26
Tono	1977	1	2500	1600	26	23	0.1	0	0	0	0	0	0	0.1	25	26
Nasia	-	1	1500	8000	26	23	0.1	0	0	0	0	0	0	0.1	25	26
Black Volta Irrigation	-	2	9646	20000	26	23	0.1	0	0	0	0	0	0	0.1	25	26
Kompienga	1988	1	7000	10000	26	23	0.1	0	0	0	0	0	0	0.1	25	26

Irrigation is vital in the basin since most indigenes depend on it to improve food security by increasing productivity. It is also meant to reduce rural-urban migration by providing employment opportunities for the youth. For these reasons, irrigation has been given the highest priority to meet its water demand. The water demand in table 9 is an estimation of the gross with the consumption in the model set at 80% and 20% returning to the river.

The Ministry of Works and Housing, Ghana -Water Resources Management (WARM, 1998) suggests that irrigation in the basin is assumed to be for 4months with 12hrs of pumping per day. Therefore, the monthly variation was calculated based on this assumption. The demand is high during the dry season as specified in table 9. However, monthly variation was made constant for all the irrigation sites due to the unavailability of data.

Table 10 Water supply and livestock water use in the basin.

Water Supply and Livestock water use	**Priority in WEAP**	**Population (Million)**	**Annual water use rate (m^3/cap)**	**Monthly variation in Percentage (%)**											
				January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
M.D (white volta)	1	1.84	8.3	9.5	8.7	9.5	9.2	9.5	8.2	7.5	7.5	7.2	6.4	8.2	8.5
M.D. (Bamboi)	1	0.12	31.0	9.5	8.7	9.5	9.2	9.5	8.2	7.5	7.5	7.2	6.4	8.2	8.5
I. W. (Black Volta)	1	0.44[1]	5[1]	9.5	8.7	9.5	9.2	9.5	8.2	7.5	7.5	7.2	6.4	8.2	8.5
M.D (Oti basin)	1	0.83	32.9	9.5	8.7	9.5	9.2	9.5	8.2	7.5	7.5	7.2	6.4	8.2	8.5
U.W.S (Burkina Faso)	1	7.8	20	9.5	8.7	9.5	9.2	9.5	8.2	7.5	7.5	7.2	6.4	8.2	8.5
L.W.D (Black Volta)	1	0.6	2.8	9.5	8.7	9.5	9.2	9.5	8.2	7.5	7.5	7.2	6.4	8.2	8.5
L.W.D (White Volta)	1	2.5	5.5	9.5	8.7	9.5	9.2	9.5	8.2	7.5	7.5	7.2	6.4	8.2	8.5

Where **M.D**. is the Municipal Demand, **I.D** is Industrial water use, **U.W.S** is Urban Water Supply and **L.W.D** is Livestock Water Demand.

[1] For the Industrial Water use, production is measured in tonnes, so water demand was estimated based on total production in tonnes

To define the livestock (primarily, Sheep, cattle, and goats) water use information available in Environmental Protection Agency (EPA)- National Action Program to Combat Drought and Desertification (April 2002) has been used. It indicates that the livestock population as of 2008 in the Volta basin is approximately 2.5million and the unit water consumption per livestock is 10-15litres per day. The annual water use rate is given by the relation.

$$Annual\ water\ use\ rate\ (m^3/cap/year) = \frac{Water\ abstraction\ (Million\ m^3/year)}{Population\ (cap)}$$

The monthly water use rate is originally gotten from dividing the number of days in a month by the total number of days in a year. For example, January has 31 days, so that the water use rate will be: The reason for using this format is that, unlike crops, livestock and municipal water demand is a daily requirement for sustaining lives.

$\frac{31}{365} \times 100 \ = 8.49\%.$

The monthly variations were adjusted as seen in the table for the purpose of calibration.

Large hydropower dams in the Volta Basin

This chapter describes data from various sources for hydropower dams in the volta basin. The major existing hydropower dams used in this study are the Akosombo, Bagré and Kompienga. To simulate dam operations in WEAP, the following parameters are required.

- The storage capacity
- Volume elevation relation
- Maximum turbine flow
- Net evaporation
- Inactive storage
- Top of buffer zone of the reservoir below which turbined-water is constrained
- Buffer coefficient i.e. the rate of release of the fraction of water contained in the buffer zone

Table 11 *Large reservoirs in the Volta basin*

Reservoir	Storage Capacity (Mm^3)	Inactive storage (Mm^3)	Top of buffer (Mm^3)	Maximum turbine flow (Mm^3/Year)	sources
Akosombo	148000	70000	85000	31200	VRA, van de Giesen et al. (2001),
Bagré	2025	400	500	800	SONABEL
Kompienga	7000	500	700	550	SONABEL

SONABEL- Société National d'Electricité du Burkina, translates as Burkina National Electricity Company.

Priority in WEAP for water allocation

It has been used to describe how demand sites are prioritized relative to all other demands regarding the supply of water. The priority ranking is from 1 to 99. Priorities can change over time and with different scenarios. In this study, first priority was given to all demand sites except for Black volta irrigation, which was given a second priority to aid in the calibration process as shown in table 9 and 10.

Reservoir Zones and Operation

The reservoir storage is divided into four zones. These include, from top to bottom, the flood-control, conservation zone, buffer zone and inactive zone. The conservative and buffer zones together constitute the active reservoir storage. WEAP allows the reservoir to freely release water from the conservation pool to fully meet withdrawal and other downstream requirements, and demand for energy from hydropower .There is a restriction in the release when the level drops into the buffer zone due to the buffer coefficient varying from 0 to 1. The active volume can have a monthly variation using the buffer coefficient. For all reservoirs, the buffer coefficient has been set to 1, and the active volume is constant throughout the year.

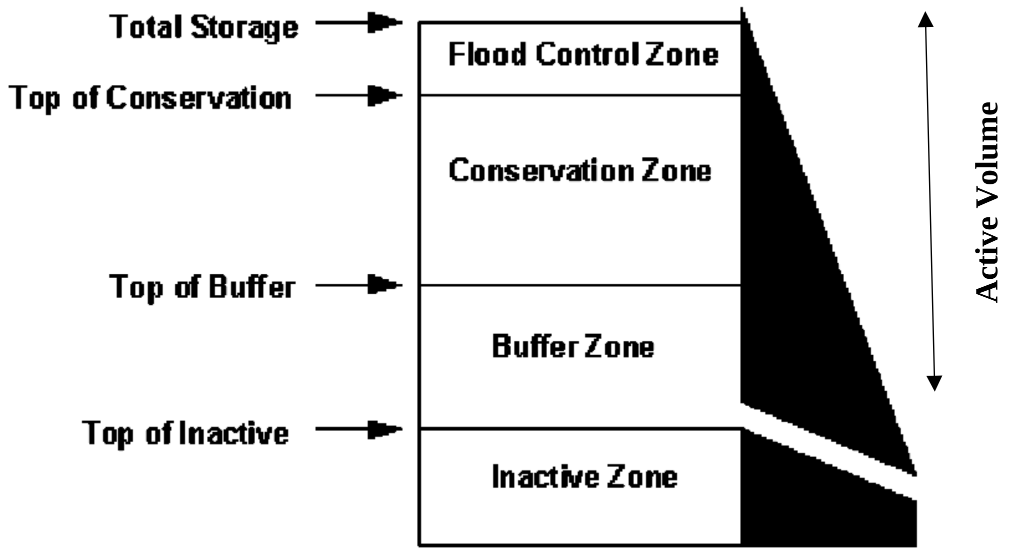

Figure 21 *Different reservoir zones adapted from WEAP user guide (SEI, 2015)*

Reservoir Volume – Elevation curve.

To calculate the power generation, one must know the volume of release (Mm^3) and the head (m). A volume-elevation curve has therefore been defined for each of the reservoirs. The points on the curve have also been used to define a function to convert between volume and elevation for each reservoir. Opgrand et al., 2019 have defined volume-elevation curve data for the Akosombo reservoir, which has been used in this report, as shown in figure 30. Due to data constraints for other reservoirs in the basin, a linear function was assumed with starting points (0,0) and the highest point (highest elevation, maximum dam capacity) for all other reservoirs.

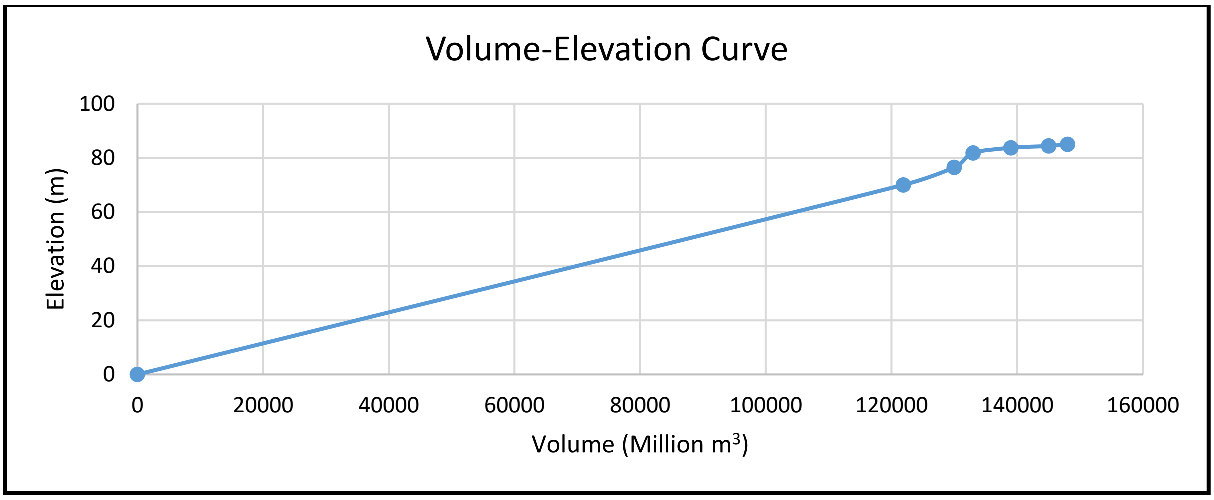

Figure 22 Volume-elevation curve used for Akosombo dam in WEAP.

Net Evaporation on reservoirs

The monthly net evaporation has been calculated using the penman equation. The net evaporation for has been estimated and thoroughly described in chapter 2.5. The net evaporation is positive when there is a net loss from the reservoir and negative when there is a net gain.

$$Monthly\ net\ evaporation\ (mm) = Evaporation - Precipitation\ on\ reservoir\ surface$$

Turbine flow, Efficiency and Energy Production

The annual turbine flow was taken from the sources provided in table 11. The generating efficiencies for each of the powerhouse was assumed. The hydropower generation was also taken from sources listed in table 12.

Theoretically, the energy production is given by, $E\ (GWh) = \rho \times g \times H \times \eta \times Q_t \times hr$

Where ρ is the density of water, assumed to be $1000kgm^{-3}$, g is the acceleration due to gravity (9.81 ms^{-2}) , H is the net head, Q_t is the Maximum turbine flow (m^3s^{-1}) and hr is the hours of generation.

Energy generation is given in GWh, but in WEAP, it is expressed in thousand GJ, so the values were appropriately converted before putting in the model. It should be noted that 1 Gigawatt hour is equivalent to 3600 Gigajoule.

Table 12 Power stations and their Annual energy productions

Power Station	**Efficiency (%)**	**Annual Energy Production (GWh)**	**Sources**
Akosombo	85	6502.8	VRA
Bagré	85	140.16	SONABEL
Kompienga	80	122.6	SONABEL

2.9.4 WEAP MODELING

In this chapter, the research questions were answered by putting together a set of procedures to evaluate the objectives of the study. The first stage was to consider a decision-tool for hydrological/water management modelling. The model was set up by defining the Volta River Basin, historical climate data, water related infrastructure, land, and water use in the basin.

The decision-tool for water allocation in the Volta River Basin was developed using the Water Evaluation and Planning (WEAP) model of the Stockholm Environment Institute. The description of the WEAP model with its parameterization is given in this chapter. The chapter further describes different scenarios used in this study.

OVERVIEW OF THE WEAP MODEL

The distribution and management of freshwater has become a great concern to many nations. There is a limited supply of freshwater which is supposed to be allocated to agriculture, municipal, hydropower and ecological uses. It is for this reason that the WEAP model was developed to help stakeholders in addressing these fundamental problems of water sharing.

The WEAP description is mainly based on the WEAP User Guide by (Sierber and Purkey, 2015).

The WEAP software is a tool for integrated water resources planning which assist the skilled planner by providing comprehensive and flexible framework for policymaking and planning. WEAP works on the principle of water balance and can be applied to municipal and agriculture, a single catchment or complex transboundary river basin systems. WEAP has in-built algorithms to simulate evapotranspiration, crop water requirement yields, runoff and infiltration, surface water/ groundwater interaction, stream water quality and storage.

WEAP operates at a daily, weekly, and monthly timesteps depending on the size of the basin. Larger basins are represented with longer timesteps in an order of months. While smaller basins have shorter timesteps in order of days and weeks.

WEAP has been designed to analyze different scenarios with questions such as:

- What if there is an increase in population?
- What if ecosystem requirements are tightened?
- How would land use changes affect streamflow?
- What will be the effect of climate change on demand and supply?

WEAP has an automatic geographical Information System (GIS)-based interface which gives a powerful means of constructing, viewing, and modifying the configuration.

WEAP has been structured to consist of five (5) main views:

1. *Schematic View*: This is a starting point which allows you to configure your system. With this view, you can delineate your catchment and indicate where the demand sites are located using the “drag and drop” capability of the tool.

2. *Data View*: This view is used for entering data into the model. This is where assumptions and projections using mathematical expressions are made. It allows importing and exporting of excel data in the model. Climatic and other types of data imported into the model are

converted to Comma-Separated Values (CSV) file format before it can be accepted by the model.

3. *Results View*: This gives models outputs in the form of graphs and tables. The generated results can be downloaded in excel in the form of streamflow where the observed data is compared to the simulated for calibration.

4. *Scenario Explorer View*: This is used to display several results at the same time. It helps you to understand how changes in data could affect the results.

5. *Notes*: This helps you to document some key assumptions for future reference. This can easily be exported to Microsoft word.

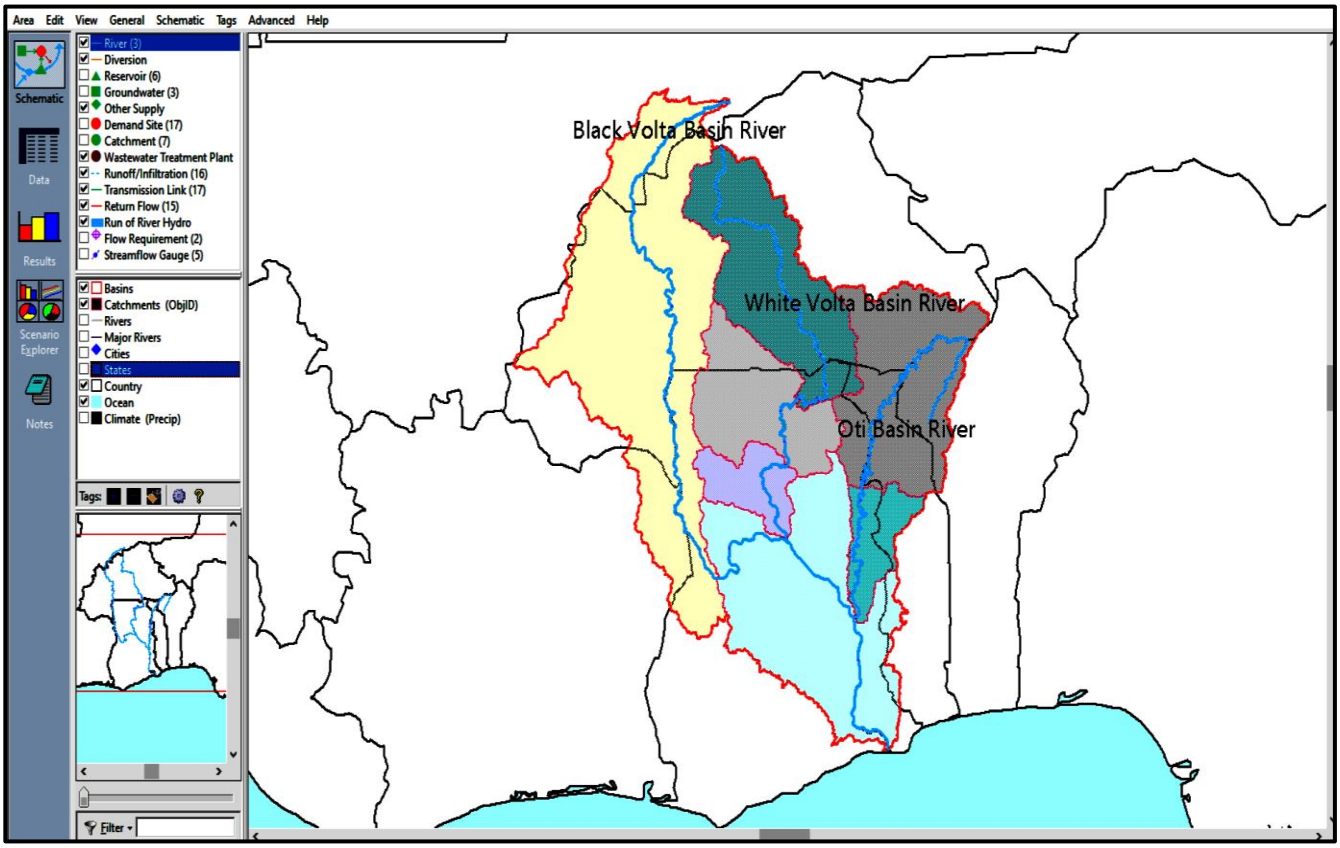

Figure 23 *Schematic diagram showing the sub-basins of the Volta River Basin.*

WEAP has been integrated with other models and software packages such as QUAL2K(Q2K), MODFLOW, MODPATH AND LEAP.

QUAL2K (Q2K): This model is incorporated into WEAP for river and streamflow quality. It is usually calibrated outside the WEAP model before linking them.

MODFLOW: This program is integrated into WEAP to simulate the flow of groundwater through aquifers.

MODPATH: This model is also linked up with WEAP for tracking particles in groundwater. It uses outputs from the MODFLOW. This implies that, it can only be linked to WEAP after MODFLOW has been linked.

LEAP: Long-range Energy Alternatives Planning system (LEAP) is a powerful tool which combines energy planning and climate change mitigation assessment. LEAP helps to set up a live connection to a WEAP model. It gives an idea of energy consumption, production, and the corresponding resource extraction (Weap21.org).

Case study applications of the WEAP model

WEAP model has been applied in different communities, catchments, and basins by stakeholders for planning and policymaking purposes.

As part of the ADAPT project, WEAP was used to develop and evaluate strategies in the Volta Basin (mainly in Burkina Faso and Ghana) to alleviate the negative impacts of climate change and variability. Different adaptation strategies were analyzed with WEAP to address the tradeoffs between water allocations that prioritize the environment and food security under changing climate and land-use conditions. (ADAPT, 2016)

In South Africa, WEAP model has been useful for water management scenarios in a water-stressed basin known as Olifants River basin. WEAP was used to create a model that could be used to simulate and analyse different water allocation scenarios as well as user activity scenarios. Water demand control was considered in scenarios and simulations for a variety of climatic scenarios from dry years to normal years (H. Leviet et al, 2003).

WEAP has been used to assess the impact of projected climate change on water availability and crop production in the volta basin and the southwestern and coastal basin systems of Ghana. WEAP modelled the water allocation (Municipal, Hydropower and Agriculture) very well according to Amisigo et al., 2015

2.9.5 Reservoir Surface Evaporation Estimation

Evaporation is one of the hydrological cycle processes that depend on precipitation, climate, runoff, temperature, etc. It is subdivided into actual evaporation (Ea) and potential evaporation (Ep). Ea is measured using hydrological and meteorological data. Ea can be estimated using the pan evaporation method and soil moisture content. This method is limited to water usage. Typically, there are no long-term data available for estimating the actual evaporation of large areas. (WMO 1974, referenced in LHOMME 1997, p. 258) defined Potential evaporation as the "quantity of water vapour which could be emitted by a surface of 'pure' water, per unit surface area and unit time, under the existing atmospheric conditions".

Evaporation from lakes constitutes the most significant percentage of the water balance; therefore, its accurate determination is critical for an acceptable estimation of the water budget (Kebede et al., 2006)

Many methods are available for estimating open water evaporation. These methods are grouped into different categories. That is empirical, energy budget, water budget, mass transfer and the combination of mass transfer and energy budget. (Singh & Xu, 1997)

The mass transfer method uses eddy motion transfer of water vapour from an evaporating surface (Singh & Xu, 1997).

The energy budget method considers the difference in energy input and output on the reservoir surface (Lenters et al., 2005; Singh & Xu 1997).

Penman equation is a classic combination of the mass transfer and the energy balance equations, which has been used in this study for estimating evaporation for reservoirs in the Volta Basin.

The Penman equation is written as (McJannet et al., 2008):

$$\boldsymbol{E} = \frac{1}{\lambda_v} \times \left(\frac{\Delta \times R_n + \gamma + 6.43 \times (1+0.535 \times U_2) \times (\delta_e)}{\Delta + \gamma}\right)$$

E : Open water Evaporation (mm/day)

$\boldsymbol{\lambda_v}$: Latent heat of vaporization (MJ/Kg) at air temperature (T_a) is calculated using the relation from (McJannet et al 2008)

$$\boldsymbol{\lambda_v} = 2.501 - 2.361 \times 10^{-3} T_a$$

An average air temperature, T_a, of 27°C was used in the calculation of λ_v which gave **2.44 MJ/Kg**

Δ: *Slope of Saturation* (KPa/K)

$$\Delta = \frac{4098 \times 0.6108 \times e^{\left(\frac{17.3T}{T + 237.3}\right)}}{(T + 237.3)^2}$$

T : Average temperature (°C)

$\mathbf{R_n}$: Net Solar radiation (MJ/m^{2}day) = R_{ns} - R_{nl}

R_{ns} : Net shortwave radiation

R_{ns} = R_s (1-a)

a = albedo (Diffuse reflection of solar radiation measured on a scale from 0, corresponding to a black body that absorbs all incident radiation, to 1, corresponding to a body that reflects all incident (Coakley, J . A, 2003)

R_s : Incoming solar radiation (MJ/m^2). Rs is a function of time of the year, location, and cloudiness. See Fig .1

R_{nl} : Longwave radiation out [MJ/m^2K^4day]

$$R_{nl} = \sigma \times [\frac{(T_{max}+273.16)^4+(T_{min}+273.16)^4}{2}] \times (0.34 - 0.14\sqrt{e_a}) \times (\frac{1.35R_s}{R_{so}} - 0.35)$$

σ: Stephan- Boltzmann constant $= 4.903 \times 10^{-9}\ MJ/K^4m^2day$

T_{max} = Highest measured temperature (℃)

T_{min} = Lowest measured temperature (℃)

$$\delta_e(KPa) = e_s - e_a$$

e_s : Saturated vapor pressure of air

e_a : vapor pressure of air given humidity

$$e_s = \frac{e_{(T_{max})} + e_{(T_{min})}}{2}, \qquad e_a = \frac{RHmean}{100} \times (\frac{e_{(T_{max})} + e_{(T_{min})}}{2})$$

$$e_{(T_{max})} = 0.6108 \times e^{\frac{17.3 \times T_{max}}{T_{max}+237.3}}$$

$$e_{(T_{min})} = 0.6108 \times e^{\frac{17.3 \times T_{min}}{T_{min}+237.3}}$$

RH_{mean} : Average Humidity

$$R_{so} = (0.75 + \frac{2Z}{10^5}) \times R_a$$

Z : Height above sea level (m) (highest reservoir level)

R_a : The extraterrestrial radiation.

Extraterrestrial radiation for each day of the year and for different latitudes, can be estimated from the solar constant, the solar declination, and the time of the year.

$$R_a = \frac{24 \times 60}{\pi} G_{sc} \times d_r[\omega_s \times sin(\varphi) \times sin(\delta) + cos(\varphi) \times cos(\delta) \times sin(\omega_s)]$$

G_{sc} : Solar constant, which is approximately (**0.0820 $MJ/m^2/day$**)

d_r : The inverse relative distance earth-sun

ω_s : the sunset hour angle (rad) ϕ : the latitude (rad)

$\boldsymbol{\delta}$ **:** the solar decimation

$$d_r = 1 + 0.033 \times cos\,[\frac{2\pi}{365} \times J\,]$$

$$\delta = 0.409\,sin\,[\frac{2\pi}{365} \times J - 1.39]$$

$$\varphi = \frac{\pi \times [\,Decimal\ degrees]}{180}$$

$$\omega_s = arcos\,[\,-tan(\varphi) \times tan(\delta)\,]$$

Where J is the number of the day in the year between 1 (1st January) and 365 or 366 (31st December). The latitude (ϕ) expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere.

ɣ : Psychometric constant (KPa/K)

$$\gamma = \frac{0.0016286 \times P}{\lambda_v}$$

P : Atmospheric Pressure (KPa)

$$P = 101.3 \times [\frac{293 - 0.0065 \times Z}{293}]^{5.26}$$

The monthly climate parameters T_{max}, T_{min}, U_2, Z, Latitude and RH_{mean} for different reservoir surfaces in the Volta river basin was generated with the AQUASTAT Climate Information Tool. The Climate Information Tool is an interactive tool used to query a spatial dataset containing long- term mean monthly climate data. The dataset covers the global land surface at a 10min spatial resolution for the period 1961-1990 (www.fao.org/aquastat/en/climate-info-tool/). The methodology used in this tool has been described in FAO irrigation and Drainage paper 56. The Akosombo reservoir has been displayed in Table 13 as an example of how reservoir surface evaporation was calculated. An excel file to show all calculations has been attached as appendix 1.

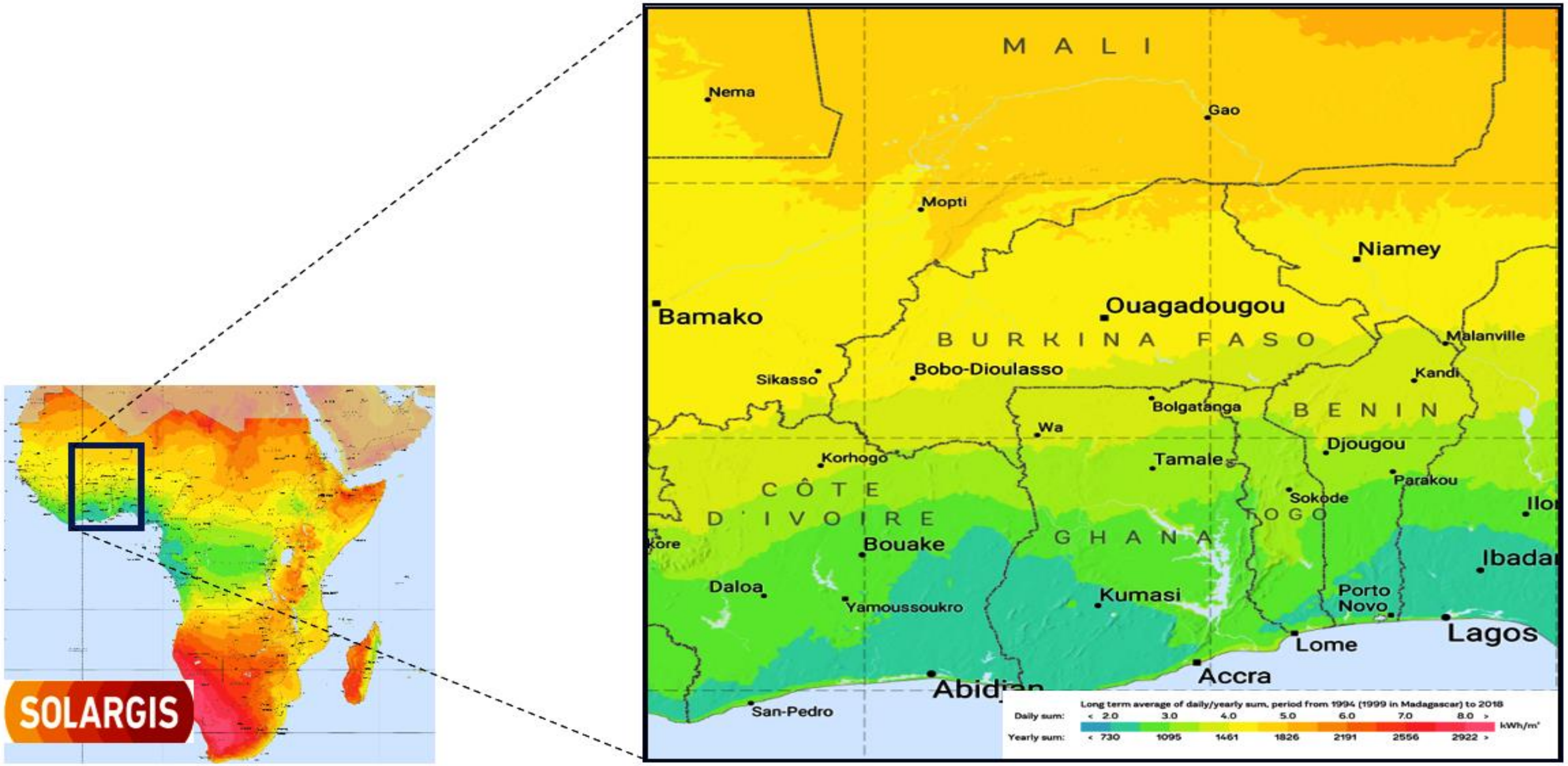

Figure 24 *Incoming solar radiation sub-Saharan Africa (https://solargis.com/maps-and-gis-data/download/sub-saharan-africa)*

The solar map shown in fig. gives a summary of incoming radiation (Rs). It shows the average daily/ yearly sum of Direct Normal Irradiation (DNI) covering a period of 25 recent years (1994-2018). This solar resource is calculated by the Solargis model from atmospheric and satellite data with 15min and 30min time step (solargis). The incoming radiation (Rs) in the Volta basin ranges annually from approximately 1095 kWh/m2 to 1826 kWh/m2 as shown in figure

Akosombo Reservoir

Table 13 Net Evaporation calculation for Akosombo reservoir

Month	Tmin	Tmax	Tc	Δ	Rs1	Rs	A	Rns	Ra	Rso	Rnl	Rn	λv	P	ɣ	U_2	RH	e_{Tmax}	e_{Tmin}	e_s	e_a	δe
Jan	21.2	33.3	27.3	0.213	**1095**	10.80	0.06	10.15	**32.94**	24.79	1.08	9.07	2.44	99.7	0.066	0.70	68.40	5.13	2.52	3.83	2.62	1.21
Feb	22.8	34.5	28.7	0.228	**1095**	10.80	0.06	10.15	**34.66**	26.09	0.86	9.29	2.44	99.7	0.066	1.00	70.30	5.49	2.78	4.14	2.91	1.23
March	23.1	33.9	28.5	0.226	**1095**	10.80	0.06	10.15	**36.72**	27.64	0.70	9.45	2.44	99.7	0.066	1.00	74.00	5.31	2.83	4.07	3.01	1.06
April	23.2	33.2	28.2	0.223	**1095**	10.80	0.06	10.15	**37.74**	28.41	0.63	9.52	2.44	99.7	0.066	1.00	77.10	5.11	2.85	3.98	3.07	0.91
May	22.8	32.2	27.5	0.215	**1095**	10.80	0.06	10.15	**37.06**	27.89	0.68	9.47	2.44	99.7	0.066	1.00	78.50	4.83	2.78	3.80	2.99	0.82
Jun	22.2	30.3	26.3	0.202	**1095**	10.80	0.06	10.15	**35.93**	27.04	0.74	9.41	2.44	99.7	0.066	0.90	84.00	4.33	2.68	3.51	2.95	0.56
Jul	21.7	29.1	25.4	0.193	**1095**	10.80	0.06	10.15	**35.79**	26.94	0.79	9.36	2.44	99.7	0.066	1.00	84.10	4.04	2.60	3.32	2.79	0.53
Aug	21.5	29.3	25.4	0.193	**1095**	10.80	0.06	10.15	**36.70**	27.62	0.74	9.41	2.44	99.7	0.066	1.10	83.00	4.09	2.57	3.33	2.76	0.57
Sept	21.6	30.2	25.9	0.198	**1095**	10.80	0.06	10.15	**37.30**	28.07	0.69	9.46	2.44	99.7	0.066	1.00	82.20	4.31	2.59	3.45	2.83	0.61
Oct	21.8	31.4	26.6	0.206	**1095**	10.80	0.06	10.15	**36.37**	27.37	0.72	9.43	2.44	99.7	0.066	0.90	81.20	4.61	2.62	3.62	2.94	0.68
Nov	21.8	32.4	27.1	0.211	**1095**	10.80	0.06	10.15	**34.32**	25.83	0.87	9.28	2.44	99.7	0.066	0.70	77.50	4.88	2.62	3.75	2.91	0.84
Dec	21.2	32.2	26.7	0.207	**1095**	10.80	0.06	10.15	**32.83**	24.71	1.04	9.11	2.44	99.7	0.066	0.70	73.90	4.83	2.52	3.67	2.72	0.96

Month	E (mm)/day	No.of days	E(mm/m)	Prec. (mm/m)	Net E. (mm/m)	Gsc	dr	ωs	ϕ	J	δ
Jan	3.88	31	**120.17**	16	**104.17**	0.082	1.033	1.52	0.110	1	-0.401
Feb	4.07	28	**113.95**	51	**62.95**	0.082	1.028	1.53	0.110	32	-0.304
March	3.97	31	**122.96**	96	**26.96**	0.082	1.016	1.56	0.110	61	-0.136
April	3.85	30	**115.60**	123	**-7.40**	0.082	0.999	1.58	0.110	93	0.086
May	3.75	31	**116.15**	141	**-24.85**	0.082	0.982	1.60	0.110	124	0.277
June	3.44	30	**103.29**	181	**-77.71**	0.082	0.970	1.62	0.110	156	0.394
July	3.40	31	**105.44**	109	**-3.56**	0.082	0.967	1.62	0.110	187	0.395
Aug	3.48vj	31	**107.73**	73	**34.73**	0.082	0.973	1.60	0.110	219	0.282
Sept	3.53	30	**105.77**	138	**-32.23**	0.082	0.987	1.58	0.110	251	0.086
Oct	3.57	31	**110.60**	138	**-27.40**	0.082	1.005	1.56	0.110	282	-0.130
Nov	3.63	30	**108.76**	67	**41.76**	0.082	1.021	1.54	0.110	313	-0.309
Dec	3.67	31	**113.78**	27	**86.78**	0.082	1.031	1.52	0.110	345	-0.404

Table 14 Parameters used for evaporation calculation

Parameter	Units	Parameter	Units
Tmax	ºC	λv	MJ/Kg
Tmin	ºC	P	KPa
T	ºC	γ	KPa/K
Δ	KPa/K	U2	m/s
Rs1	KWh/m^2 · yr	RH	%
Rs	MJ/m^2 ·day	$e_{(Tmax)}$	-
Ra	MJ/m2 · day	$e_{(Tmin)}$	-
Rso	MJ/m2 · day	es	KPa
Rnl	MJ/m2 · day	ea	KPa
Rn	MJ/m2 · day	δe	KPa
E	mm/day		

Table 14 Location and elevation of the reservoirs

Reservoir	Latitudes (Decimal)	Elevation (m.a.s.l)
Akosombo	6.32	133
Kpong	6.16	77
Bui	8.38	167
Bagre	11.52	224
Vea	10.87	202
Tono	10.88	154
Kompienga	11.08	150
Pwalugu	10.61	293
Juale	9.28	116

The estimated surface evaporation has been compared to the monthly evapotranspiration values on the AQUASTAT Climate Information Tool (http://www.fao.org/aquastat/en/climate-info-tool/). It is observed that the calculated surface evaporation was less than what was generated with the FAO climate tool. This could be because Evapotranspiration (ETo) combines evaporation with transpiration making it higher than surface water evaporation. Appendix D shows the comparison between the calculated evaporation to the FAO generated Evapotranspiration.

3.0 Calibration of WEAP Model

According to (Hassan 2005), model calibration is the process of evaluating and testing the different aspects of a model to refine, enhance, and build confidence in the model predictions in such a way that allows for sound decision-making. The calibration procedure was done by applying optimum values to the sensitive parameters to optimize the model's predictive ability. By comparing observed hydrographs with simulated ones, the study evaluated the accuracy and performance of the model.

Calibration Period Selection

Calibration was done using monthly runoff data from the Global Runoff Data Center (GRDC). There were a lot of missing data, so calibration was done using the full dataset. No data was set aside for validation. Runoff data from three stations in the Black, White, and Oti basins were calibrated separately. Table 21 shows the available period used for calibration in the three sub-basins. It was also realized from the GRDC database that some of the observed data were calculated from daily data and were not original. There were considerable variations in the observed and simulated data, so these data were taken out before calibration.

Table 15 *Calibration period for the sub-basins*

Sub-basin	**Streamflow Stations**	**Period**	**Valid Calibration Years**
Black	Bamboi	1960-2006	31
White	Nawuni	1960-2006	43
Oti	Sabari	1960-2006	22

These gauging stations were considered for the study because they are the last runoff measuring points before the water flows into the Volta lake. Therefore, it is likely to predict the flow into the lake even though there may be some abstractions downstream that will reduce the flow.

Parameters used for Calibration.

A Parameter Estimation Tool (PEST) is included with WEAP, which allows the user to automate the process of comparing WEAP outputs with historical observations and modifying model parameters to improve accuracy (Sieber and Purkey, 2015). However, manual calibrations were performed in this study. Parameters in the model were modified manually, and visual inspections were done continuously to see the response in the simulated runoff. WEAP calculates the hydrological cycle components by simulating the rainfall-runoff process on the catchment surface. The WEAP model contains different methods for simulating catchment processes. These methods include Irrigation Demands Only Method, Rainfall-Runoff Method (Simplified coefficient method), Rainfall-Runoff Method (Soil moisture method), MABIA method and Plant growth model. The choice depends on the data availability and purpose of the analysis (Sieber and Purkey, 2015). The soil moisture method was used in this study.

The Soil Moisture Method represents the catchment with two soil layers and the potential for snow accumulation. The upper soil layer is made to simulate evapotranspiration considering rainfall and irrigation on agriculture and non-agriculture land, runoff and shallow interflow, and changes in soil moisture. The lower soil layer represents deep water capacity (figure 37).

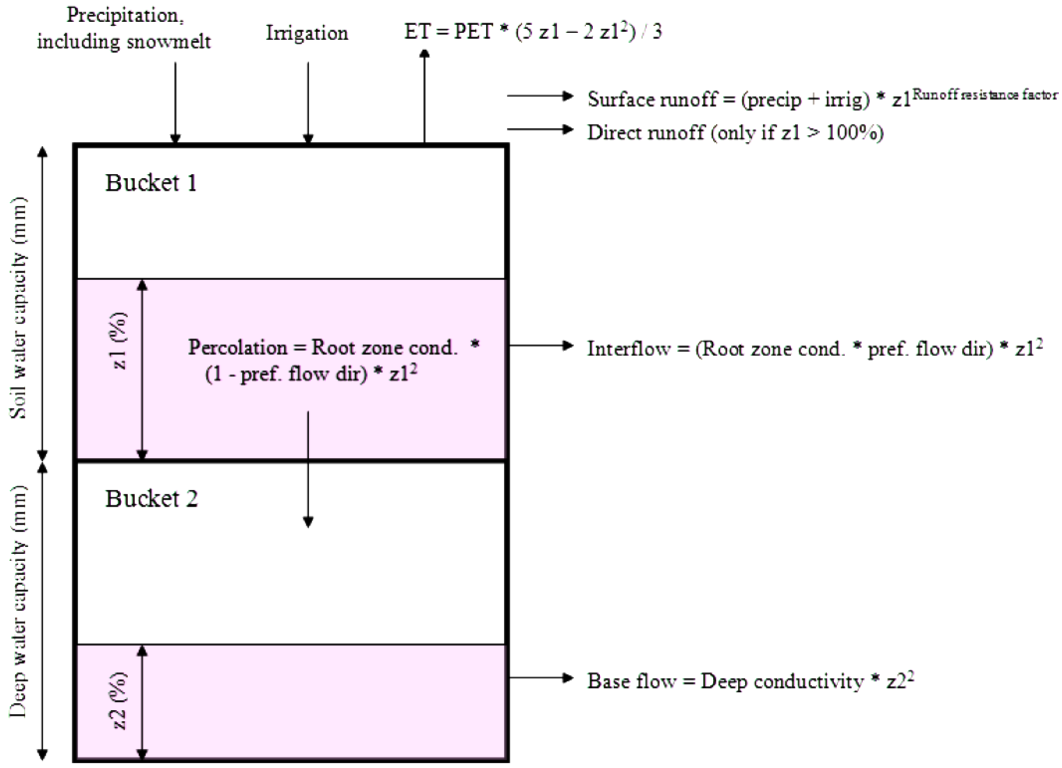

Figure 25 Conceptual diagram and equations incorporated in the soil moisture model (modified from Sieber and Purkey, 2015).

Table 16 Parameters used for the Soil Moisture Method (Source: Sieber &Purkey, WEAP user guide, 2015)

Parameters	Description
Area (mill ha)	Land area for land cover class within basin
Crop Coefficient (K_c)	The crop coefficient, relative to the reference crop, for a land class type. K_c values varies as vegetation and ground cover changes during the growing period. Default =1
Soil water capacity (mm/month)	The effective water holding capacity of the top layer of soil (top bucket). Default: 1000mm
Deep water capacity (mm/month)	Effective water holding capacity of lower deep soil layer (bottom bucket). Default: 1000mm
Deep conductivity	Conductivity rate (length/time) of the deep layer (bottom bucket at full saturation. Default: 20mm/month
Runoff Resistance	It is used to control surface runoff response. Runoff decreases with higher values (ranges from 0.1-10). Default: 2

Factor (RRF)	
Root zone Conductivity	Root zone (top bucket) conductivity rate at full saturation (when relative storage z1 = 1.0). Default: 20mm/month
Preferred flow Direct	Preferred flow direction 1.0 = 100% horizontal, 0.0 = 100% vertical flow. Default: 0.15
Initial z1 (%)	Initial value of z1 at the beginning of the simulation, z1 is the relative storage given as a percentage of the total effective storage of the root zone water capacity. Default: 30%
Initial z2 (%)	Initial value of z2 at the beginning of simulation. z2 is the relative storage given as a percentage of the total effective storage of the lower soil bucket. Default: 30%

Table 17 *Climate Parameters in WEAP*

Parameter	Description
Precipitation (mm/month)	Monthly precipitation time series. Usually a CSV-file (Excel file)
Temperature (°C)	The average monthly temperature Usually a CSV-file (Excel file)
Humidity (%)	Average monthly humidity. The humidity values generated in WEAP were extremely low, so FAO humidity data from AQUASTAT was used.
Wind (m/s)	Average monthly wind speed. Default: 2m/s
Cloudiness fraction (%)	Fraction of daylight hours with no shade from clouds. 0= complete overcast, 1= No clouds. Default: 1. Sunshine fraction was used as cloudiness fraction in this study. Sunshine fraction is the percentage of time when bright sunshine is recorded during the day. This was assumed to be equal throughout the entire Volta basin, but there may be some variations across the basin. (Source: FAO-SDRN-Agrometeorology group 1997)
Latitude	Latitude in degrees
Initial Snow (mm)	The Initial value of snow accumulation at the beginning of the first simulation
Melting point (°C)	Liquid water threshold for snowmelt. Default: +5°C
Freezing Point (°C)	Solid water threshold for snow accumulation. Default: -5°C
Albedo	A measure of diffused reflection out of the total solar radiation. Default: for lower albedo bound = 0.15 and upper albedo upper bound = 0.25. In this study, albedo values were put into the model to override the default.

The WEAP model was calibrated with the parameters in table 22 and 23. However, the parameters related to snow were left blank since the Volta basin does not experience any precipitation in the form of snow. Therefore, the calibration parameters used for this study are presented in table 24.

Table 18 Parameters used for calibration with monthly variations (Black Volta Basin)

Elevation (0-500m)					**Crop Coefficient (K_c)**							
	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Agricultural_Non Irrigated	20	2	6	4	4	2	0.35	0.5	1.5	0.35	1	0.3
Forest	3	2	6	4	4	2	1	0.5	1	0.35	1	0.3
Grassland	20	20	20	20	20	20	20	20	20	20	20	20
Wetland	5	3	3	4	2	3	1	1.2	1	0.35	1	1
Urban	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Shrubland	60	60	60	60	60	60	60	60	60	60	60	60
Barren or sparse vegetation	20	20	20	20	20	20	20	20	20	20	20	20
Open water	100	100	100	100	100	100	100	100	100	100	100	100
Irrigated Agriculture	5	7	6	4	4	2	1	0.5	0.5	0	1	0.3

Elevation (0-500m)					**Soil Water Capacity**							
	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Agricultural_Non Irrigated	100	100	150	100	150	300	600	600	800	700	200	150
Forest	600	600	600	600	600	600	600	600	600	600	600	600
Grassland	800	800	800	800	800	800	800	800	800	800	800	800
Wetland	100	100	150	100	150	300	600	600	700	700	200	150
Urban	100	100	150	100	150	300	600	600	700	700	200	150
Shrubland	300	300	300	300	300	300	300	300	300	300	300	300
Barren or sparse vegetation	100	100	150	100	150	300	600	600	700	700	200	150
Open water	100	100	150	100	150	300	600	600	700	700	200	150
Irrigated Agriculture	100	100	150	100	150	300	600	600	700	700	200	150

Table 19 Calibrated Parameters (Black Volta Basin)

Root Zone Conductivity	**Monthly values**
Agricultural Non-Irrigated	10
Forest	30
Grassland	20
Wetland	20
Urban	20
Shrubland	20
Barren or sparse vegetation	20
Open water	20
Irrigated Agriculture	10

Calibration Parameters	**Value**
Deep water Capacity (mm)	1000
Initial z1 (%)	30
Initial z2 (%)	30
Preferred flow direction (%)	0.15
Deep conductivity	200
Latitude	11.48

The Black volta basin has been used as an example of how the sub-basins were calibrated. The calibrated values of the other sub-basins are found in appendix 2C.

Measurement of Calibration Performance

The goodness of fit was measured using a statistical criterion known as Percentage bias (PBIAS). PBIAS is the relative bias of the data being assessed, expressed as a percentage. PBIAS measures the average tendency of simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1994). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation PBIAS and negative values indicate model overestimation PBIAS (Legates & McCabe, 1999). PBIAS is calculated with the equation:

$$PBIAS = \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})}{\sum(Q_{obs})} \times 100$$

Where Q_{obs} is the observed discharge, Q_{sim} is the simulated discharge and n is the total number of years.

The interpretation of PBIAS after calibration is given in table 26.

Table 20 *Percentage Bias Interpretation.*

PBIAS (%)	INTERPRETATION OF THE MODEL
PBIAS < ± 10	Very good
± 10 < PBIAS < ± 15	Good
± 15 < PBIAS < ± 25	Satisfactory
PBIAS > ± 25	Unsatisfactory

Calibration Results

The calibration results are shown in Figures 38-43 for Nawuni, Bamboi, and Sabari gauging stations for monthly timesteps. The results presented are for annual total and monthly average runoffs in the sub-basins, revealing that the simulated and observed hydrographs are similar with very good statistics. The PBIAS for each gauging station has also been shown on table 21.

Performance of the Model

The WEAP model was calibrated and used to analyze the climate impact on streamflow. The purpose was to make sure the model accurately reflected the current situation in the study area. The streamflow between the period of 1960-2010 was used in calibrating the model. Generally, the model was efficient in calibrating all three sub-basins. The PBIAS values in table 27 show that the calibration was perfect since the PBIAS was less than ± 10% for gauging stations.

Table 21. *PBIAS values for the calibrations*

Sub-basin	Streamflow gauge	Annual Total PBIAS (%)	Monthly Average PBIAS (%)	Interpretation
White Volta basin	Nawuni	**-7.6**	**-7.5**	Very good
Black Volta basin	Bamboi	**-6.0**	**-6.2**	Very good

Oti basin	Sabari	**-9.8**	**-9.8**	Very good

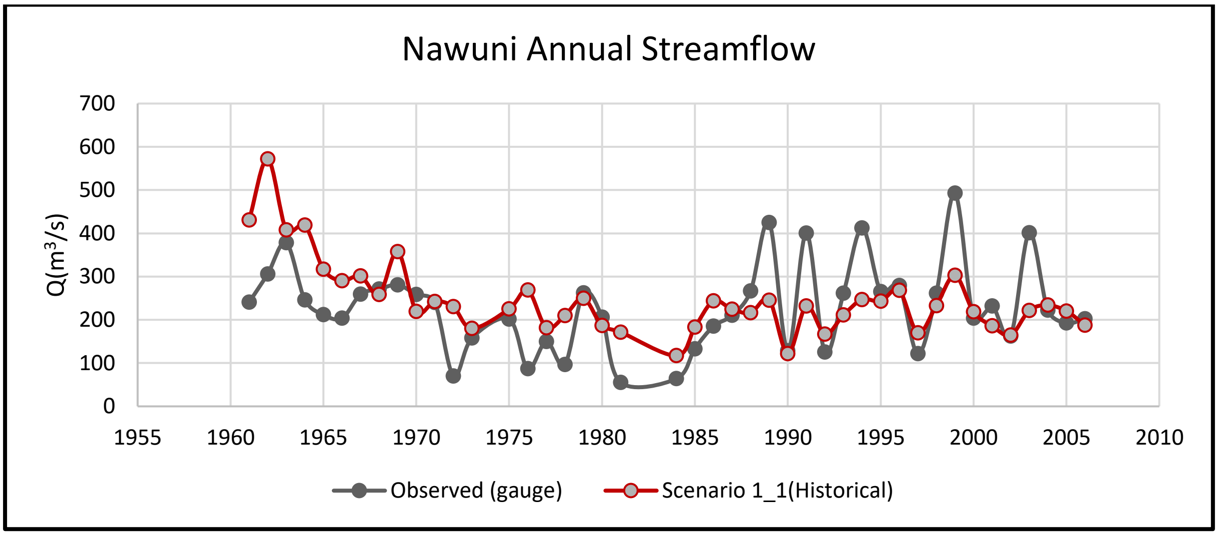

Figure 26 Annual total runoff calibration for Nawuni gauge (White volta basin)

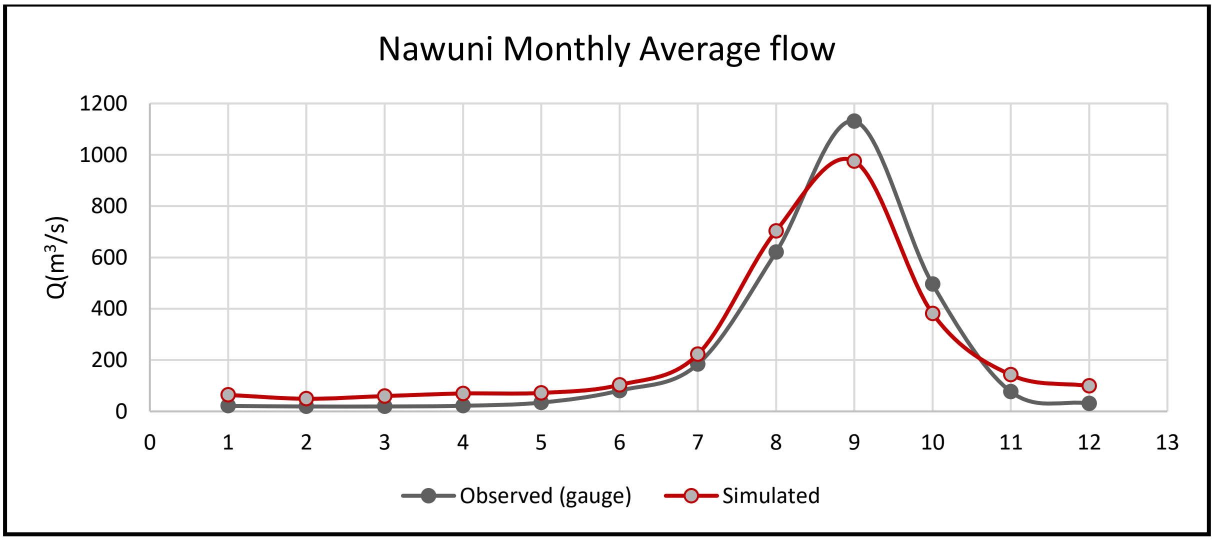

Figure 27 monthly average streamflow, Nawuni

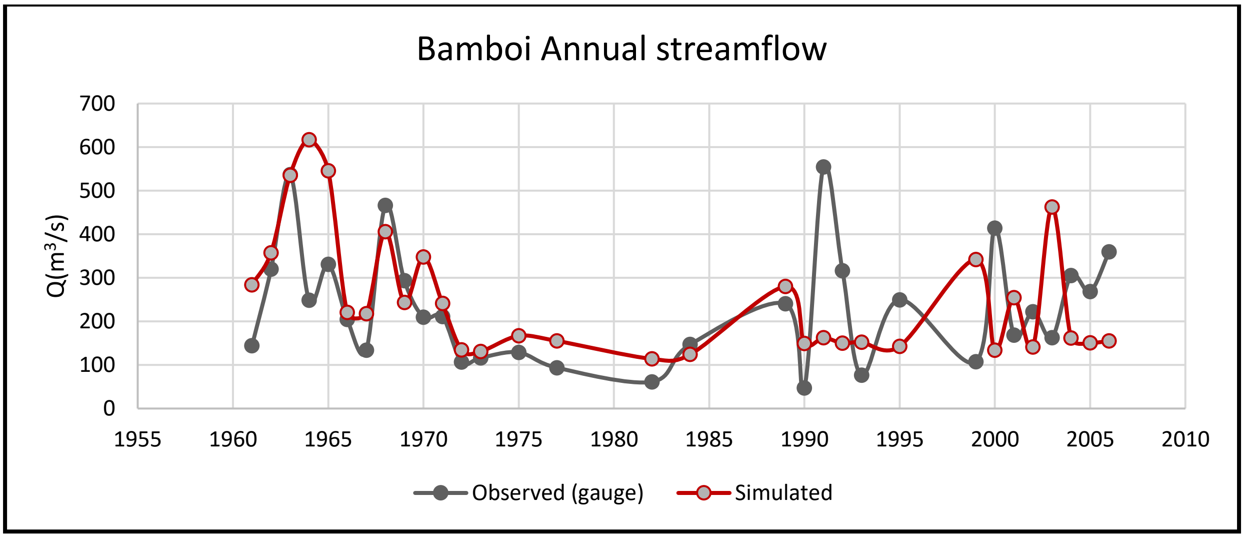

Figure 28 *Annual total runoff calibration streamflow, Bamboi*

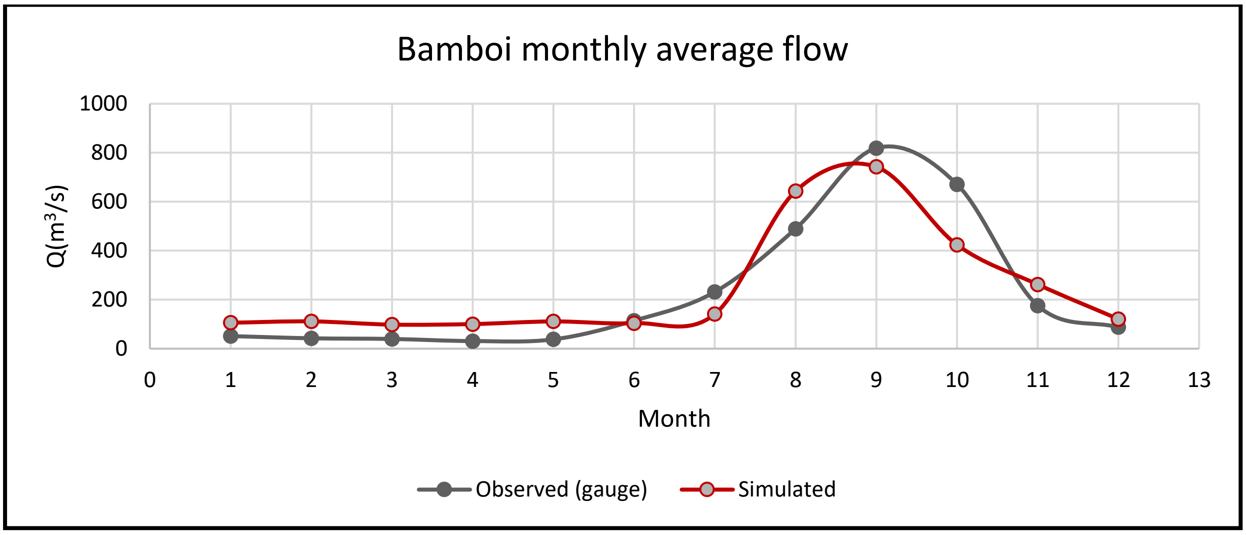

Figure 29 *Monthly average streamflow, Bamboi*

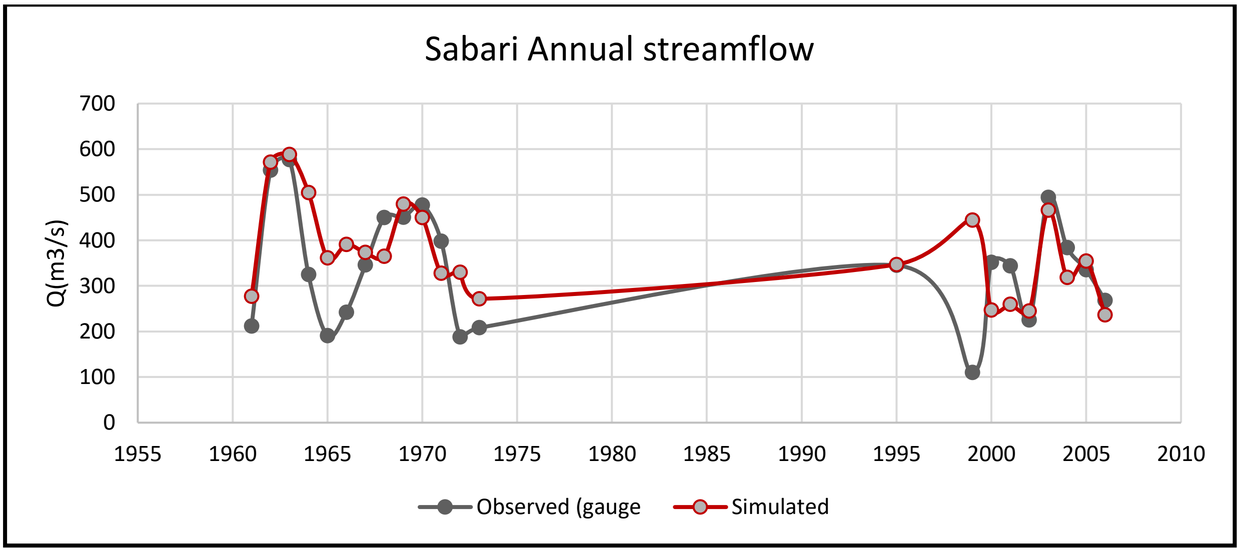

Figure 30 *Annual total runoff calibration, Sabari*

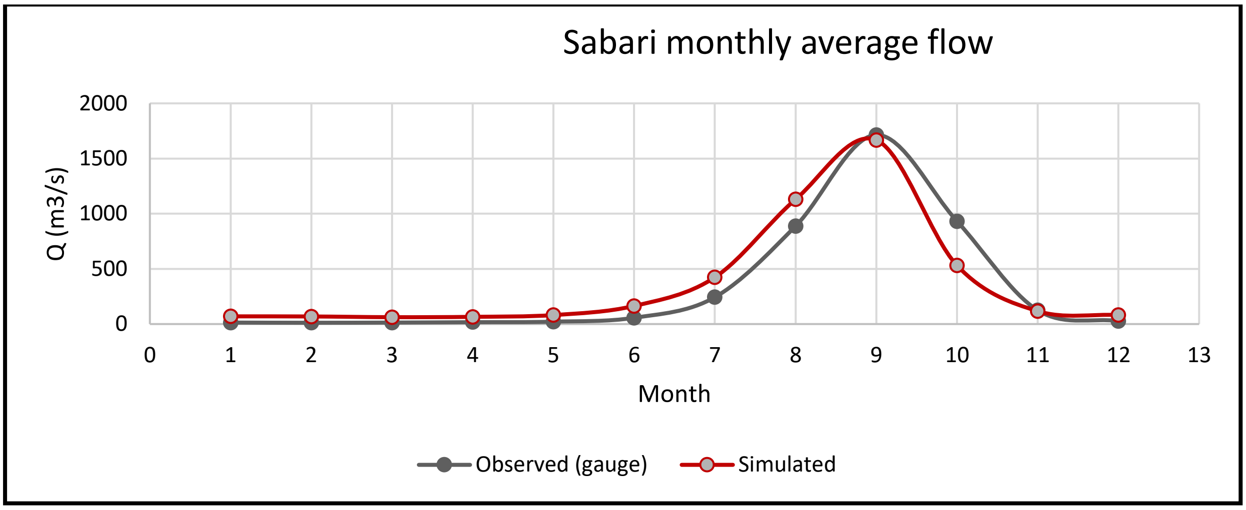

Figure 31 Monthly average streamflow Sabari.

3.1 Planned future projects in the Volta Basin

There have been some proposals to provide large scale and transboundary implementation of integrated flood and drought management strategies. Also, due to Sustainable Development Goals (SDG 2, zero hunger), it has been necessary to develop irrigation schemes to increase crop yields through improved agronomical practices and improve food security. Ghana signed the 2015 Paris Climate Agreement to increase renewable energy by 10% by 2030 to reduce greenhouse gas emissions. For this reason, three dams have been proposed in the Oti, White and Black volta sub-basins to develop hydropower. These dams will harbour one of the largest irrigation schemes in Ghana and reduce the frequency of floods downstream. Table 16 gives an overview of the future projects in the Volta Basin.

Table 22 Overview of planned/future projects in the Volta basin.

Sub-basin	Reservoir	Storage Capacity (Mm^3)	Purpose	Installed Capacity (MW)	Proposed Irrigation area (ha)	Sources
Black Volta basin	Bui[1]	12750	H, I, WS, C	400	30,000	Buipower.com
White volta basin	Pwalugu	3260	H, I, WS, C	50	25,000	VRA
Oti basin	Juale	1200	H	87	Unknown	McCartney et.al, 2012

[1] The Bui dam was commissioned in 2013, and since then, it has been generating enough power, which has been added to the national grid. In this study, the Bui dam has been assumed to be a planned reservoir due to the global database's unavailability of current climate data. The data available in the global database was from 1960 to 2010.

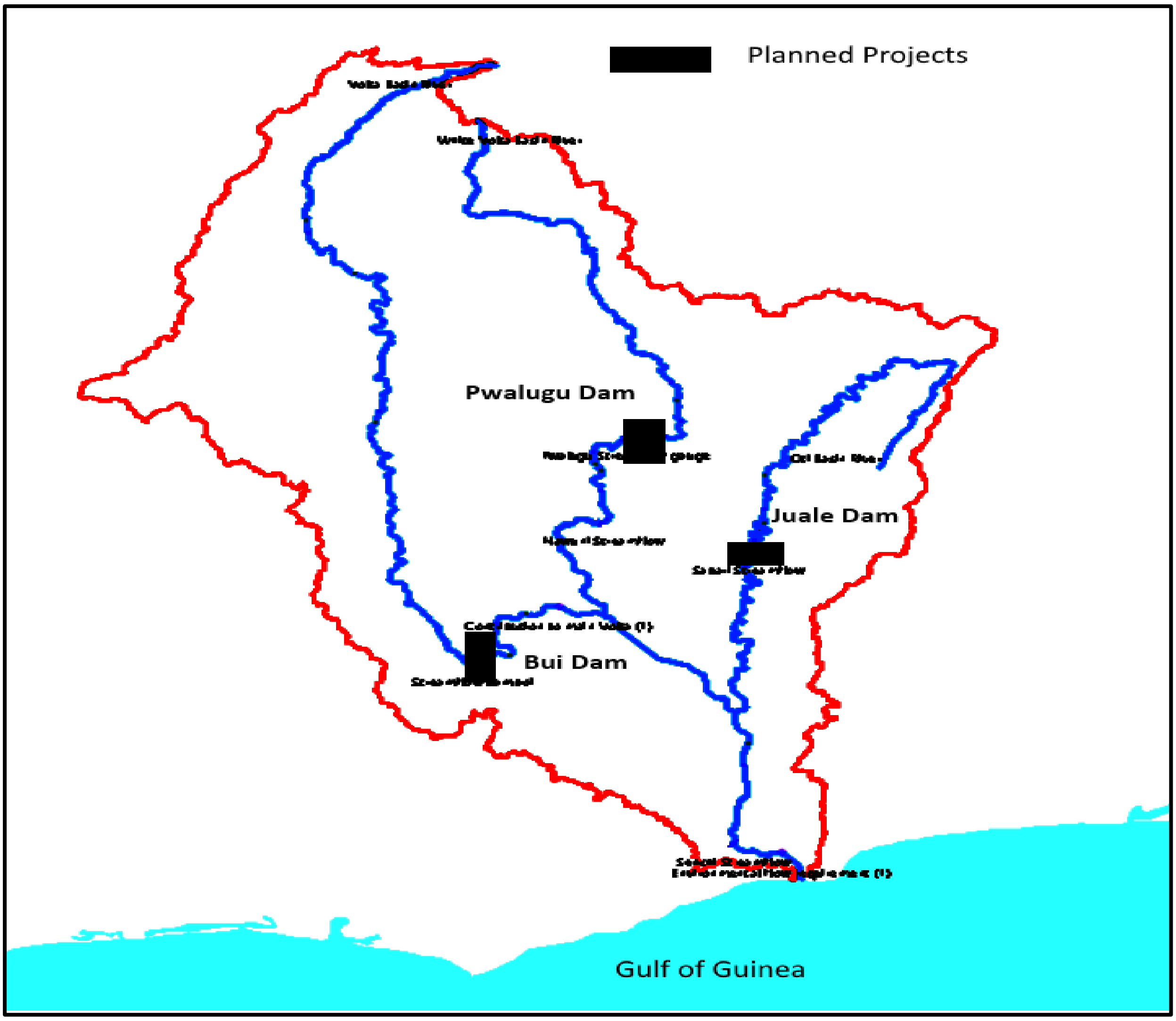

Figure 32 Volta basin showing planned reservoirs

Table 17 overview of Planned irrigation schemes in the Volta basin

Planned Irrigation	Startup year	Priority in WEAP	Irrigated area (Ha)	Annual water use rate (m^3/ha)	Monthly variation in Percentage (%)											
					January	February	March	April	May	June	July	August	September	October	November	December
Bui	unknown	2	30,000	20,000	26	23	0.1	0	0	0	0	0	0	0.1	25	26
Pwalugu	unknown	2	25,000	15,000	26	23	0.1	0	0	0	0	0	0	0.1	25	26

Data used in Planned reservoir for hydropower

Several data have been assumed and taken from other sources to run the model. Table 18 gives an overview of data used for planned reservoir for hydropower production. Evaporation data for planned reservoirs can be found in Appendix 1A.

Table 23 *Overview of data used in WEAP for planned hydropower reservoir.*

Hydropower Reservoir	Maximum Turbine flow (m^3/s)	Inactive Storage (Mm^3)	Top of Buffer (Mm^3)	Head (m)	Efficiency (%)	Annual Energy Production (GWh)
Bui	1000	4850	4850	183	90	1034
Pwalugu	200	1600	1600	165	90	525.6
Juale	300	500	500	40	90	762.12

3.2 The Effect of large-scale development of floating solar panels on Pwalugu Multipurpose reservoir

As part of the planned future projects in the Volta basin, it is interesting to investigate the impact of floating solar panels on the Pwalugu reservoir for water management. Using hydropower reservoirs for floating solar panels adds benefits to the reservoir. Solar power can utilize the hydropower facility's existing infrastructure and transmission lines, reducing capital costs. Also, the two technologies can balance each other when the reservoir level is low. The floating solar power plant is an innovative way to conserve land and increase the efficiency of photovoltaic modules by using them on water infrastructures. The water is also saved due to the evaporation of water from the reservoir surface. Rising temperatures due to climate change will cause an increase in reservoir surface evaporation. It is, therefore, essential to analyze the use of floating photovoltaics in saving water in the reservoir.

This part of the study investigates the energy that could be produced by the floating photovoltaic systems and the amount of water that could be saved by covering 10% of the reservoir surface. Installing a floating photovoltaic system increases energy production by 5.93% due to the cooling effect of the reservoir (Majid et al., 2014).

For a reduction of 10%, we need to get the evaporation down 90% of the maximum value. A linear relationship has been assumed for area coverage and reservoir surface evaporation. This implies that 10% of the area covered is equivalent to reducing the evaporation by 10%. The maximum inundation for the future Pwalugu multipurpose dam is assumed to be 350km2. The evaporation calculation in Appendix 1A shows that the annual estimated reservoir surface evaporation for the Pwalugu dam is 1920mm. So, the covered area of 35km^2 is equivalent to 192mm of the saved water. Evaporated water saved because of the solar panel is given by:

$$Volume\ of\ water\ Saved\ per\ year\ (m^3)\ = Area(m^2) \times surface\ evaporation\ (m)$$

$$Volume\ (m^3) \qquad = 35000000m^2 \times 1.92m$$

$$Volume \qquad = \quad 6.72 \times 10^7 m^3/year$$

The volume is converted to discharge (Q) in m^3/s to calculate the amount of energy that could be produced with the saved water.

$$Q\ = \frac{6.72\ \times 10^7 m^3}{365 \times 24 \times 60 \times 60}$$

$$\boldsymbol{Q = \ 2.13 m^3/s}$$

The Energy obtained from this discharge is given by:

$$Energy\ (kWh)\ =\ \rho \times g \times H \times \eta \times Q_t\ \times hr$$

$$Energy\ (kWh)\ =\ 1000\ kg/m^3 \times 9.81 m/s \times\ 165m \times 0.9 \times 2.13 m^3/s\ \times 365 \times 24hrs$$

$$\boldsymbol{Energy\ \ = 2.72 \times 10^7\ (kWh)/year}$$

The idea behind these calculations is to help us understand the Kilowatt hour (kWh) of electrical energy, which could have generated revenue for the country.

According to the Electricity Company of Ghana (ECG), energy price in 2020 was 0.064 USD/kWh which was used for this estimation. This implies that, the revenue that could be generated from the saved water is *1,740,800 USD.*

Energy Calculation from Solar Panel

Krishnaveni et al., 2016 estimated that 1kW of floating solar panels would require an area of 10m2. So, a 35km^2 solar panel will generate about 3500 megawatts (MW). This provides an energy of 12,775 GWh per year. The energy generated in year looks unrealistic today but may be important in the future. Daylight hours of solar is 10hrs (7:00 to 16:00) everyday which may not be the case. So, these assumptions led to high values in energy production which may change in the field.

The revenue generated from the solar panel is *817, 600,000 USD*.

Investment cost of Solar Panel.

According to Solar Power FAM, the cost of a solar panel per square meter is $40. The investment cost of a 35km^2 area of floating solar panels is estimated to be *1.4 billion USD*. This estimation doesn't include installation costs.

The above solar panel calculations show that the country benefits from floating solar panels by conserving water and generating revenue. It also helps to contribute to an increase in renewable energy to reduce the impact of climate change globally.

3.3 Climate Change

The Intergovernmental Panel on Climate Change (IPCC) defines climate change as any change in climate over time, whether due to natural variability or human activity. Climate change data for this study is from the World Bank Group Climate Change Knowledge Portal. According to Taylor et al., 2012, the data used in the portal is from the CMIP5 (Coupled Intercomparison Project Phase 5) distribution. CMIP is a standard experimental framework for studying the output of coupled atmosphere-ocean general circulation models. Representative Concentration Pathways- RCPs are also used to represent different possible future radiative forcing scenarios through a selected evolution of distinct emissions and land-use change. (Moses et al., 2010). The techniques considered are RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. These numbers attached to the RCPs represent global mean radiative forcing in watts per square meter (W/m2) achieved in each scenario by the end of the century (2100). The ensemble mean was used as the modelling tool for climate change. The ensemble mean describes how the collection of up to 35 CMIP5 models on average project the climatological changes. The scenario used for this study is RCP4.5 for medium-low emissions.

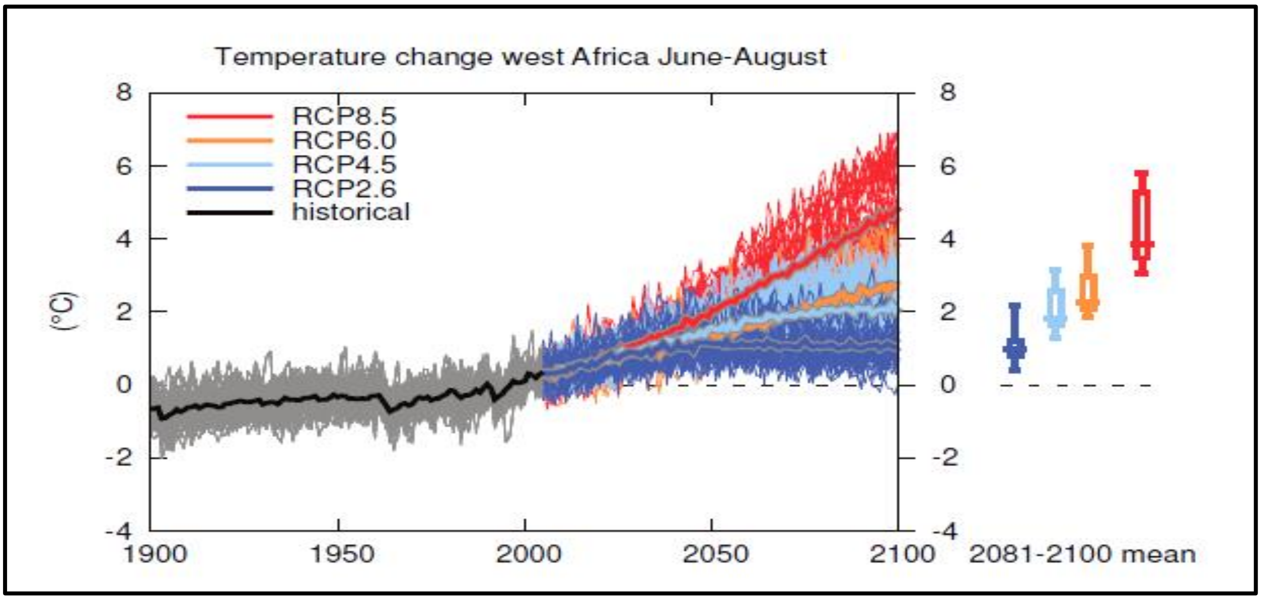

Figure 33 *RCP temperature scenarios in West Africa (source: Atlas of Global and Regional Climate Projections, IPPC 2013)*

3.4 Scenario Description

To evaluate the hydrological change in the Volta river basin as an impact of climate change, the historical streamflow was compared to the future scenarios for 2020-2039 and 2080-2099. The relative change in this comparison is used to determine the impact of climate change in the basin. The following scenarios were considered for all the three sub-basins.

- The calibrated streamflow is the first scenario (*Current 1_1*). This represents the present demand site data in the basin with current climatic information (1960-2010)
- *Current 1_2*: In this scenario, planned reservoirs with hydropower are introduced with current climatic information.

- *Current 1_3*: This scenario combines reservoir with hydropower and irrigation demands.

Climate change was introduced for the second scenario for the period 2020-2039.

- *Scenario 2_1*: The model was run with a change in climate parameters from 2020-2039. No reservoirs and demand sites were introduced in this scenario.
- *Scenario 2_2*: Climate change and reservoirs (hydropower) were introduced in this scenario.
- *Scenario 2_3*: Climate change, reservoirs (hydropower), and irrigation demand sites were introduced.

Climate change towards the century, i.e., 2080-2099, was considered the third scenario.

- *Scenario 3_1*: The model was run with a change in climate parameters from 2080-2099. No reservoirs and demand sites were introduced in this scenario.
- *Scenario 3_2*: Climate change and reservoirs (hydropower) were introduced in this scenario.
- *Scenario 3_3*: Climate change, reservoirs (hydropower), and irrigation demand sites were introduced.

These scenarios were analyzed to see the impact of future infrastructure and climate change on the inflows into the Volta lake (Akosombo reservoir). The only exception in the scenarios was the Juale reservoir on the Oti basin with no known future irrigation projects, so there were no irrigation withdrawals for the Juale reservoir.

In this study, the changes in temperature and precipitation were based on RCP 4.5, as represented in figures 35 and 36. RCP 4.5, being a medium-low emission variant, was used to analyze different scenarios in this study. Therefore, changes in temperature and precipitation were the available climate data analyzed at different periods; 2020-2035 and 2080-2099. Figure 35 shows how climate change will cause an increase in temperature from 2020-2035 and 2080-2099. The changes in temperature from a lighter yellow to a darker yellow show an increase in temperature for that period. Generally, there is an average increase of about 2^{o}C in the Volta basin from now till the end of the century. However, the projections also show a decrease in precipitation towards the end of the century, as seen in figure 36. Globally, the values of monthly precipitation changes vary from -100mm to 200mm (World Bank Group).

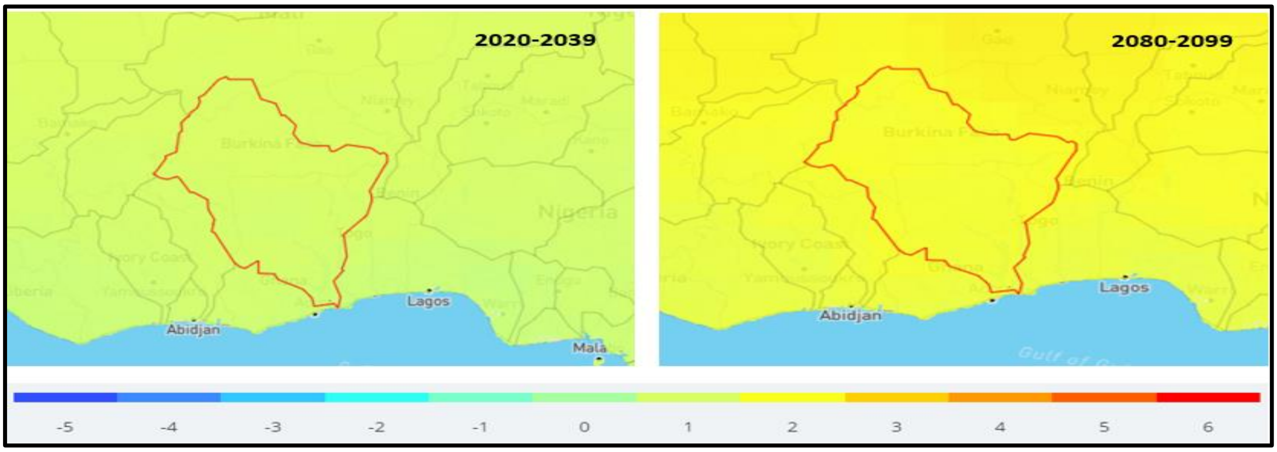

Figure 34. Projected change in monthly temperature (ºC) with RCP 4.5 scenario (World Bank Group).

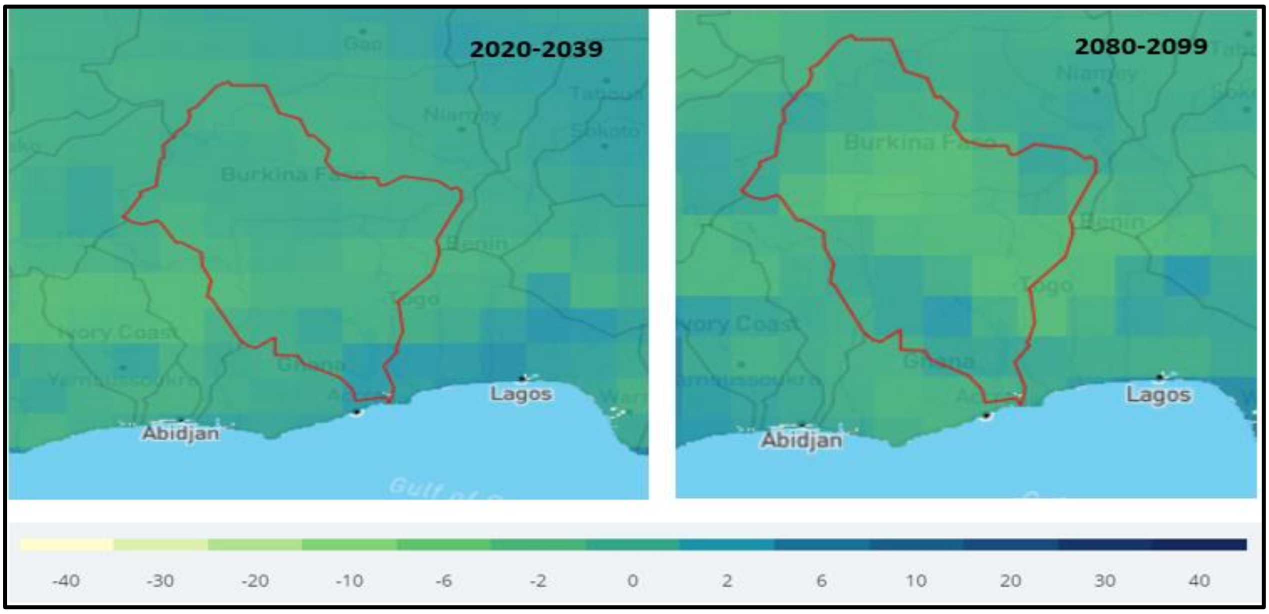

Figure 35. Projected change in monthly precipitation (mm) for RCP 4.5 scenario (World Bank Group).

Table 24 Monthly Changes in climate for the period 2020-2039 (World Bank Group)

Month	**Jan**	**Feb**	**Mar**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
ΔP (mm)	0.03	0.36	0.19	-1.04	-1.63	-6.94	-1.61	-0.04	2.23	-2.18	-1.34	0.30
ΔT (ºC)	1.15	1.14	1.13	0.93	0.99	0.97	0.98	0.90	0.88	0.85	1.07	1.17

Table 25 Monthly Changes in climate for the period 2080-2099 (World Bank Group)

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
ΔP (mm)	0.17	0.08	-0.67	-4.75	-4.05	-5.1	-5.41	-2.3	5.87	-2.24	0.04	0.15
ΔT (ºC)	2.12	2.04	2.28	2.14	2.09	1.96	1.72	1.74	1.75	1.75	1.90	2.08

Bias Correction Methods

The methodologies used in adjusting projections for monthly precipitation and temperature are the Linear transformation, Local Intensity scaling, Power transformation, Variance Scaling, Distributing mapping, and the Delta change approach (Teutschbein & Seibert, 2012). In this study, the delta change approach is being used for estimating the projections.

Delta Change Correction of Precipitation and Temperature

For future scenarios, delta change values were imposed on the observed historical climatic data (1961-2010) to derive new time series for 2020-2039 and 2080-2099. The change in precipitation is given by the relation:

$$\Delta P = \frac{(P_{future} - P_{current})}{P_{current}} + 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

$$P_{future} = \Delta P \times P_{current}$$

Change in temperature is given by the relation:

$$\Delta T = T_{future} - T_{current} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

$$T_{future} = T_{current} + \Delta T$$

The delta values for precipitation and temperature in table 19 and 20 are multiplied and added to the observed data respectively. In doing so, the projected climatic data is calculated.

4.0 Scenario Results

The results for the various scenarios have been presented in this chapter. The results will be discussed in detail in the next chapter.

The change in streamflow was determined using the relation below

$$Change\ in\ streamflow\ (\%) = \frac{MAS_p - MAS_h}{MAS_h} \times 100$$

Where *MAS* is the Mean Annual Streamflow, *p* is projected, and *h* is historical.

Current 2_3, and 3_3 for Bamboi looks like what is seen in figure 46, so it has been put in appendix 5. However, it will be discussed in the next chapter.

Several of the scenario results have been put in appendix 4(I-V).

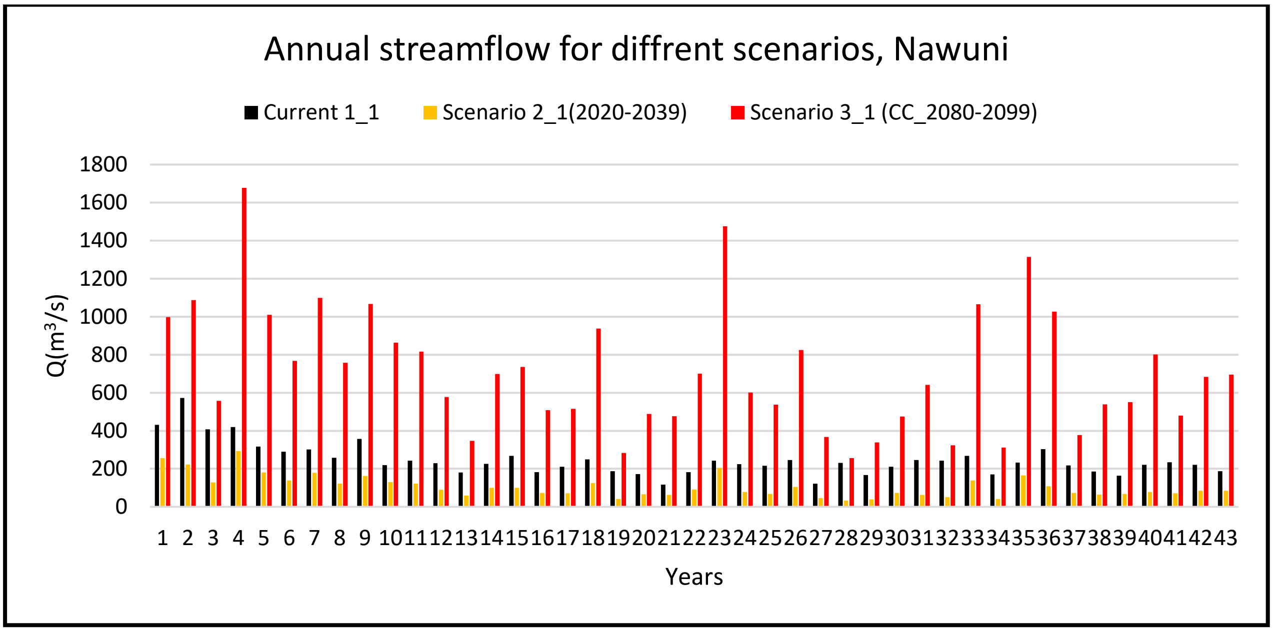

Figure 36. Comparing annual streamflow for historical and future climates

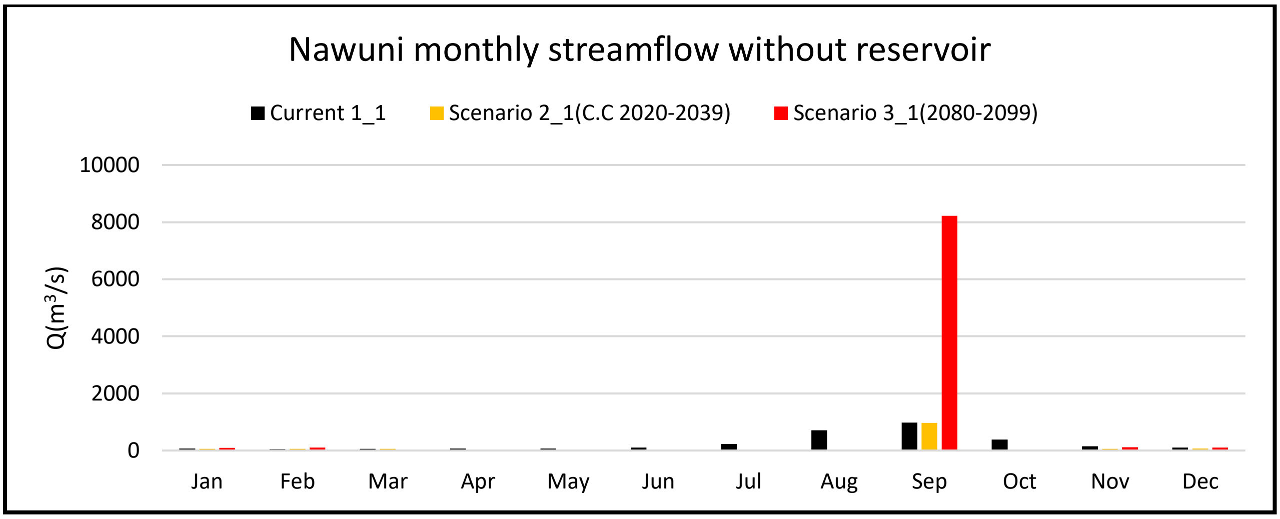

Figure 37 Monthly streamflow with climate scenarios, Nawuni.

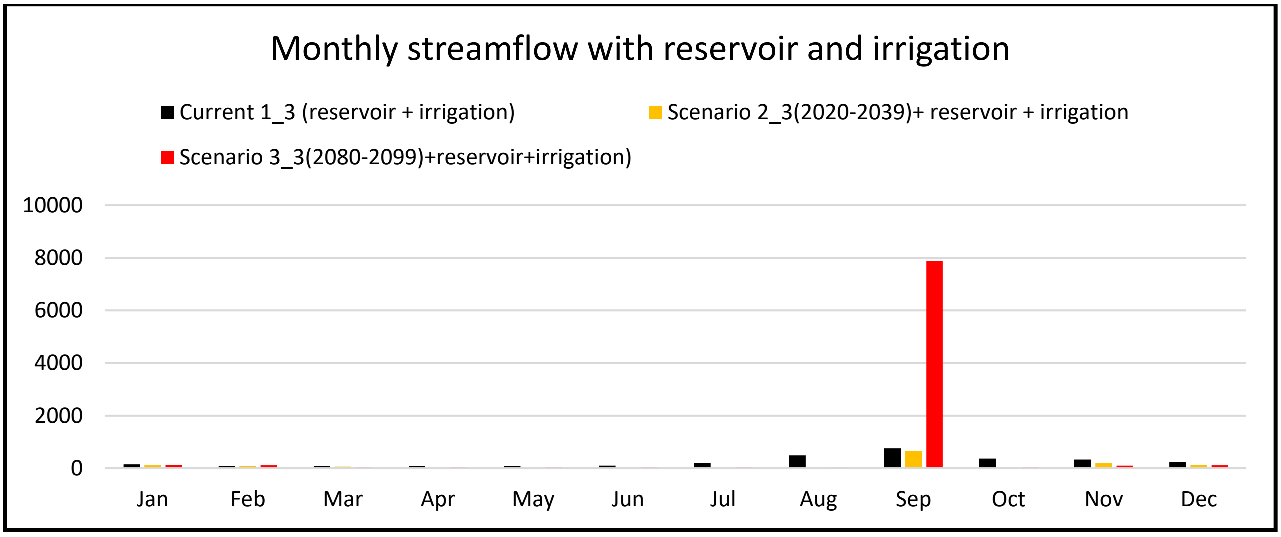

Figure 38 Monthly streamflow with reservoir and irrigation, Nawuni.

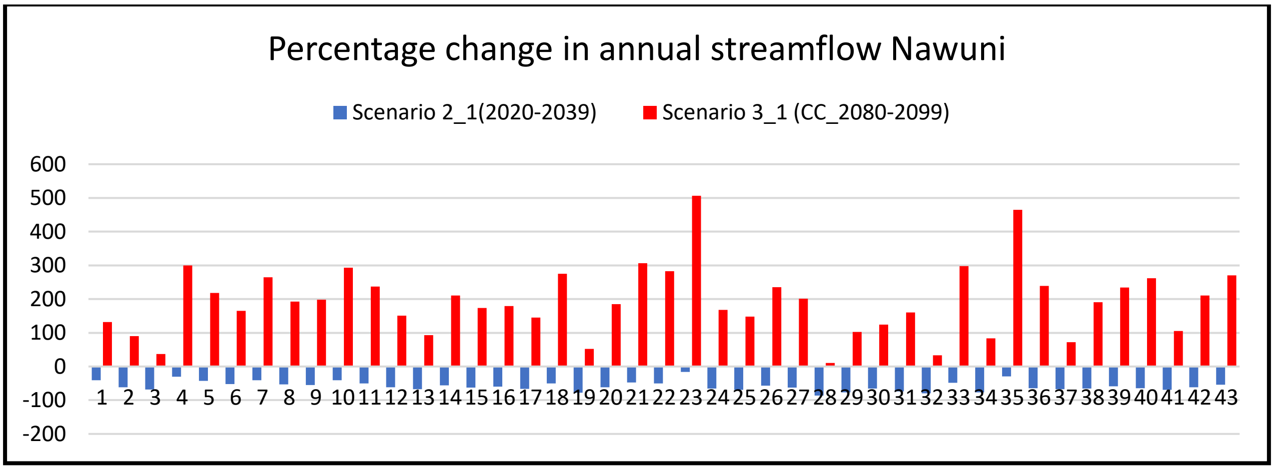

Figure 39 Comparing changes in future streamflow with historical streamflow, Nawuni.

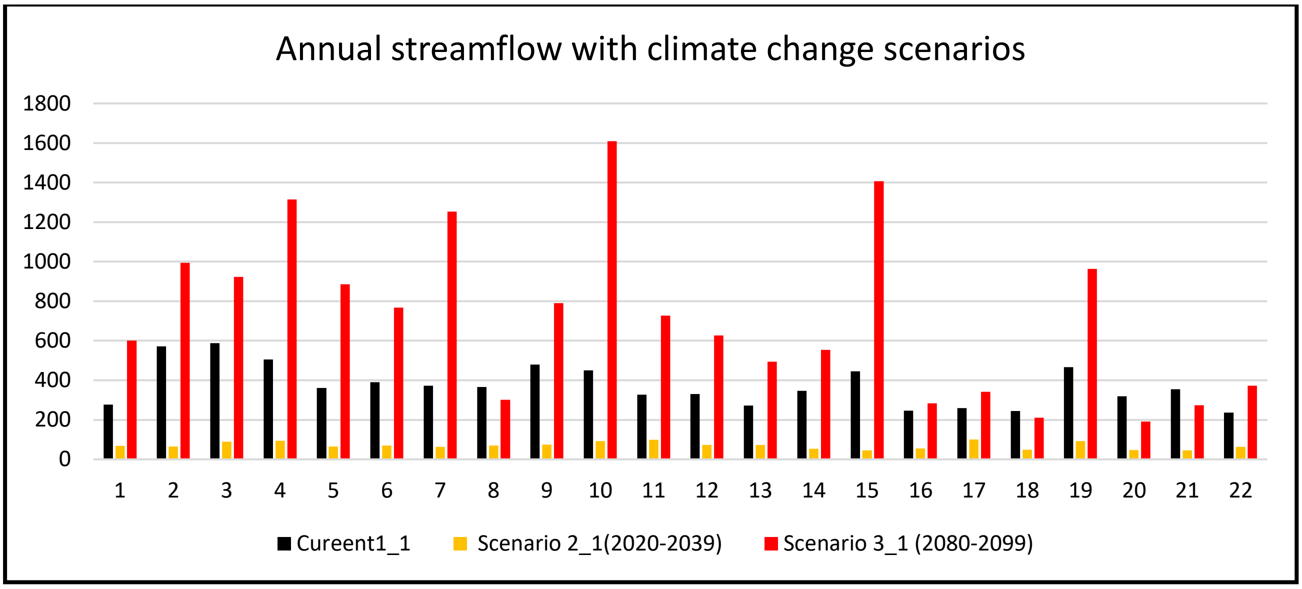

Figure 40 Annual streamflow in the Oti Basin considering climate change.

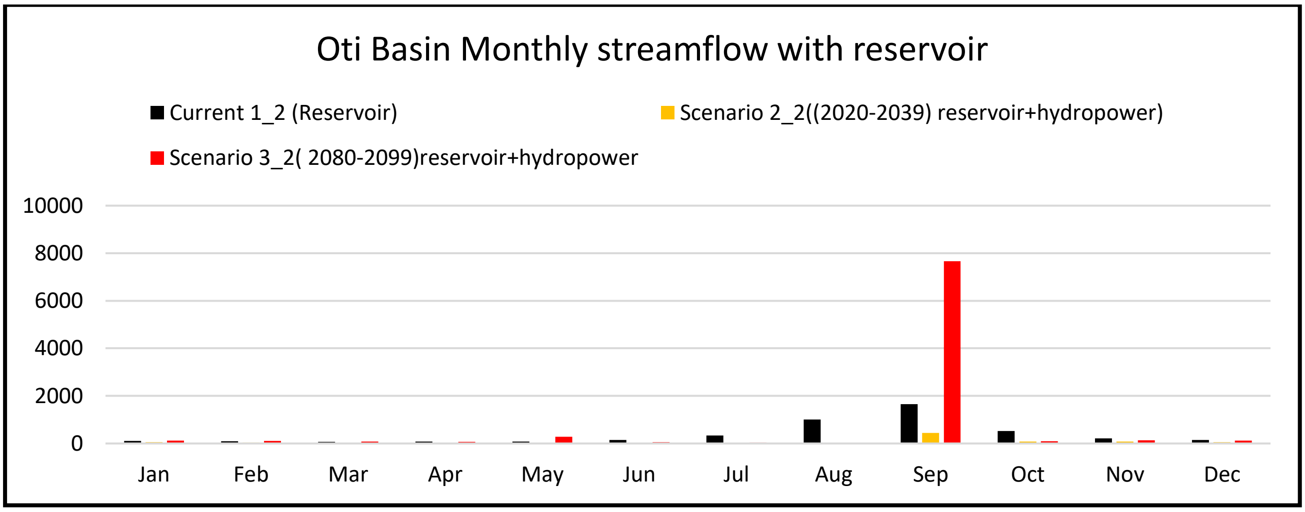

Figure 41 Monthly streamflow in the Oti Basin when Juale dam is introduced.

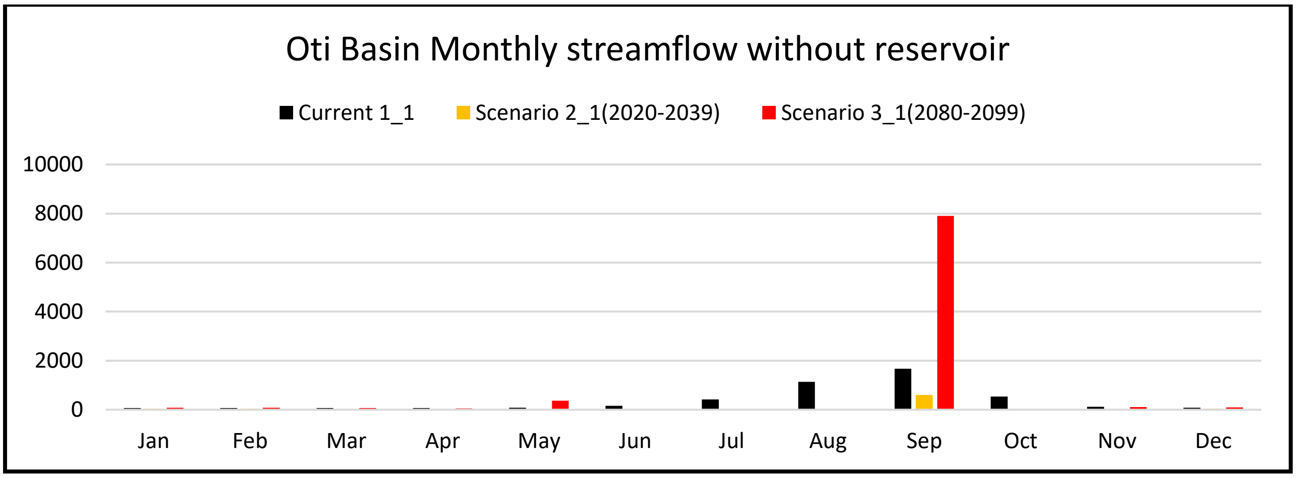

Figure 42 Monthly Streamflow without reservoir.

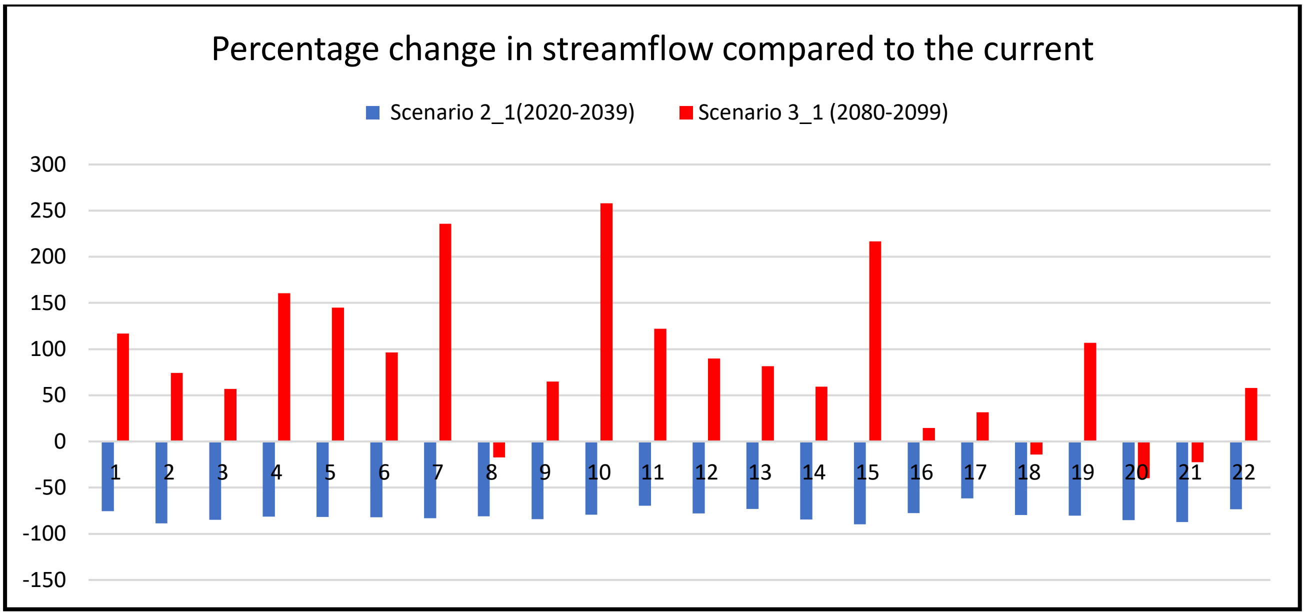

Figure 43 Comparing streamflow changes for different scenarios with respect to the current, Oti Basin.

5.0 Discussion

In this chapter, the results obtained will be presented and described further. Even though the model performs very well, it must be noted that it is still not perfect and therefore does not represent the reflection of the natural watercourse though it is accepted. Also, the model's accuracy is affected by many assumptions and simplifications used in the modeling process. The quality of input data is essential when considering the model's suitability and its results—garbage in garbage out as described in computing. Data on runoff obtained from GRDC can be accepted as being of good quality even though there were some missing data.

The main source of uncertainty in the model can be attributed to estimating competing water needs in the study area. Unfortunately, comprehensive data on water use in the study area is not readily available, and the ones available can be of questionable quality.

5.1 Calibration Results description

The biggest uncertainty is considered being irrigation withdrawals. Reliable data on location of withdrawals, volume and timing of water withdrawals was difficult to find via publicly available data sources (databases, articles, report). The data on withdrawals used were based on what has been reported in some scientific journals. The likely effect of this is an underestimation of water demands introducing errors in the model.

Another weakness of the model is missing data on runoff. As seen in figure 41, there is a gap from 1973 to 1995 with no data in the GRDC database. Even though there is a possibility of modeling groundwater in WEAP, groundwater was not modeled in detail due to groundwater data use in the sub-basins. Due to this, the model only depends on rainfall to estimate streamflow. The calibration period for the model is from 1960-2010, and more recent streamflow data would have been better. All these weaknesses could be the possible reason why the model did not give a perfect fit.

The most important strength of the model is the "Very Good" result obtained for the PBIAS in all the sub-basins, as shown in table 27.

5.2 Scenario Results description

The main objectives of the thesis are to investigate the effect of inflow on the Volta lake (Akosombo reservoir) when planned future reservoirs are developed upstream to secure water for hydropower, irrigation, water supply and to serve as flood protection. Also, the effect of climate change on the inflows into the Volta lake was investigated.

5.2.1 Impact of inflow on water resource considering current scenario (Current 1_2)

The current result shows that there is generally an increase in streamflow when the reservoir is introduced without climate change scenarios. The Pwalugu reservoir increases streamflow in the 27th year by almost 40%, whereas there is a maximum reduction of about 21% in the 40th year (shown in appendix 4XIV). This could be due to low runoff without reservoir. Introducing a reservoir means that it will be required to release an environmental flow which will increase runoff in a year of low flows and the opposite in the 40th year. Interestingly for the monthly streamflow, the months of January, February, November, and December, which is noted to be months with low or no precipitation, have increased in streamflow of a maximum of 151% in December and about 130% in January when a reservoir is introduced. On the other hand, streamflow decreases in August and September by about 30% and 20%, respectively. This means that reservoir operations even out the flow rate throughout the year, reducing the peaks in August and September and increasing the low flows from November to April. See figure in Appendix (4XV). Overall, there is an increase in streamflow by 0.89%. This percentage increase is quite strange since introducing a reservoir will facilitate more withdrawals and increase evaporation.

This will help in reducing the devastating effect of the Bagré dam spillage in August and September. There is a similar situation in the Oti basin when the Juale dam is introduced. Streamflow increases to a maximum of about 89% in November and decreases in July to a maximum of about 20% (Appendix 4XVI). It is also observed that irrigation demand is introduced as a scenario (Current 1_3) the streamflow decreases slightly.

5.3 Climate change Impact on Streamflow (Scenario2_1(2020-2039))

WEAP was also used to investigate the future climatic effect on the inflow into the Volta lake. Temperature is projected to increase under the RCP 4.5 scenario across the Volta basin. The increase in temperature corresponds to the findings of Niang et al., 2014 which projects temperature increase across Africa.

The projection of rainfall in table 19 shows that there is a reduction in precipitation. A decrease in rainfall signifies a decrease in streamflow in the Volta river basin. Increasing temperature and decreasing precipitation mean that the rate of evaporation will increase across the basin (Kankam-Yeboah et al., 2013).

The projected mean annual streamflow for scenario 2 (2020-2039) shows a significant decrease in the yearly streamflow across the basin, as shown in Figures 37 and 42. In the White Volta basin, there is a drastic decline in monthly streamflow. The average streamflow is estimated to decrease by 99% in August. This was not expected since the streamflow before climate change was quite high. Interestingly, there was no change in streamflow in September for the scenario (2020-2039).

According to Oguntude et al., 2017 an increase in drought intensity and spatial extent are projected over the Volta basin. This is consistent with the findings in the projection for 2020-2039. A streamflow decrease to this great extent is going to cause water shortages in the White Volta Basin. This streamflow reduction could be linked to the decline in rainfall in the basin for this scenario.

Mahe et al. 2013, explain that any change in rainfall affects to a certain degree the difference in streamflow. This is like what happens in both the Oti basin and the black volta basin, as shown in figure 38.

5.3.1 Scenario 3_1(2080-2099)

Engaging projections are observed for climate scenarios 3(2080-2099). It is observed in all sub-basins that there is an increase in annual streamflow for all years. This is made clear in the monthly average streamflow in figure 42 (Nawuni) where it is mostly dry in all the months except for September, which has streamflow of about 8000m3/s. This high flow in September will cause floods due to the prolonged dry season in the basin.

5.4 Impact of climate change on hydropower production

The current scenario (current 1_1) does not negatively impact hydropower since it has no climate change effect. There is increasing streamflow in the basin for the present scenario even with the introduction of future planned infrastructure, which means that there is no negative impact on hydropower. On the other hand, climate change for scenario 2_1(2020-2039) and scenario 3_1(2080-2099) have drastic effects leading to drought for all months except for September, where there are incredibly high flows in the basins. This condition by itself says a lot about the impact of climate change in the basin. One of the potential effects of variability and change in climate, primarily reduction in the amount and variation in the distribution of rainfall, is the possibility of changes to streamflow which will affect energy supply from hydropower sources (Energy Commission and United Nations, 2012; Harrison, Whittington & Gundry, 1998).

5.5 Impact of climate change on irrigation water demand

From the results obtained in the sub-basins, it is noticeable climate change will influence irrigation and food supply. The sustainable development goal (SDG2) to end hunger by 2030 seemed to be affected by the streamflow simulation in 2020-2039. This is because without water to meet irrigation demands, and it will be challenging to end hunger. The considerable reduction of streamflow due to low precipitation means that farmers who depend on the rain for their crops will be affected.

5.6 Impact of floating solar panels on water conservation

In policies for water resources management, strategies will need to be developed to match the continued evolution of water availability's complex dynamics to address the issues. Implementation of adaptation measures such as water conservation with floating solar panels will play a crucial role in determining and reducing the impacts of climate change on water resources in the Volta Basin. High temperatures over a long period will cause evaporation on the reservoir surface. From the estimation, covering 10% of Pwalugu will help to conserve annually. This amount of water will be helpful in municipal supply if it is not used to generate excess energy.

5.7 Contradictory results from another model for future projection of 2030-2039

Future simulated annual discharge and changes in hydrology obtained using the CIMP5 models from the World bank group climate portal used in this study for the Volta Basin is in line with what has been obtained in other investigations. Jung (2006) coupled WaSiM version 1 with MM5 and reported that for the future of 2030-2039, an average of 5 % increase in rainfall was expected with a wide variation of 20 % - 50 % between the Sahel and the Guinea Coast. In her report, no changes are expected for interflow for the future in the entire basin. However, surface runoff is projected to increase by 17% resulting in an overall increase in discharge. This contradicts what has been found in this work: different models and different water use for each scenario.

6.0 Conclusion and Recommendation

The study aims to apply the WEAP tool to simulate the effect of planned future reservoirs on streamflow into the Volta lake and investigate the impacts of climate change on water resources in the Volta Basin.

The model simulated historical streamflow in all the three sub-basins to a very good degree. The overall scenario results show that building the Pwalugu in the White Volta Basin, the Bui dam on the Black volta and the Juale dam in the Oti Basin with irrigation demands and abstractions specified in this study will not have an effect on streamflow assuming the climate change predictions give no change in precipitation.

However, Climate scenarios for the period (2020-2039) and 2080-2099 show a prolonged drought in the basin with an unpredictable intensity of rainfall in the month of September, especially for scenario 3(2080-2099).

The introduction of a 35km^2 large-scale floating solar panel of is vital in conserving water during droughts in the basin due to climate change. It will save water of about 6.7 x 10^7 m^3/year which is quite significant to the municipality. The solar panel will also produce about 12, 775 GWh per year. These are high values which may reduce.

This study concludes that water resources in the Volta basin are consequently affected by climate change. Therefore, the study recommends that further investigation be done on location, volume, and timing of water withdrawals in the Volta basin. This helps in proper management of water in the basin.

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Marquis, K.B. Averyt

8. Appendix

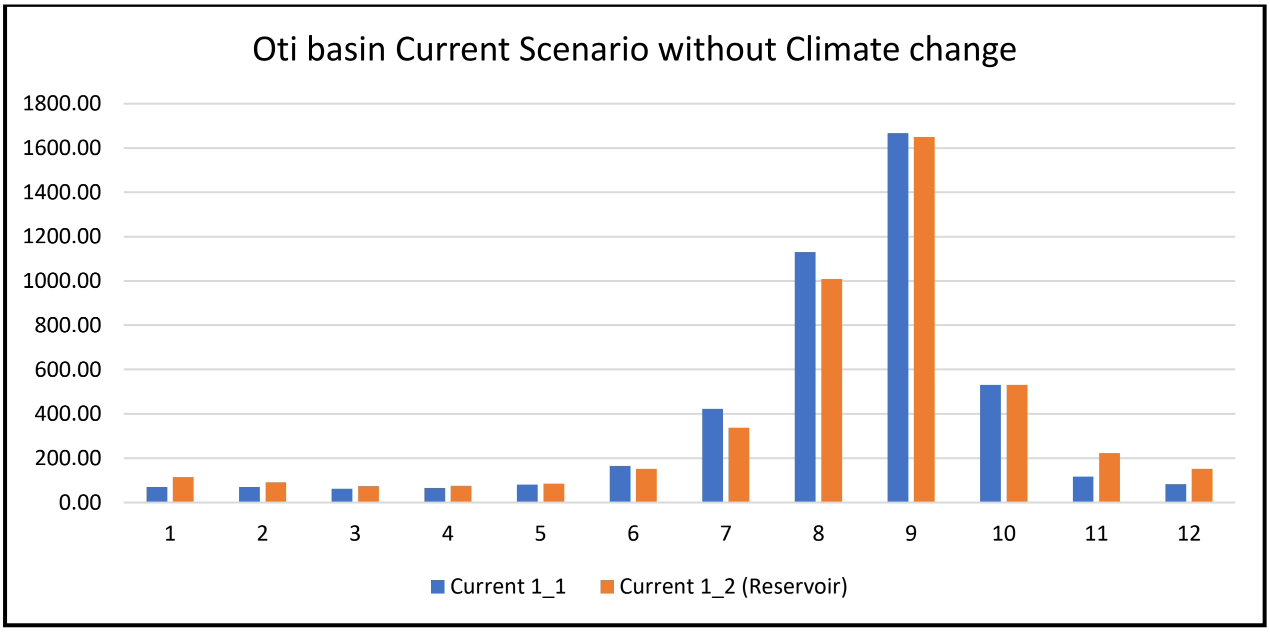
Appendix. 3 Calibration Parameters

Elevation (0-500m)					Cloudiness Factor (%)							
	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Agricultural_Non Irrigated	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9
Forest	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9
Grassland	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9
Wetland	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9
Urban	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9
Shrubland	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9
Barren or sparse vegetation	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9
Open water	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9
Irrigated Agriculture	0.9	0.9	0.95	0.95	0.8	0.6	0.4	0.3	0.4	0.7	0.8	0.9

Elevation (0-500m)					Humidity (%)							
	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Agricultural_Non Irrigated	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7
Forest	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7
Grassland	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7
Wetland	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7
Urban	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7
Shrubland	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7
Barren or sparse vegetation	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7
Open water	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7
Irrigated Agriculture	46.9	50.1	61.3	71.7	76.6	81.1	82.3	82.8	82.7	79.1	72.5	58.7

Elevation (0-500m)	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
					Runoff Resistance Factor							
Agricultural_Non Irrigated	2	2	2	2	2	10	40	200	50	22	2	2
Forest	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Grassland	2	2	2	2	2	2	2	2	2	2	2	2
Wetland	2	2	2	2	2	2	2	2	2	2	2	2
Urban	2	2	2	2	2	2	2	2	2	2	2	2
Shrubland	2	2	2	2	2	2	2	2	2	2	2	2
Barren or sparse vegetation	2	2	2	2	2	2	2	2	2	2	2	2
Open water	2	2	2	2	2	2	2	2	2	2	2	2
Irrigated Agriculture	2	2	2	2	2	2	2	2	2	2	2	2

Appendix 4 (I)



(II)

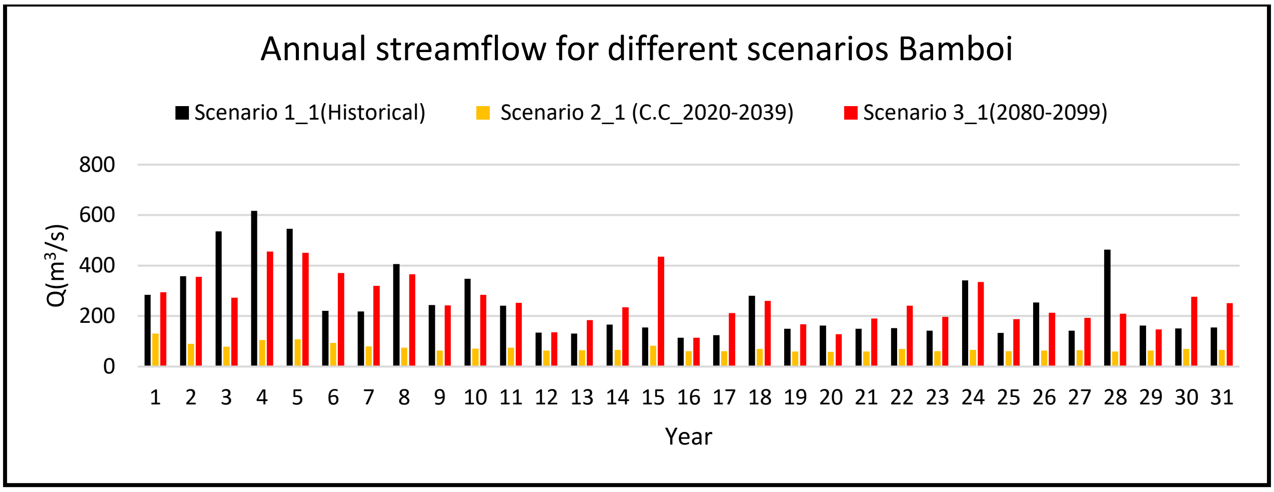
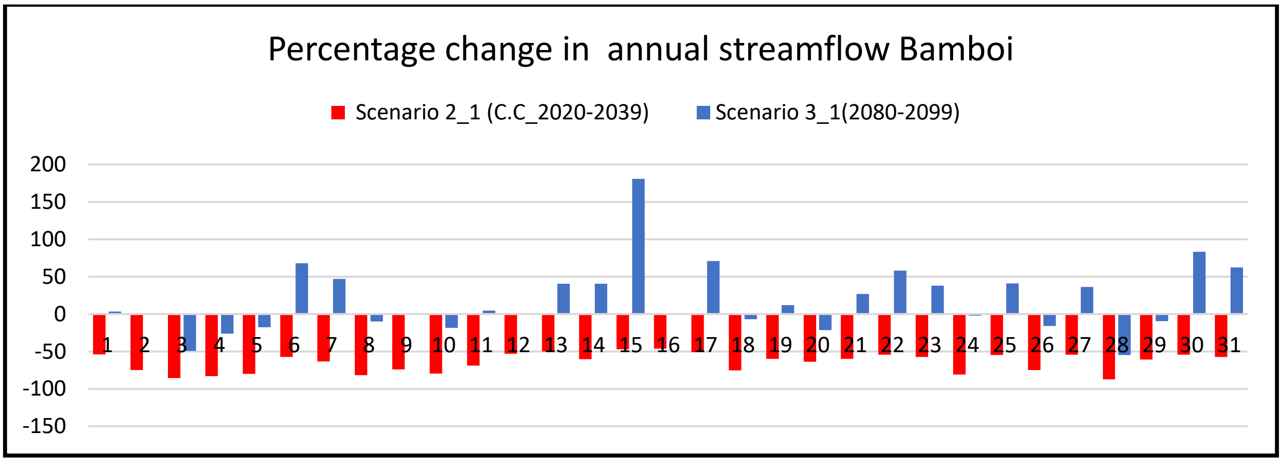
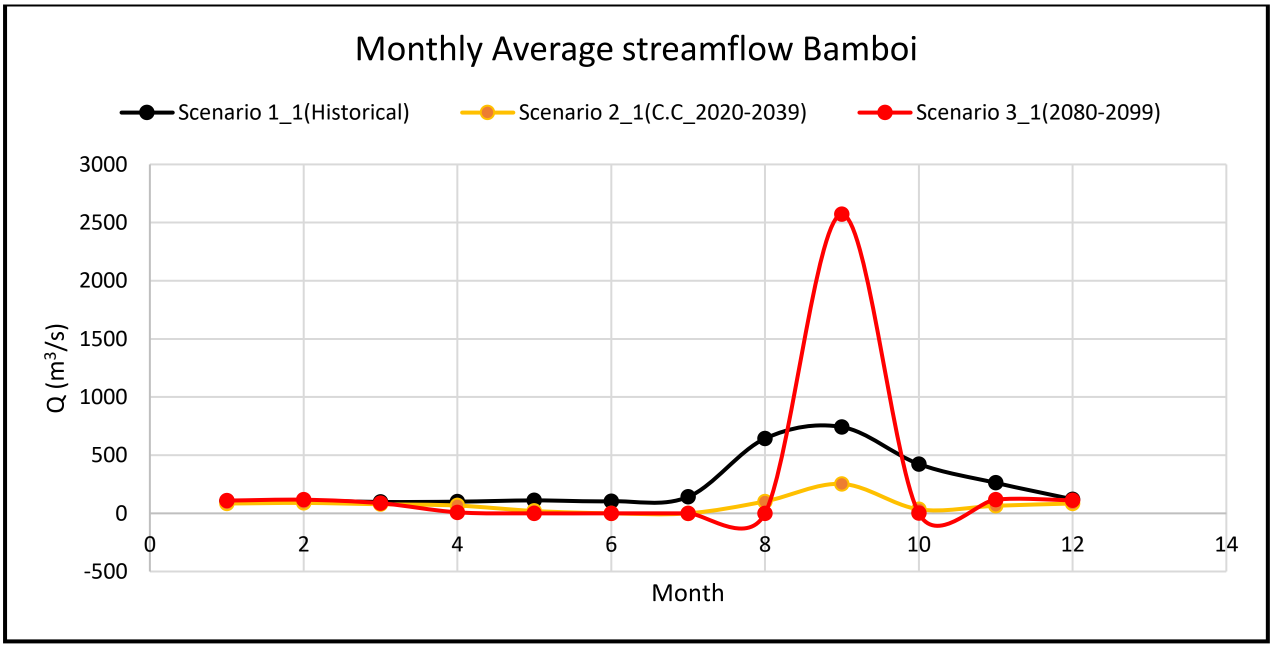


Figure 43. Comparing the annual streamflow for historical and future climates

(III)

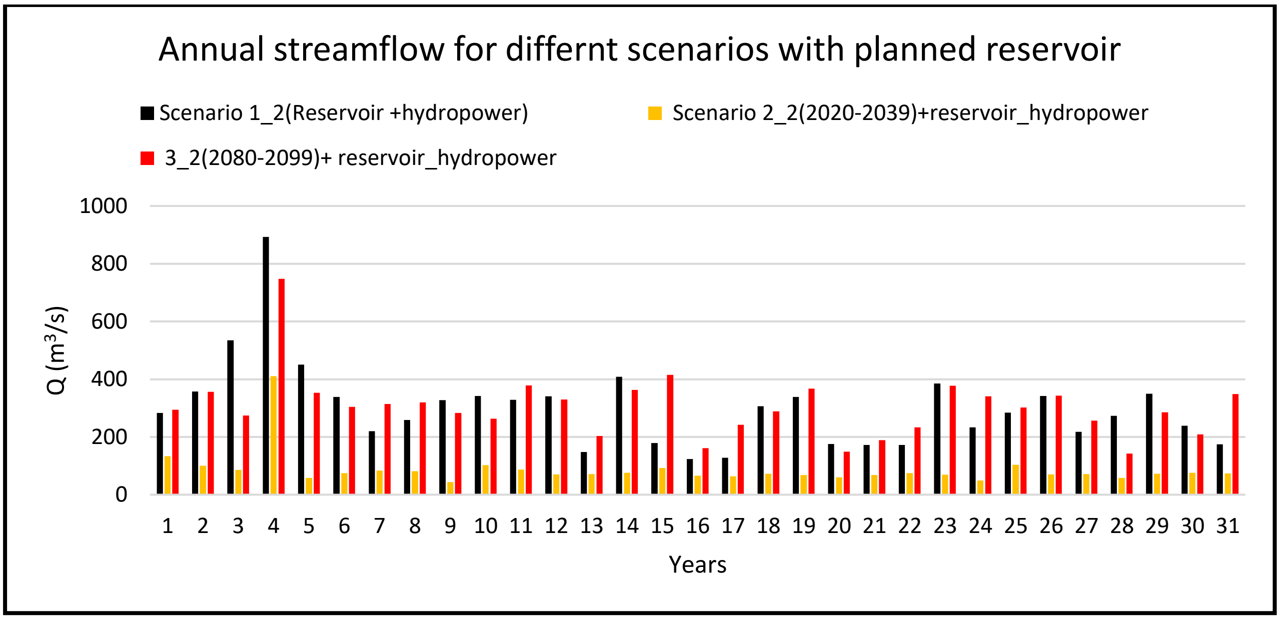


(IV)



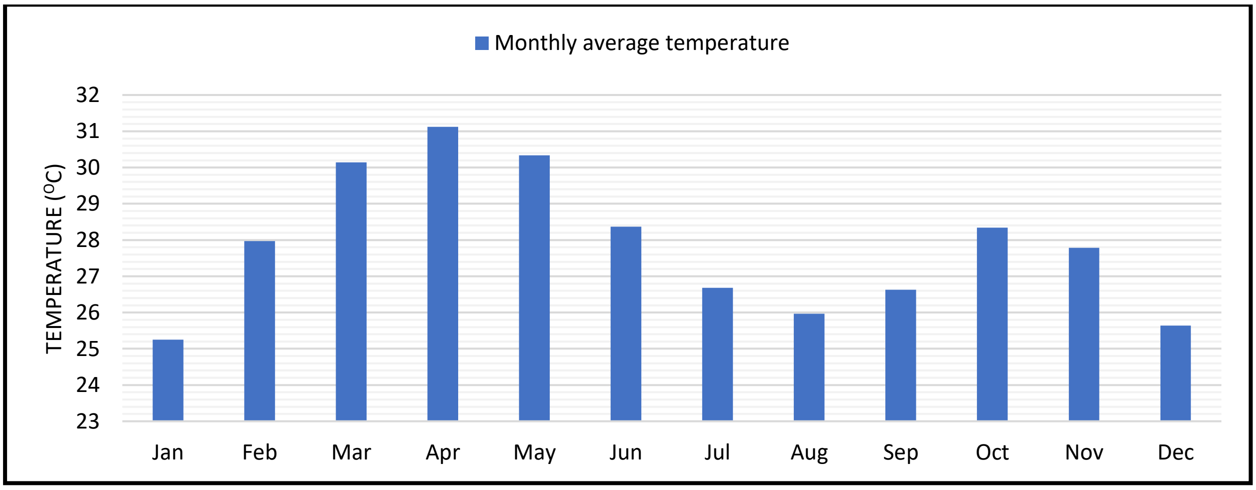
Monthly streamflow averages for historical and climate change scenarios, Bamboi.

(V)



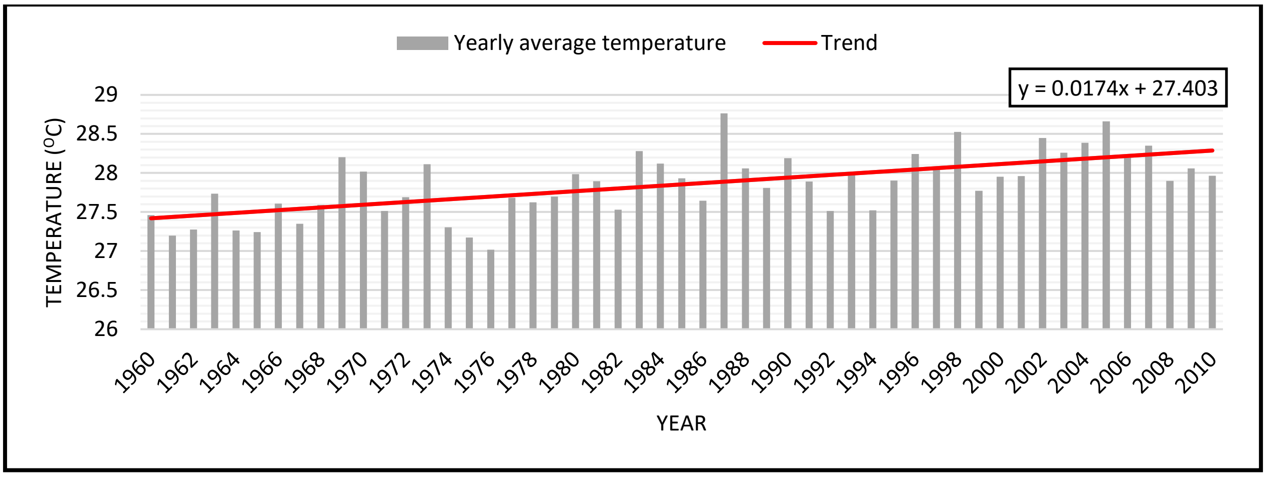
Annual stream flow with planned reservoir and climate change scenario for Bamboi.

(VI)



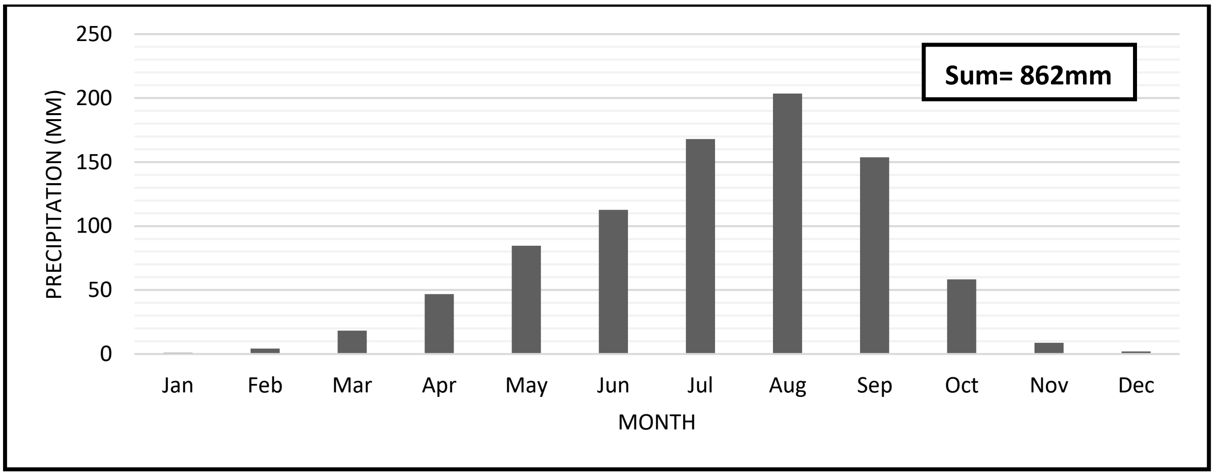
Monthly average temperature for Black volta basin (1960-2010).

(VII)



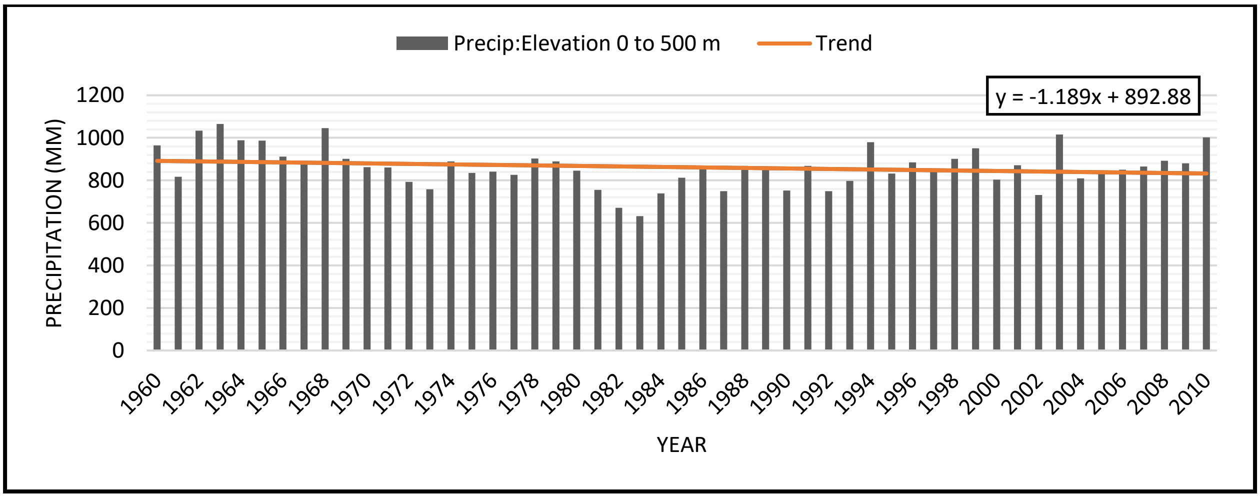
Yearly average temperature for Black volta basin.

(VIII)



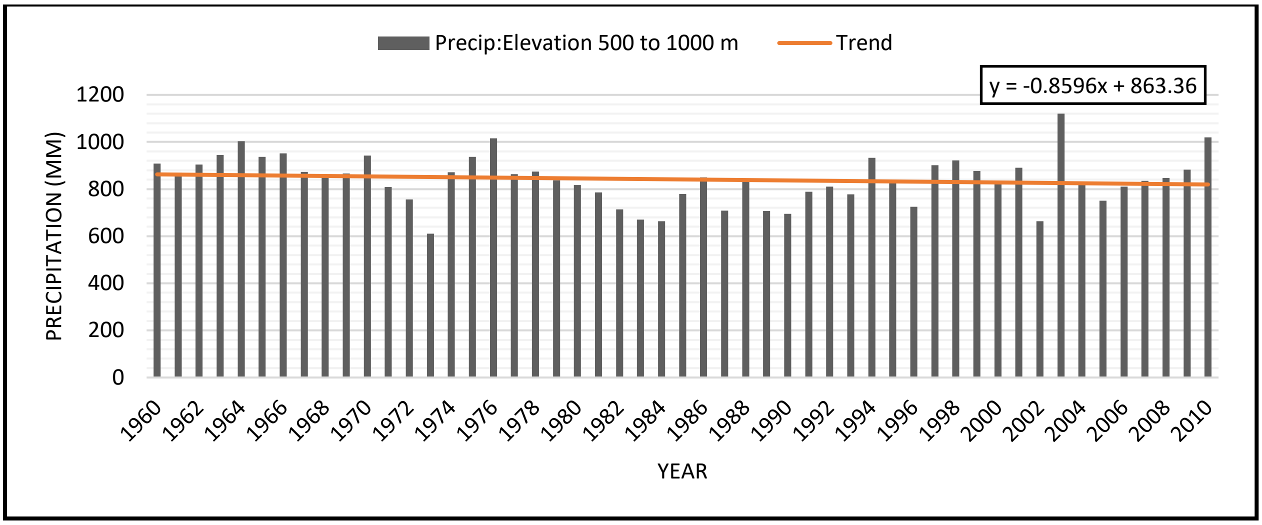
Average monthly precipitation in Black Volta basin (1960-2010)

(IX)



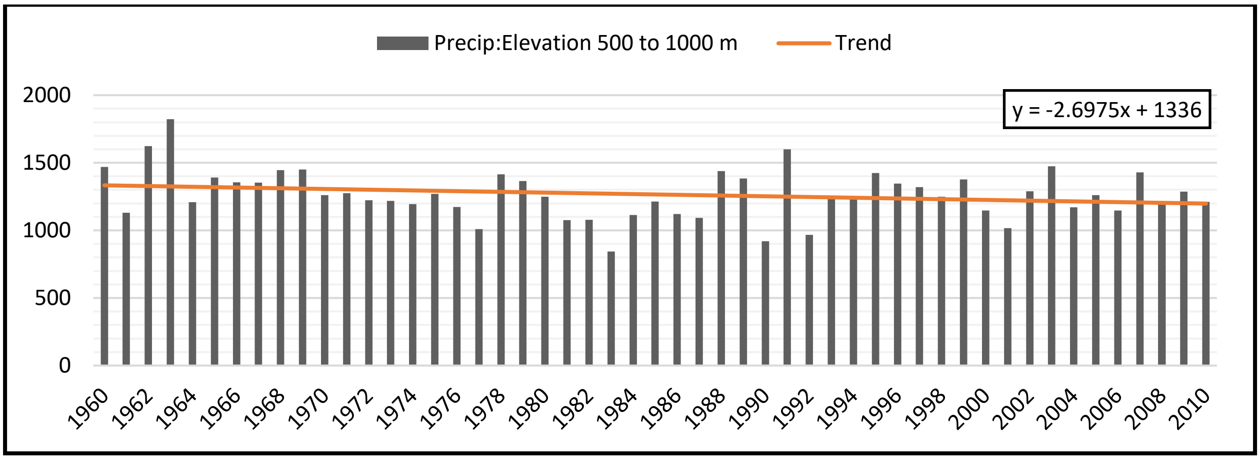
Annual precipitation in the Black volta basin at an elevation of 0-500m

(X)



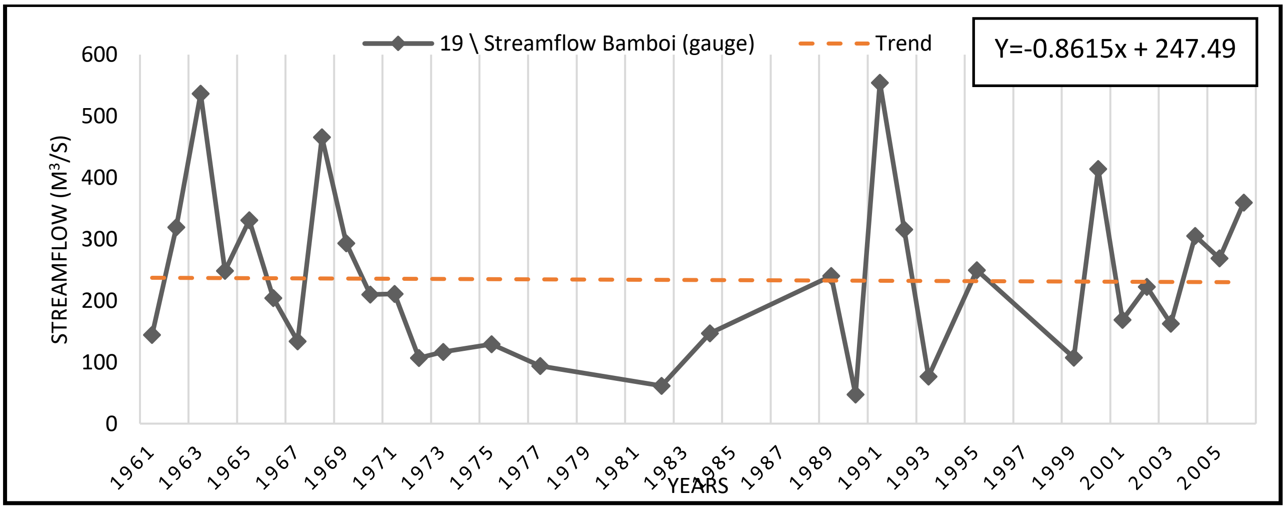
Annual precipitation in the Black volta basin at an elevation of 500-1000m.

(XI)



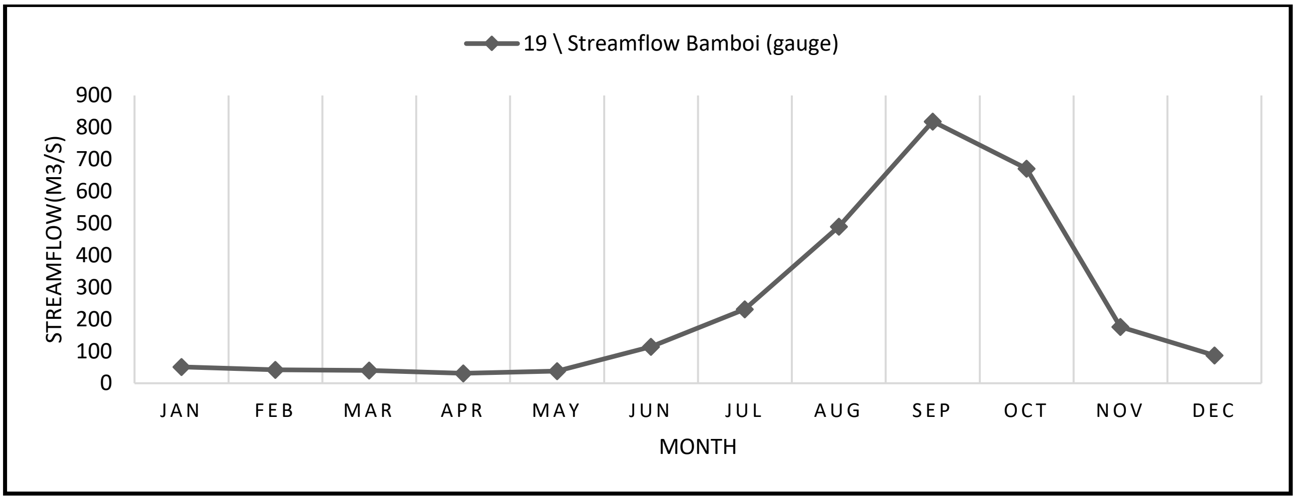
Annual precipitation in the Oti basin at an elevation of 500-1000m

(XII)



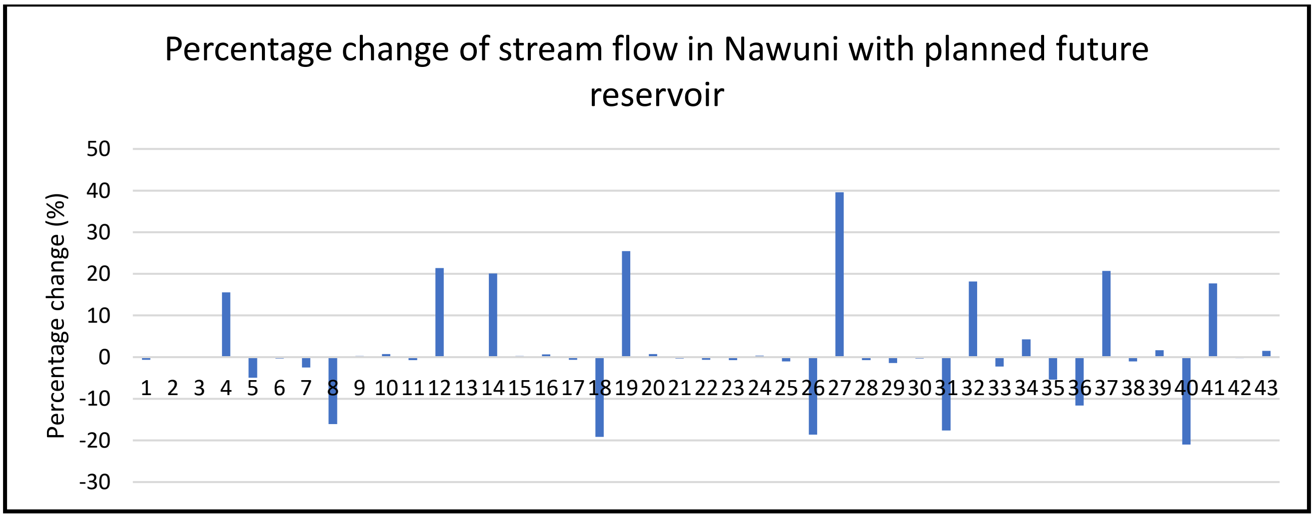
Bamboi annual streamflow in the Black basin

(XIII)



Bamboi monthly average streamflow from 1960-2006.

4(XIV)



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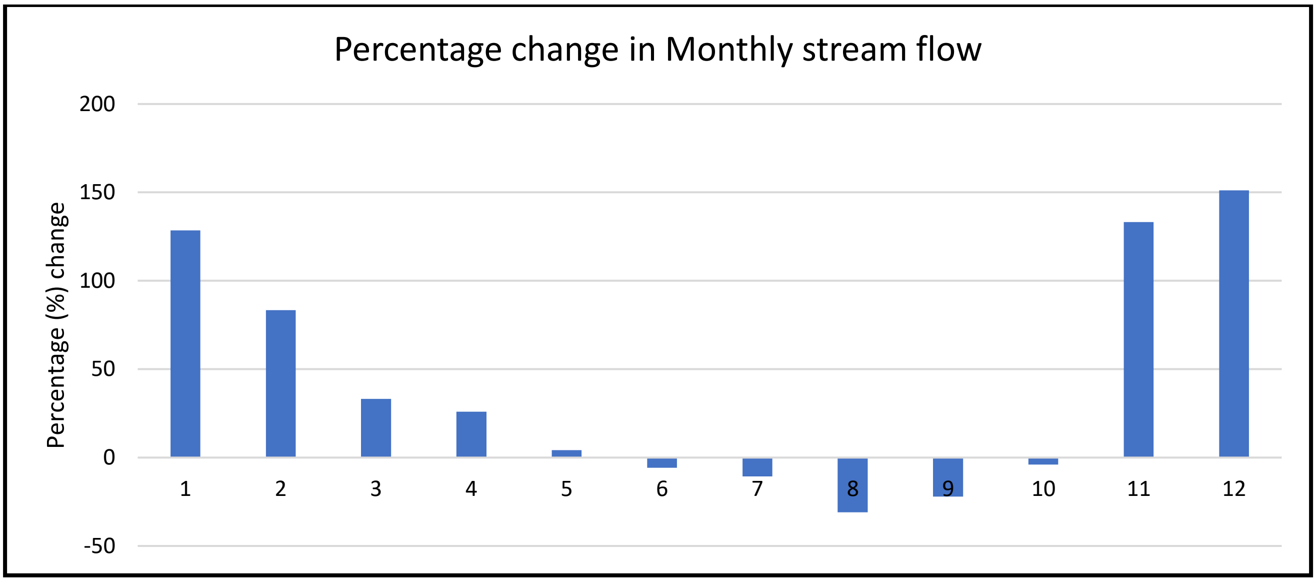

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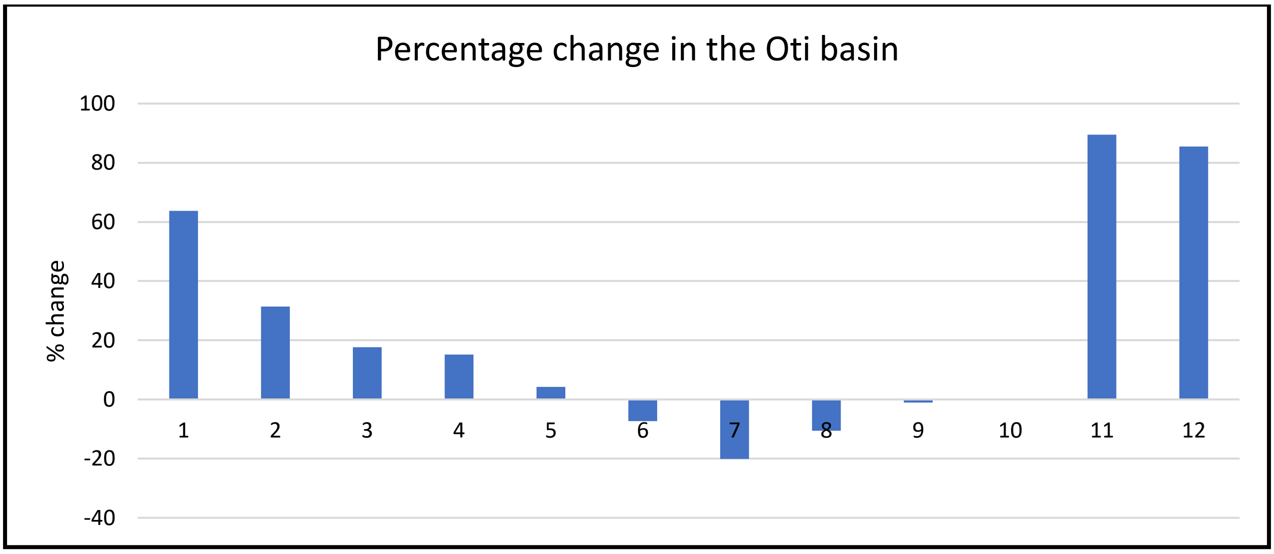

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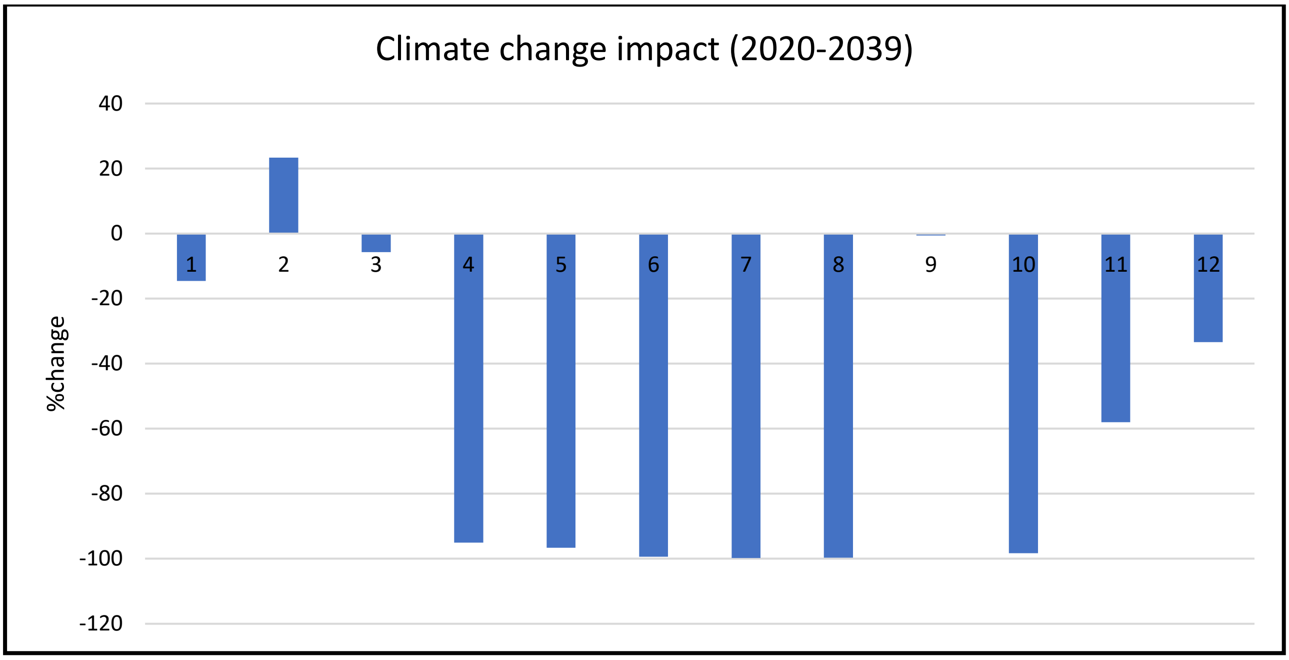
Climate change impact (2020-2039)
%change
40
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-20
-40
-60
-80
-100
-120
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