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Modelling the Impacts of Climate Change on Water Resources in Ghana: A Case study of the Densu River Basin

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DECLARATION

STUDENT'S DECLARATION

I, Jonathan Opoku Oti, hereby declare that this thesis titled "Modelling the Impacts of Climate Change on Water Resources in Ghana: A Case study of the Densu River Basin" is my original work realized to the best of my knowledge and has not been submitted to the University or any other institute or published earlier for the award of any degree or diploma. I also declare that all information, material and results from other works presented in this thesis have been duly cited and recognized as required of academic rules and ethics.

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SUPERVISOR'S DECLARATION

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ABSTRACT

Climate change continues to pose a threat to the sustainability of water resources. Global warming can have several effects on the water resources and water demands in the Densu River Basin especially household water use and agriculture use among several others. However, the extents to which the hydrology of the Densu River Basin is will be altered in the future remains unknown. In this research, the Water Evaluation and Planning (WEAP21) system was used to study the impacts of future climate change on water resources in the Densu River Basin. Future climate data (precipitation and temperature) for the period 2051-2080 was generated from the Swedish Meteorological and Hydrological Institute's climate models (ICHEC-EC-EARTH and RCA4) for RCP4.5 scenario under CORDEX experiment. The results of the study indicate that the Densu River Basin will experience a temperature increase and reduction in rainfall that will reduce water resources in the area. The climate change impact analysis indicates a reduction in the river streamflow due to decrease in rainfall. Consequently, the water demand for domestic and irrigation uses will not be met for the study period as a result of decrease in streamflow. It is recommended that an Integrated Water Resources Management (IWRM) plan be fully developed and implemented in the basin to ensure proper management of the water resources. In addition, future research on climate change adaptation for water management in the Densu River Basin should be conducted.

Keywords: Water Evaluation and Planning System (WEAP), Climate Change, Densu River Basin

RÉSUMÉ

Les changements climatiques continuent de menacer la durabilité des ressources en eau. Le réchauffement climatique peut avoir plusieurs effets sur les ressources et la demande en eau dans le bassin de Densu, notamment l'utilisation de l'eau par les ménages et l'agriculture, entre autres. Cependant, la mesure dans laquelle l'hydrologie du bassin de Densu sera modifiée à l'avenir reste inconnue. Dans cette recherche, le système d'évaluation et de planification de l'eau (WEAP21) a été utilisé pour étudier les impacts des changements climatiques avenir sur les ressources en eau du bassin de Densu. Les données climatiques futures (précipitations et température) pour la période 2051-2080 ont été générées à partir des modèles climatiques de l'Institut suédois de météorologie et d'hydrologie (ICHEC-EC-EARTH et RCA4) pour le scénario RCP4.5 dans le cadre de l'expérience CORDEX. Les résultats indiquent que le bassin de la rivière Densu connaîtra une augmentation de la température et une réduction des précipitations qui réduiront les ressources en eau de la région. L'analyse de l'impact des changements climatiques indiquent une réduction du débit du fleuve en raison de la diminution des précipitations. Par conséquent, la demande en eau pour les usages domestiques et l'irrigation ne sera pas satisfaite pour la période à l'étude en raison de la diminution du débit du cours d'eau. Il est recommandé qu'un plan de gestion intégrée des ressources en eau (GIRE) soit entièrement élaboré et mis en œuvre dans le bassin pour assurer une gestion appropriée des ressources en eau. En outre, des recherches avenir sur l'adaptation aux changements climatiques pour la gestion de l'eau dans le bassin de Densu devraient être menées.

DEDICATION

I dedicate this work to the Almighty God, my source of strength, to my parents Mary Nkrumah and Emmanuel Oti Anane for their prayers and encouragement, to my family, friends and loved ones who have supported me in attaining this height in education.

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CGIAR-CSI	Consultative Group for International Agricultural Research - Consortium for Spatial Information
DEM	Digital Elevation Model
DRB	Densu River Basin
GCMs	Global Climate Models
GIS	Geographical Information System
GSS	Ghana Statistical Service
IPCC	Inter-Governmental Panel on Climate Change
IWRM	Integrated Water Resources Management
LULC	Land Use Land Cover
NSE	Nash-Sutcliff Efficiency
PEST	Parameter Estimator Tool
RCMs	Regional Climate Models
RCP	Representation Concentration Pathway
SDG	Sustainable Development Goals
SRTM	Shuttle Radar Topography Mission
UNFCCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Programme
WEAP	Water Evaluation and Planning
WRC	Water Resources Commission

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CHAPTER ONE

1 INTRODUCTION

1.1 Background of Study

The economic growth and social development of every nation is dependent on the availability of freshwater especially in the sub-Saharan Africa. Adequate freshwater supply is fundamental for ensuring the sustainability of several economic and social activities such as water supply and sanitation, agriculture, urban development, hydropower generation, and recreation (Marquès, Bangash, Kumar, Sharp, & Schuhmacher, 2013). Water is a key component in all of these activities. These activities lead to high water demand putting pressure on water resources, stresses that are likely to be exacerbated by climate change and population growth (Sun, McNulty, Cohen, & Myers, 2005; Li, Deng, Huang, Zhang, & Huang, 2013; Arsisoa, Tsidua, Stoffberg, & Tadesse, 2017). Besides the economic value, freshwater availability is vital in addressing issues of health, poverty and hunger. Regardless of all the economic and social advantages of the water resources, its sustainability is threatened by a phenomenon termed as climate change. With climate change as another factor, the competition for water demand is becoming more severe (Arsisoa, Tsidua, Stoffberg, & Tadesse, 2017).

The change in climatic conditions over the past years has seen a rise in the earth temperature and variation in precipitation pattern across Africa (IPCC, 2007). Research by renowned scientist and organizations indicates that increasing amounts of carbon dioxide and greenhouse gases lead to changing global climate drastically during this century (IPCC, 2014). This will lead to rise in the average Earth's temperature: a phenomenon known as global warming (IPCC, 2014). Global warming can have several effects on the water resources and water demands especially household water use, agriculture use and hydropower generation among several others (Peterson & Keller, 1990). The rise of global surface temperature and changes in spatial and temporal patterns of precipitation will result in severe extreme weather events, including higher intensity rainfall events, increased/decreased streamflow conditions as well as increase in extreme high sea levels (UNFCCC, 2007; IPCC, 2014). These changes could affect the hydrological cycle, and it could have significant impacts on the availability (both quantity and quality) (IPCC, 2014; Hrdinka, Vlasák, Havel, & Mlejnská, 2015; Arsisoa, Tsidua, Stoffberg, & Tadesse, 2017) and distribution of water resources especially in Ghana (Gyau-Boakye & Tumbulto, 2006).

A report by the United Nations Framework Convention on Climate Change (UNFCCC) estimates about seventy-five to two hundred and twenty people across Africa to experience water shortage by 2020 (UNFCCC, 2007). A study in the Volta Basin (Gyau-Boakye & Tumbulto, 2006) showed significant decreases in annual rainfall and river discharges in recent years: there was a 12% reduction in the average annual rainfall in some areas of the Volta basin. The same study observed a reduction in river discharges of up to about 35% on major tributaries of the Volta River. In a research on some river basins in Ghana, the projection revealed an increase in temperature and decrease in rainfall for the 2020s and 2050s respectively in the White Volta and Pra basins. As a consequence, the mean annual streamflow in the White Volta and Pra basins were estimated to decrease by more than 20% for the 2020s and 2050s (Kankam-Yeboah, Obuobie, Amisigo, & Opoku-Ankomah, 2013).

This situation is likely to be intensified by increasing change in climate and there could be a similar event in the Densu River Basin (DRB) (Water Resources Commission, 2018). According to the Inter-Governmental Panel on Climate Change's report, Africa is very likely to become much warmer than the rest of the Earth, projecting an increase in average surface temperature of about 3 - 6 ^{o}C by the end of the 21st century, comparative to the late 20th century as a result of climate change (Niang, et al., 2014). This will lead to devastating situations as long as our water resources are concerned especially with increasing population (Sun, McNulty, Cohen, & Myers, 2005). Climate Change won't affect the availability of water resources only but water demand: this is anticipated to increase with a decrease in water supply as a result of warmer climate (Peterson & Keller, 1990). For instance, agriculture consumption, which is the major demand for water supply, will be increased due to both decreasing precipitation and increasing evapotranspiration and this will diminish crop productivity (Peterson & Keller, 1990; Amisigo, McCluskey, & Swanson, 2015). In water-stressed basins, where the water demand is already approaching the available supply, the impacts of climate change can be extremely severe (Rosenzweig, et al., 2004). Therefore, the aim of this study is to investigate the climate change and variability in the Densu River Basin of Ghana and assess its impact on the water resources.

1.2 Problem Statement and Justification

Climate, freshwater, biophysical and socio-economic systems are connected to each other in complex ways such that a change in any one of these will affect the others. Nations already facing the issue of sustainable freshwater use will experience a lot of pressure due to anthropogenic induced climate change. Freshwater challenges have to do with either having

excess water, having very less water or having excess pollution. These challenges are no different from the Densu River Basin (Water Resources Commission, 2007). The demand for water supply in the basin has increased (Water Resources Commission, 2007) as a result of the increasing population (Ghana Statistical Service, 2013) within the Basin and this has put a lot of pressure on the river. The population pressures in the basin has led to increased domestic, municipal, and agricultural activities causing a progressive deterioration of the water quality and quantity. Agricultural activities in the basin including livestock raring, improper application of fertilizers and land tillage have resulted in significant damage to the environment and polluted the river (Karikari & Ansa-Asare, 2006; Water Resources Commission, 2007).

Karikari and Ansa-Asare (2006) observed a poor microbial quality in the Densu River due to contamination by human excreta and livestock. Land use changes through time has altered the ecology of the Densu River Basin dramatically (Water Resources Commission, 2007) disrupting the natural ecosystem. Removal of vegetation and thinning of forest has intensified contributing to the loss of water from the river through high rate of evaporation. Illegal mining activities within the river basin, most of which happen in the river bed is also contributing highly to the deterioration of the river water quality as well as the quantity. These activities forms the major land use activities within the basin (Ayivor & Gordon, 2012) and are drivers of climate change. The changes in climate will result in temperature rise and variation in rainfall patterns (Stanturf, et al., 2011; Niang, et al., 2014). These changes alters the hydrological processes in the basin posing a threat to the quantities of water available, water demand and its quality affecting economic and social development of the country (Arndt, Asante, & Thurlow, 2015), sustainability of the water resources and the natural ecosystem. The extents to which the hydrology of the basin is altered or will be altered in the future remains unknown.

However, previous studies within the basin have generally focused on the river water quality (Karikari & Ansa-Asare, 2006; Amoako , Karikari, Ansa-Asare, & Adu-Ofori, 2010), groundwater quality (Tay & Kortatsi, 2008), land use change, soil erosion (Ayivor & Gordon, 2012; Ashiagbori, Forkuo, Laari, & Aabeyir, 2014), and pesticide residue (Fianko, et al., 2011). There are very few studies on the impact of climate change on hydrological process within the basin (Kasei, Barnabas, & Ampadu, 2014) as other researchers (McCartney, et al., 2012; Kankam-Yeboah, Obuobie, Amisigo, & Opoku-Ankomah, 2013)

focus more on the Volta river basin and Pra basin. The basin is water stressed (Water Resources Commission, 2007) and this might be extreme as a result of climate change.

Therefore, the relationship between climate change and water resources is important to understand the possible impact on the hydrology of the river and subsequent impact on the water demand coverage. Understanding the relationship between changing climate and the Densu river will provide impact-specific information. This information can be used to directly inform scientists and policy makers to mitigate the negative effects of global warming. Realization of the impact of climate change on various components of the water cycle is very important for long-term sustainable management of the water resources. This will be achieved by introducing proper water management scenarios in preparation of local and national action plans on climate change adaptation for the river basin. These adaptation plans will contribute to the realization of agenda 2063 of the African Union and the realization of the United Nation Sustainable Development Goals (SDGs) especially SDG 13 and subsequently SDGs 6, 3, 2 and 1. SDG 13 is concerned with taking urgent action to combat climate change and its impacts and as this is done, it will ensure a future where there is enough fresh water for all to practice good sanitation and hygiene (SDG 6: Water and sanitation). Availability of water will promote agricultural activities: production of food thereby eradicating hunger (SDG 2: Zero hunger). Attainment of SDG 6 will in effect promote good health and wellbeing of the populace (SDG 3: Good health and well-being) and this will increase productivity of the populace, improve their economic and social living standards contributing to eradication of poverty (SDG 1: No poverty).

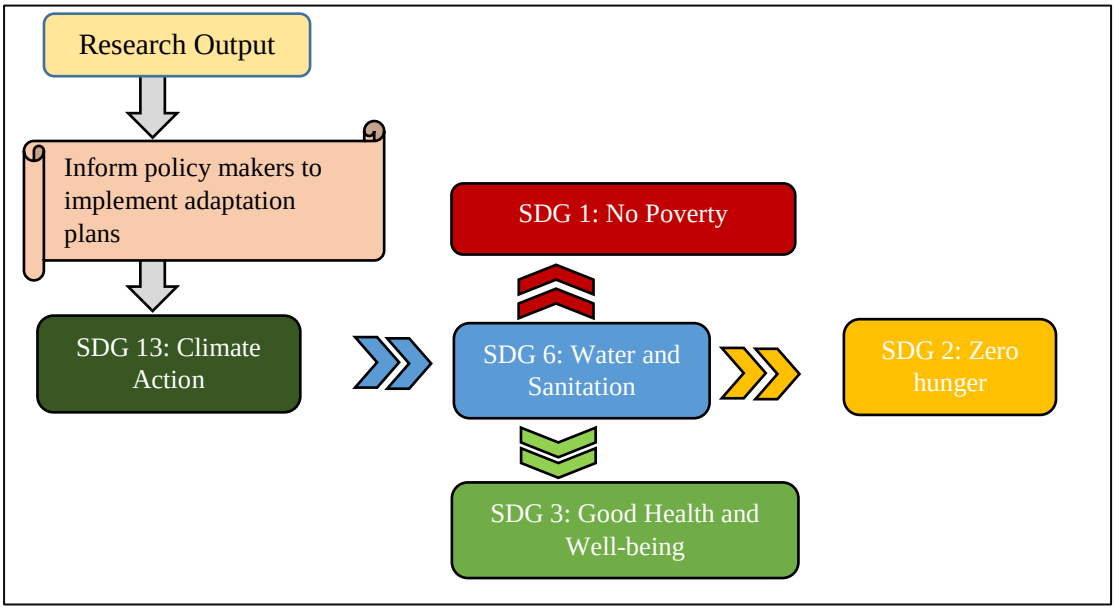

Figure 1.1: A chart indicating the relevance and relationship of the output of this research to Sustainable Development Goals

1.3 Study Objectives

The overall study goal is to assess the impacts of climate change on Densu River Basin using the Water Evaluation and Planning (WEAP) System model. The specific objectives are:

1. To simulate historical data within the Densu basin by calibrating and validating the WEAP model for the basin.
2. To assess the changes in future climate of the Densu River Basin for the period of 2051-2080.
3. To simulate the projected future precipitation and temperature (weather data) using WEAP model.
4. To assess the impact of climate change on water resources for irrigation and domestic water supply by comparing the historical and projected future simulations of the Densu basin.

1.4 Thesis Structure

The structure of this thesis consists of five chapters. These chapters are organized as follows:

Chapter 1, this chapter introduces the background to the study, the problem definition in the study area, the objectives and the relevance of the studies.

Chapter 2, deals with the review of literature on vital studies that are related to climate change, water resources in general, land use changes, amongst others. This chapter is an overview of previous studies, which provides the information as a reference for this research.

Chapter 3, deals with the methodology. The methods and materials used for analysis and modelling are described in this chapter. This chapter is in five phases: 1. Preparation, 2. Data Collection, 3. Data Preparation, 4. Modelling, and 5. Reporting.

Chapter 4, presents the results and discussion of the research and the last chapter, 5, deals with the key conclusions and recommendations.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Aspect of Climate Change

Climate change is gaining popularity among countries and international organizations due to the extent of its impacts on the environment, society and the economy. There has been observation of a long-term climatic changes across the globe due to the rate at which greenhouse gases especially carbon is being introduced into the environment. These changes include the variation in precipitation patterns and the quantity, change in temperature mostly on the rise and aspects of extreme weather events such as droughts and floods (IPCC, 2007). The mean annual temperature on the African continent is expected to exceed 2°C in the last 2 decades of this century (Niang, et al., 2014). Africa will see a faster rate of rise in land temperatures than the global land average especially in the more arid areas according to IPCC (Niang, et al., 2014). West Africa is projected to experience an increase in temperature up to 6.5^{o}C by the end of 21st century (Sylla, Nikiema, Gibba, Kebe, & Klutse, 2016). The change in temperature will affect the pattern of precipitation and how it is distributed across the continent. The changes in precipitation will include the amount, the intensity and the frequency. A study by (Trenberth & Shea, 2006) indicates an increase in precipitation in the eastern North America and northern Europe and decreased in most parts of Africa and southern Asia. The Northern Africa and Southwestern parts of South Africa is likely to experience a reduction in precipitation by the end of the 21st century with an increase and extreme rainfall in regions of high topography. However, in the sub-Saharan Africa, there are uncertainties in rainfall changes by the end of the century (Niang, et al., 2014). In West Africa, the uncertainty of rainfall variability in the future is estimated to fall between the range of -30% to +30% (Sylla, Nikiema, Gibba, Kebe, & Klutse, 2016). However, in Ghana, the future mean annual temperature is projected to increase by 1.5 – 5°C in the 2090s with rainfall variability (McSweeney, New, & Lizcano, 2006).

2.2 Climate Change and Water Resources

Climate and water are connected in a complex way through several variables such as precipitation, temperature, and solar radiation, however, these conditions differ from region to region. The impacts of a change in any of these variables alter the hydrological cycle by increasing runoff, the intensity of rainfall and evaporation rate (Kabo-bah, Anornu, Ofosu, Andoh, & Lis, 2014; Huang, Lee, & Lee, 2014). These will be manifested in floods, drying-

up of rivers, lakes, and water bodies, change in rainfall patterns and the occurrence of droughts (Faramarzi, et al., 2013). The changing climate will increase strongly from decades with higher temperatures and extreme precipitation, resulting in declined water supplies, water quality and increased water demand (IPCC, 2014) with a severe impact on the Northern-Saharan communities.

One of the key components of water resources is runoff and it will be highly impacted by climate change. Runoff is affected by changing of temperature and precipitation (Beyene, Lettenmaier, & Kabat, 2010). Due to importance of runoff for water supply a lot of research has been conducted to quantify the effects of climate change on runoff. The impact of climate change and variability on water resources is evident across the globe (Niang, et al., 2014). Previous studies using climate models projected a decreased in runoff in California and other parts of the West, while runoff will be increased in the East (Seager, et al., 2007; Bates, Kundzewicz, Wu, & Palutikof, 2008; Lettenmaier, Major, Poff, & Running, 2008). A research conducted on the Thac Mo catchment in Vietnam also indicates variation in the streamflow depending on the season under future climate projections (PHAM, YU, YANG, KUO, & TSENG, 2017). Yan, et al., (2018) recorded a decrease in streamflow over the Miyun reservoir in the Northern China as a result of climate change. Northeastern China will experience lack of water availability in the future as a result of changing climate (Rosenzweig, et al., 2004).

The climate change impact on the African continent is no different from the global situation: it is expected to be worse (Niang, et al., 2014). Africa is reported to experience future decrease in water availabilty resulting from range of drivers including climate change especially in the Northern and Southern Africa. The UNFCCC has reported increasing water stress for many countries within the African continent. The report projects drying up and desertification especially in the Sahel and the Southern Africa (UNFCCC, 2007). According to Beck and Bernauer (2011), countries within the Zambesi River Basin will compete for increasing water shortages due to changing climate. However, the future water availability in the basin will be strongly impacted by non-climate drivers such as population and economic growth (Beck & Bernauer, 2011). The Rozva dam in Zimbabwe is estimated to experience water shortages for the downstream users due to climate change in the region (Ncube, Makurira, Kaseke, & Mhizha, 2011). In Botswana, the Okavanga Delta is projected to experience reduction in river flows (Murray-Hudson, Wolski, & Ringrose, 2006) and future water shortages (Milzow, Burg, & Kinzelbach, 2010; Wolski, Todd, Murray-Hudson,

& Tadross, 2012) due to climate change. Studies shows that the Breede River in South Africa will experience a reduction in runoff in the future under changing climate (Steynor, Hewitson, & Tadross, 2009).

It is estimated that climate change will account for 22% of future water shortages in the Northern Africa by 2050 (Droogers, et al., 2012). In Tunisia, higher temperatures and declining rainfall would reduce water resources in the Merguellil basin (Abouabdillah, Oueslati, Maria De Girolamo, & Porto, 2010). The Blue Nile will see a reduced flows by late century due to climate change combined with upstream water development (Elshamy, Seierstad, & Sorteberg, 2009; McCartney & Girma). Another studies in the Nile river also estimated that the streamflow will increase between the periods of 2010-2039 due to increasing precipitation and it will decrease during the mid and late century as a result of decline in precipitation and increased evaporation (Beyene, Lettenmaier, & Kabat, 2010). Seasonal and annual runoff volumes in the Gilgel Abay catchment in Lake Tana Basin are estimated to decrease (-33%) by the 2080s (Abdo, Fiseha, Rientjes, Gieske, & Haile, 2009).

Change in rainfall patterns in West Africa has affected runoff in the past years (Nicholson & Grist, 2001). The river discharge in West Africa is strongly influenced by variations in rainfall: there is three times reduction in runoff whenever there is a unit decline in rainfall (Mahe, et al., 2013). The West African region is projected to experience an increase in temperature by the end of the 21st century, however, that of rainfall is uncertain (Niang, et al., 2014; Roudier, Ducharne, & Feyen, 2014). McCartney, et al., 2012 anticipated a decrease in the mean annual runoff of the Volta Basin by the middle of the twenty-first century. A projection in the Volta Basin indicates a slight mean increase in total annual precipitation (Kunstmann, Jung, Wagner, & Clottey, 2008) and in the Bani River Basin in Mali, the runoff is estimated to reduce substantially due to redution in rainfall (Ruelland, Ardoin-Bardin, Collet, & Roucou, 2012). The Congo Basin will experience reduction in runoff in the future as a result of changing climate (Tshimanga & Hughes, 2012).

In Ghana, a research conducted on some river basins projected a reduction in the annual streamflow for the Pra and White Volta basins in the 2050s (Kankam-Yeboah, Obuobie, Amisigo, & Opoku-Ankomah, 2013) as well as the Densu River basin (Kasei, Barnabas, & Ampadu, 2014). Gyau-Boakye and Tumbulto (2006) simulated the impact of climate change on the streamflow in the Volta basin in West Africa. The study revealed a 12% reduction in the average annual rainfall and a 35% streamflow reduction in some areas of the Volta Basin. Water requirement for irrigation will be highly affected due to climate change and this will

pose a threat to crop production (McCartney, et al., 2012; Niang, et al., 2014; Amisigo, McCluskey, & Swanson, 2015) and human survival. Sustainable domestic water supply is also a major challenge in the era of increasing climate change and variability. The availability, distribution and quality of fresh water for human consumption will be a challenge due to climate change (Kankam-Yeboah, Obuobie, Amisigo, & Opoku-Ankomah, 2013) as well as the generation of hydropower (McCartney, et al., 2012).

2.3 Land Use Land Cover Changes and Related Impacts

Land use changes has generally occurred locally, regionally and worldwide over the past few decades and this will continue in the future as well. The increment in urbanization has a major impact on both surface waters and groundwater. Land use land cover changes over the years has been a major factor influencing the sustainability of the water resources (Pielke, et al., 2011; Kishtawal, Niyogi, Tewari, Pielke, & Shepherd, 2010). An increase in agricultural land use has direct consequences on ecosystem services (Zhang, Ricketts, Kremen, Carney, & Swinton, 2007; Dale & Polasky, 2007). (Mehta, Haden, Joyce, Purkey, & Jackson, 2013) observed increase in irrigation demand in Yolo County as agriculture increases, however, water supply from the upstream reservoir is less vulnerable due to increased precipitation. The increase in population and the rapid socio-economic development drives land use change (Dams, Woldeamlak, & Batelaan, 2008) putting stress on the environment especially the water resources (Sun, McNulty, Cohen, & Myers, 2005; Sharma, et al., 2017). Land use change has become one of the most researched topic in the field of hydrology (Genxu, Lingyuan, Lin, & Ku, 2005). A study in India on Land Use change estimated an increase in runoff due to urbanization (Wagner, Kumar, & Schneider, 2013). A study on the Heihei river Basin in China reported a significant impact of land use land cover change on the water yield (Geng, Wang, Yan, Zhang, & Jin, 2015). A trend studies in the eastern sub-basins of Lake Urmia showed a decrease in streamflow due to Land use Land cover (LULC) changes (Fathian, Dehghan, & Eslamian, 2016).

LULC changes can alter the ecosystem services, hydrologic system and have potentially large impacts on water resources (Daily, et al., 2009). A recent study by (Kundu, Mathivha, & Nkuna, 2015) indicates a disruption in hydrologic processes (reducing infiltration, interflow, surface runoff) due to frequent development in the Luvuvhu River Catchment. The climate system such as atmospheric temperature, humidity, cloud cover, circulation, and precipitation, is highly influenced by LULC changes (Fathian, Dehghan, & Eslamian, 2016). The impacts are observed at the local and regional scales to sub-continental and global scales

(Marquès, Bangash, Kumar, Sharp, & Schuhmacher, 2013; Mahmood, et al., 2014; Deng, et al., 2014). The supply of freshwater flows and water-related ecosystem services are closely related to land use management (Marquès, Bangash, Kumar, Sharp, & Schuhmacher, 2013). Climate change has greater influence on the water supply services. Changes in seasonal stream flow in the Black Volta for wet and dry periods has increased and decreased by 6% and 1% respectively due to LULC (Akpoti, Antwi, & Kabo-bah, 2016). The changing climate is expected to intensify the hydrological cycle in semi-arid areas through increases in global temperature, rainfall concentration in short periods of the year, and more frequent droughts (Marquès, Bangash, Kumar, Sharp, & Schuhmacher, 2013). The amount and timing of water movement through the landscape will shift due to changing climate and this will alter the water yield (Hoyer & Chang, 2014).

2.4 Water Evaluation and Planning System (WEAP)

2.4.1 Background

WEAP is the hydrological model to be used in this research. A model is a simplified representation of real world system (Sharma, Sorooshian, & Wheater, 2008). The model that gives accurate with the use of least parameters and model complexity can be said to best model. One important reason for using hydrological models is to predict system behaviour and understand various hydrological processes. WEAP is developed by the Stockholm Environment Institute (SEI). WEAP is an easy-to-use model used to assist in water resources management. WEAP was developed to assess water demand and to evaluate water resource development projects, climate change impacts and water management scenarios (Seiber & Purkey, 2015). The Water Evaluation and Planning (WEAP) system is advanced, integrated modeling software that attempts to combine an integrated modelling tool for water resources planning and management (water supplies, water demands and environmental requirements) considering effects of policies on water quantity, water quality and the ecosystem. (Seiber & Purkey, 2015).

WEAP is applicable to many scales: municipal and agricultural systems, single catchments or complex transboundary river systems. It operates on the basic principle of a water balance and can be applied to a single watershed or a complex transboundary river basin system (Yates, Sieber, Purkey, & Huber-Lee, 2005). WEAP is considered a conceptual model taking into account the schematization approach for the physical system and the nature of the models used for describing the hydrological processes (Riepl, 2013). It has a user-friendly graphical user interface (GUI) which makes it easier to work around.

2.4.2 WEAP applications

The WEAP model has been applied in different basins across the Globe and it is still being applied. It is one of the most used model for integrated water resources management. WEAP model is widely used to assess the impact of climate change in the future possible climate (Rosenzweig, et al., 2004; Purkey, Huber-Lee, Yates, Hanemann, & Herrod-Julius, 2007; Alemayehu, McCartney, & Kebede, 2010; Mehta, Haden, Joyce, Purkey, & Jackson, 2013; Santikayasa, Babel, & Shrestha, 2015) and adaptation scenarios on water resources (Joyce, Mehta, Purkey, Dale, & Hanemann, 2011).

Hoff, et al., (2011) applied WEAP to analyze the management of transboundary water resources in the Jordan River basin. The WEAP software was applied on the Ali Efenti catchment in Greece to design water efficiency measures to address the issue of water shortages due to rapid increase in water abstraction (Psomas A. , Panagopoulos, Konsta, & Mimikou, 2016; Psomas A. , Panagopoulos, Stefanidis, & Mimikou, 2017). In the city of Volos, Greece, the future water demand was assessed considering the impact of water prices and climate change under several scenarios (Mylopoulos, Fafoutis, Sfyris, & Alamanos, 2017). (PHAM, YU, YANG, KUO, & TSENG, 2017) used WEAP to analyze the climate change impact on the hydrological processes in the Thac Mo catchment in Vietnam. The Chancay-Huaral Basin in Peru plays a vital role in the socio-economic development of the Lima province. Due to competing and increasing demand of water in the basin (resulting from population growth), (Olsson, et al., 2017) investigated the impact of climate change on the river discharges for the future using WEAP. (Al-zubari, El-sadek, Al-aradi, & Al-mahal, 2018) assessed the impacts of climate change on the municipal water management system in the Kingdom of Bahrain. They used WEAP to evaluate the performance of the water management system (vulnerability and adaptation) considering the effects of climate change in the case of municipal water demands and their associated cost.

The WEAP model has been applied in the South Phuthiatsana catchment, Lesotho, to allocate water resources in the catchment (Maliehe & Mulungu, 2017). (Alemayehu, McCartney, & Kebede, 2010) applied WEAP to assess the possible impacts of likely development on the lake Tana water level. (Droogers, et al., 2012) projected the state of water demand and supply in the Middle East and Northern Africa (MENA) region using the WEAP model. In the Cache Creek watershed in California, the WEAP model was used to assess the future irrigation water demands (Mehta, Haden, Joyce, Purkey, & Jackson, 2013). With a projected

water-stress future in Addis Ababa, (Ki, Mengistu, & Hendrik, 2017), applied WEAP to analyze the future water demands under population growth trends and climate change scenarios. The future water availability of the Zambezi River Basin considering the combine effects of water demand and climate change was assessed using the WEAP model (Beck & Bernauer, 2011; Fant, Gebretsadik, & Strzepek, 2013).

An environmental assessment was conducted in an arid/semi-arid area in China where the WEAP model was applied for assessing the impact of the planned activities on local water resource system under several scenarios (Gao, Christensen, & Li, 2017). In Algeria, WEAP has been used to assess future water demand in Boumerzoug, in the upper sub-catchment of Kébir-Rhumel basin (Guettaf, Maoui, & Ihdene, 2017). The current and future water supply in Seybouse River basin under changing climate scenarios was assessed using WEAP (Berredjem & Hani, 2017). The WEAP model was used to assess the future water demands and water quality in the Ciliwung River basin, Indonesia (Kumar, Masago, Kumar, & Fukushi, 2018) and the future agricultural water demands in some areas in Indonesia (Santikayasa & Basit, 2017). To ensure the sustainability of a water-stressed basin (Upper Litani River Basin, Lebanon), WEAP was used to assess the potential future climate change impacts on water availability in the basin (ALAMEDDINE, FAYYAD, NAJM, & EL-FADEL, 2018). In Central Chile, WEAP has been used to estimate the future water consumption and streamflow regimes under climate change scenarios (Dole, Gironas, & Vicuna, 2015). The WEAP model was applied to balance water availability and demand on groundwater resources in the context of changing climate and population growth in Mali (Toure, Diekkrüger, Mariko, & Cissé, 2017).

In Ghana, Integrated water resources management plan was developed for the Densu River Basin using WEAP as a tool to allocate future water demand and supply under different scenarios (Water Resources Commission, 2007). In the assessment of climate impact on water resources on the Volta Basin and other basins in Ghana, the WEAP model was used to allocate water resources for municipal, hydropower and agricultural demand (McCartney, et al., 2012; Amisigo, McCluskey, & Swanson, 2015). WEAP has also been used to assess the impact of small reservoirs on downstream users (Hagan, 2007), the future impact of climate change on water resources availability in the Vea catchment in the Upper East region of Ghana (Limantol, Afouda, Lenartz, & Agyare, 2015), the assessment of sustainable irrigation in the White Volta (Ofosu, 2011) and the potential impacts of Bui Hydropower Dam on downstream users (Okyereh, Ofosu, & Kabobah, 2019). The above review indicates

that the WEAP model is a unique model, very relevant and plays a vital role in recent research especially in Climate studies and for this reason, it was selected for this study.

CHAPTER 3

3 RESEARCH METHODOLOGY

Different methodologies have been applied to achieve the objectives of this research. The methodology comprises 5 phases, namely; 1. Preparation/Desk study, 2. Data Collection, 3. Data Preparation, 4. Modelling, and 5. Reporting. The preparation phase comprises of literatures study that relate to the topic and fieldwork preparation. Data collection phase comprises of fieldwork activities in collecting spatial, hydrological and meteorological data example, DEM, river discharges, precipitation, and temperature. These data were used in the description and modelling of the study area. The Data preparation phase comprises of the processing of the data collected into a final product that can be used for further analysis. The modelling phase consist of building and running a model that represent the study area using a hydrological software (WEAP). The last phase deals with reporting whole the research activities and the results.

3.1 Preparation

This phase is about the review of literatures related the topic of interest and the preparation for data collection. Literature review was carried out to develop the methodology for this research and to obtain research knowledge. This was done along the research process. The literature review was mostly about climate change and water resources (impact on streamflow, domestic water demand and agriculture demand), climate change and population, and more specifically the application of WEAP software in climate change studies. The WEAP software was studied in-depth to understand its operation and to know how to apply it to the case of the Densu River Basin. In addition to this, statistical packages including the R-studio environment and Microsoft Excel were studied to obtain knowledge on how they are used in processing data. The last step was preparation for data collection. Available reports and journals on the topic were collected and studied to get an idea of the required data, available data, where to obtain the data and how to obtain the data including field visitation and point of contacts. Previous IWRM report on the basin was obtain from the Water Resources Commission and studied. These reports and journals served as a reference for the study area and also for study area description.

3.2 Data Collection

In this research, both spatial and non-spatial datasets were used. The spatial dataset consists of Digital Elevation Model (DEM) and the non-spatial data are the geographical coordinates, meteorological (precipitation, temperature, wind speed) and hydrological (streamflow) datasets. Some data were collected from the national agencies and others from online data archives.

3.2.1 Digital Elevation Model (DEM)

DEM represents terrain elevations with respect to any reference datum. DEMS are used to display terrain attributes such as elevation at any point, slope and aspect. The current DEM for the study was a 90meter resolution Shuttle Radar Topography Mission (SRTM) DEM which was downloaded from the Consultative Group for International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI) GeoPortal (Reuter, Nelson, & Jarvis, 2007; Jarvis, Reuter, Nelson, & Guevara, 2008; CGIAR-CSI, 2018).

3.2.2 Geographical data

Geographical coordinates of the climate stations were collected on field and used in mapping the climate stations in the Geographical Information System software.

3.2.3 Climate and hydrological data

Daily climate data (rainfall, temperature, wind speed) were collected from the Ghana Meteorological Agency, Princeton data source and the CORDEX archives. The hydrological data (stream discharge) was obtained from the Hydrological Services Department of Ghana.

3.2.4 Study area description

The research is carried out in the Densu River Basin in Ghana, West Africa. The Densu River Basin covers an area of about 2600km^2 located at the South Eastern part of Ghana and it lies within longitudes 0° 10'W – 0° 37'W and latitudes 5° 30' – 6° 17'N (Water Resources Commission, 2007). It spans through 12 Local Government Assemblies in the Central, Eastern and the Greater Accra region. The main Densu River takes it source from Atewa Range near Kibi and flows for 116 km into the Weija Reservoir before entering the Gulf of Guinea. The Densu River is of specific importance because it serves as the raw water source for the Weija Water Treatment Plant and Nsawam Water Treatment Plant in the Greater Accra and Eastern Regions of Ghana respectively. With Odaw and Volta Basins to the east and north of the Densu River, it also shares its catchment boundary with the Birim in the

northwest and the Ayensu and Okrudu in the west (Water Resources Commission, 2018). The main economic activities in the catchment are agriculture which includes the cultivation of crops and the raising of livestock and fishing. Some crops cultivated in the area includes cocoa, maize, vegetables, pineapples, and cocoyam.

The major use of water in the communities within the basin is for domestic uses and without prior treatment (Gordon & Ansa-Asare, 2012). As at the year 2010, the basin was comprised of a population of three million four hundred and sixty-seven thousand four hundred and eighty one (3,467,481) (Ghana Statistical Service, 2013) and this number is expected to increase during the next national census to be conducted in the year 2020. As an average for the entire Densu Basin, the population density is 1334pop/km^2 (year 2010) (Ghana Statistical Service, 2013), thirteen times bigger than the national average of 100pop/km^2 (Water Resources Commission, 2018). The location of a number of the major settlements/towns within the Basin is also indicated on Figure 3.2.

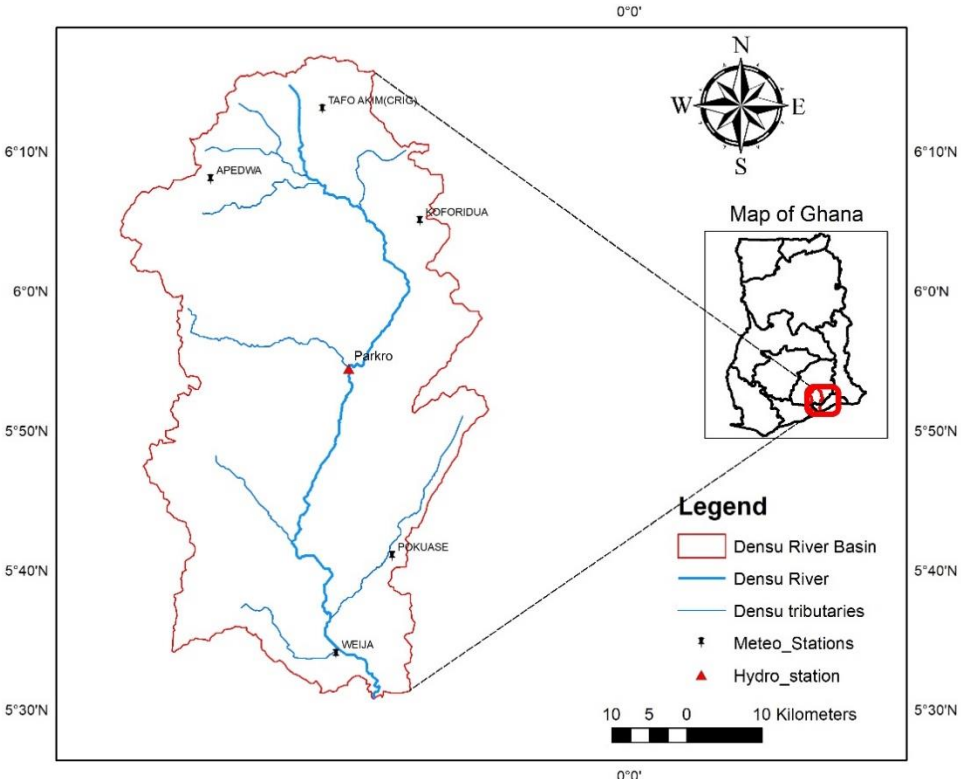

Figure 3.1: Densu River basin showing network of river flows and the hydro-climatic stations

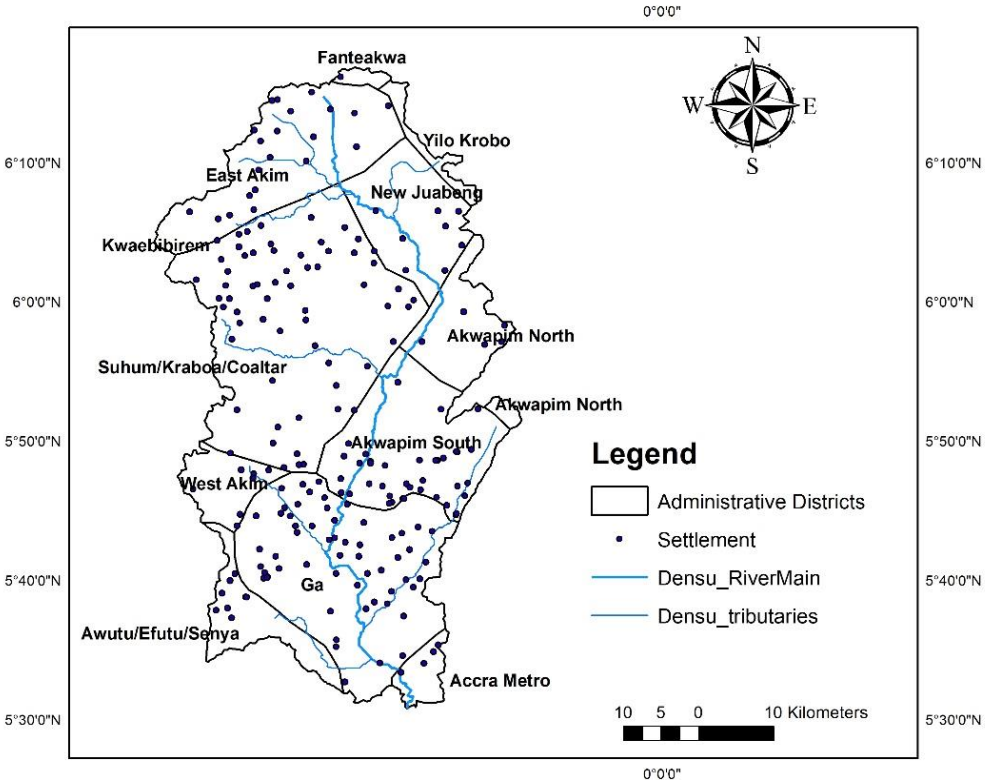

Figure 3.2: Administrative Districts and settlements in the basin

Climate of the study area

The Densu Basin has two distinct climatic zones: the relatively dry equatorial and the wet semi-equatorial climate. The dry climate is of the south-eastern coastal plains and the wet climate is recorded further north in the basin. Both climatic zones experience a bi-modal rainfall regime but the intensities differ from each one. The basin has two main rainy seasons: major and minor rainy season. The major season extends from April to July with a peak in June, whereas the minor which is less intense occurs between September and November (Water Resources Commission, 2007).

The mean annual temperature of the basin is about 27°C. The months of February and April are the hottest periods with maximum temperatures around 32°C. August is the coolest month with a mean temperature of about 23°C (Water Resources Commission, 2007). The climate is depicted in Figure 3.3.

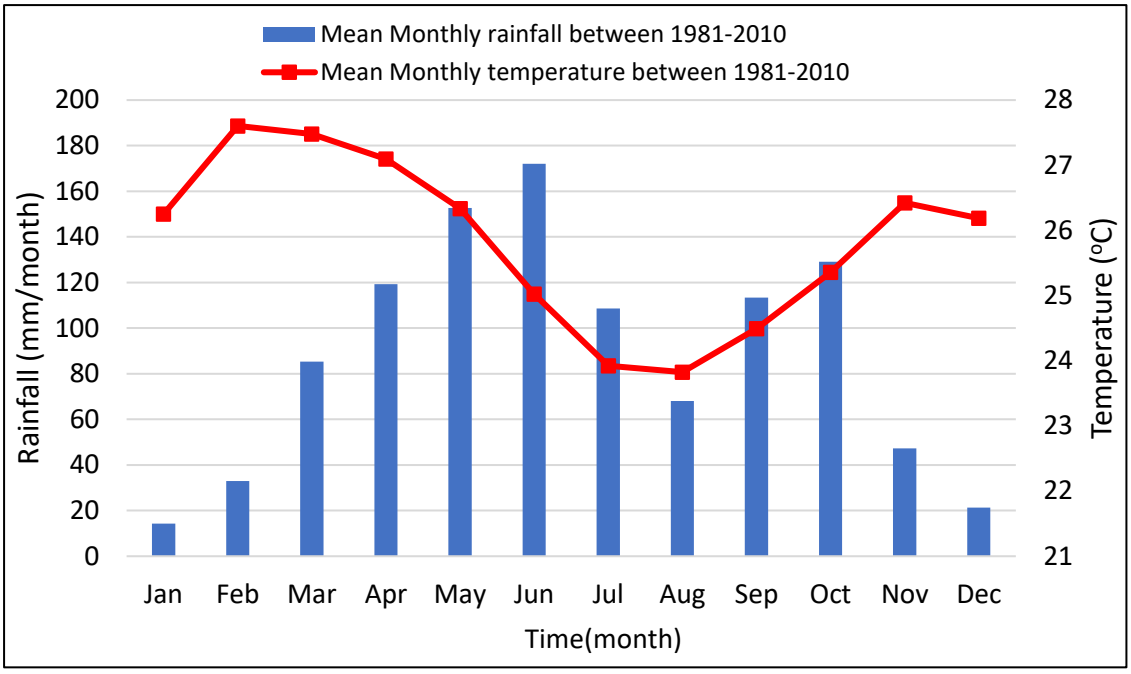

Figure 3.3: Average monthly rainfall and temperature for the period of 1981-2010

Topography

The elevation of the study area was prepared in ArcGIS Desktop 10.5 using a 90m-resolution SRTM DEM downloaded from the CGIAR consortium for Spatial Information (CGIAR-CSI) website. The topography of the Basin is diversified. The northern part of the Densu River Basin is characterized by steeply dissected landscapes with hilly and rolling lands and flat coastal plains to the south. In the upper sections of the Basin, the slope and erosion surfaces vary from 30% and less than 2% at the coast (Water Resources Commission, 2007). The Basin share its eastern boundary with the Akwapim hills and the Kwahu-Mampong scarps. The highest part of the basin reaches about 772m above sea level and occurs along the north-western basin boundary (Figure 3.4).

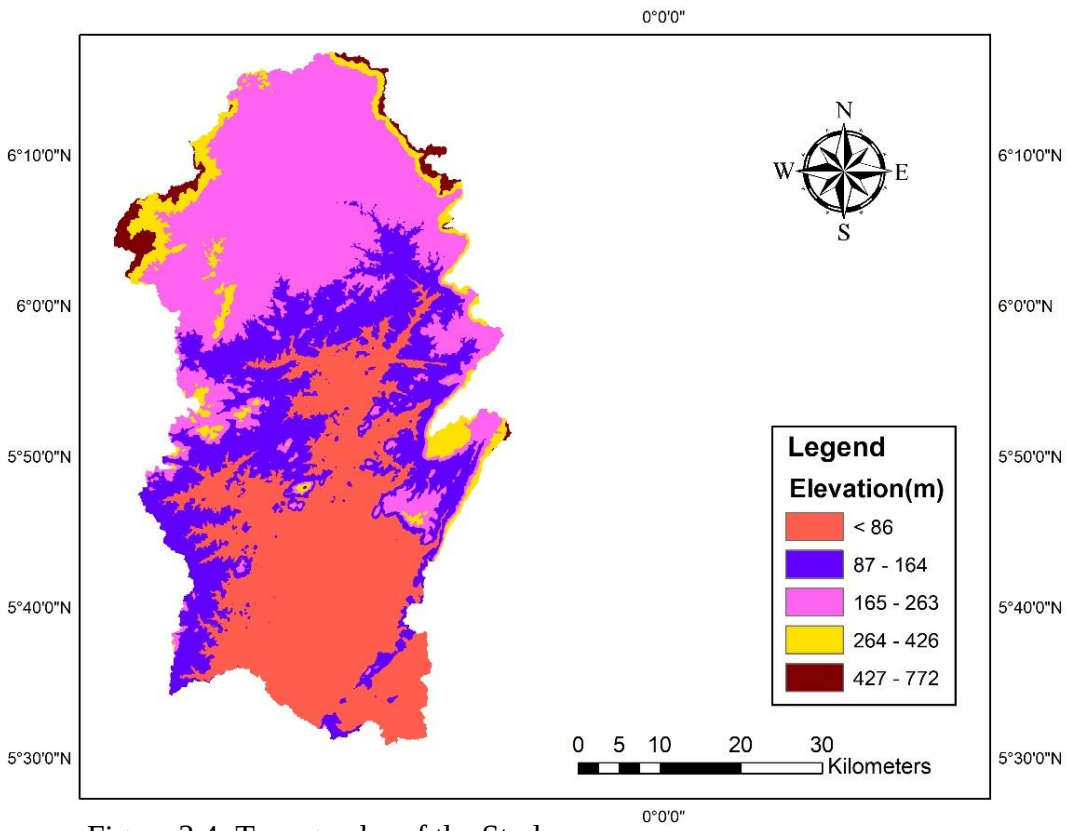

Figure 3.4: Topography of the Study area

3.2.5 Climate change projections

The future climate data of the Densu River Basin was obtained from the Coordinated Regional Climate Downscaling Experiment (CORDEX) under the World Climate Research Programme (WCRP) through the Earth System Grid Federation infrastructure (ESGF). The future daily generated climate data for the period 2051-2080-time slice was performed under CORDEX's Africa domain. One Global Climate Model (GCM) was used to drive one Regional Climate Model (RCM) under one of the most recent IPCC emission scenarios, Representative Concentration Pathways (RCP 4.5), to generate the future daily climate data for the basin. The RCPs represent the greenhouse gas concentration trajectories. The projected climate data was compared to the baseline data to assess the level of change by percent for the study period. The change was determined by the relation:

$$\boldsymbol{Relative\ change}\ (\%) = \frac{Predicted\ mean - Baseline\ mean}{Baseline\ mean}\ x\ 100\% \qquad \text{Eqn. 3.1}$$

Details on the GCM and RCM used are showed in Table 3.1.

Table 3.1: Global Climate Models (GCMs) and Regional Climate Models (RCMs) used in the CORDEX for downscaling

Model Type	Model Name	Modelling Institute
GCM	ICHEC-EC-EARTH	Swedish Meteorological and Hydrological Institute
RCM	RCA4	Swedish Meteorological and Hydrological Institute

Source: Coordinated Regional Climate Downscaling Experiment (CORDEX)

3.3 Data Preparation

The data used in this research was prepared in different environments (GIS, R-Studio and Microsoft Excel) to make them readily available for use in the hydrological software. This phase consists of the catchment delineation and climate data preparation.

3.3.1 Catchment delineation

The downloaded SRTM 90m resolution DEM was processed in ArcGIS Desktop 10.5 and the study area (catchment) was delineated using the spatial analyst tool in the Arc toolbox.

3.3.2 Climate and hydrological data

Daily climate data recorded from five climate stations within the basin were analysed to represent the entire basin. The data obtained from the Princeton data source and CORDEX archives was in a NetCDF file format which was processed in R-Studio. The stations' data was extracted in R-studio package using their respective coordinates. The temperature and wind speed from the stations were averaged to represent the entire basin. The thiessen polygon method was employed to estimate the areal precipitation of the basin from the data from five climate stations using ArcGIS Desktop 10.5 and Microsoft Excel. The hydrological data was prepared and arranged in Microsoft Excel.

Thiessen polygon

The thiessen polygon method is the weighted mean method. The rainfall is not uniform over the entire basin and varies from place to place with respect to intensity and duration. Therefore, the rainfall recorded by each station was weighted according to the area each station represents. The areal precipitation is determined by summing the weighted

precipitation recorded by all the stations within the basin. The thiessen polygon method can be done manually by hand on drawing sheet and also by a software. To generate a thiessen polygon, the stations in the basin are connected by lines to form a network of triangular-shaped polygons. Perpendicular bi-sectors are drawn through the triangle sides to intersect at a point. These bi-sectors form a polygon around the stations. The formed polygons are delineated and their respective areas are calculated. However, in this research, it was done in a GIS environment using ArcGIS Desktop 10.5. The delineated catchment was imported into ArcGIS Desktop 10.5 software and all gauge stations were plotted in the catchment using their geographical coordinates. The polygons were created around each stations using the Analysis Tools in the Arc toolbox. The weighted area of each polygon was determined and the areal precipitation was determined by summing the weighted precipitation for each station. The data was processed and arranged in the required format for the WEAP software using Microsoft Excel.

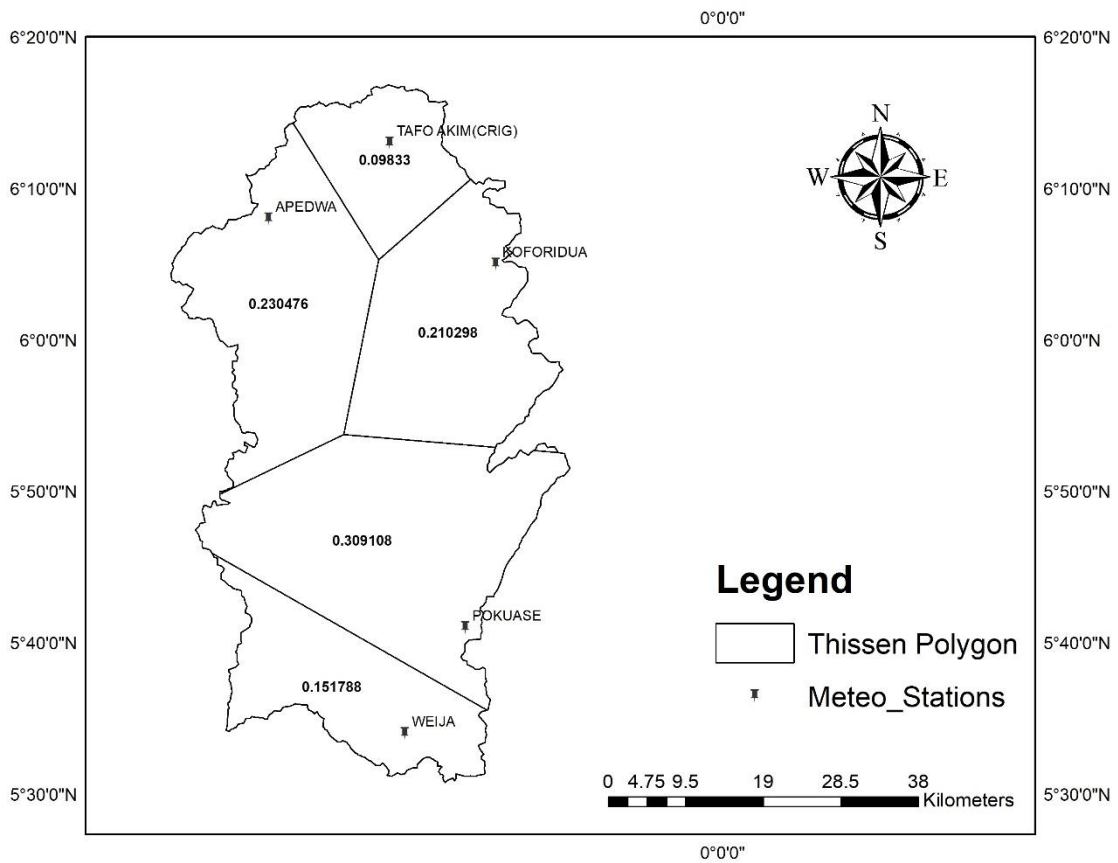

Figure 3.5: Thiessen polygons with weighted areas

3.4 Modelling

Modeling a watershed in WEAP involves the following steps:

1. Definition of the study area by setting up the spatial boundary, system components and the time.
2. The creation of Current account by specifying demands and supplies nodes. This is very important as the current account is the basic description of the system used for modelling and analyzing scenarios.
3. Creation of scenarios using policies, ecosystem constraints, etc. to address wide range of "what if" questions like: what if climate change alter the river hydrology?
4. Scenario evaluation regarding policies, costs, water quantity and quality.

The modelling phase consist of building and running the WEAP model to simulate catchment processes and demand options under different scenarios. The first stage in the modelling phase is the WEAP model setup for the study area. The next step is the calibration and validation of the WEAP model followed by catchment simulations (historical and future runoffs or river discharges) and the future water demands under changing climate.

3.4.1 WEAP model setup

The WEAP model for the study area was set up in the schematic view of the software including various demand sites such as domestic and irrigation. Transmission lines were drawn from the river to the demand sites and return flow lines were also drawn from the demand sites to the river. The hydro station was indicated on the river as well. During the setup, the current accounts, key assumptions and scenarios were also defined. Current accounts are viewed as calibration step and provide insights of actual demands, and supply within the catchment. The time step of the study was set and the data on streamflow of the Densu river was entered as well as the climate data. After the setup, the model was calibrated and validated before being run. Figure 3.12 shows the WEAP set up of the study area.

3.4.2 Model calibration and validation

The calibration of an integrated river basin model, such as WEAP, is a challenging process. In general, calibration is process of adjusting the parameters of the models to appropriately simulate historical observations. For this research, the monthly observed streamflow data from 1995 to 2007 of the Densu river were used to calibrate and validate the WEAP model. The observed streamflow data of the river between 1995-2001 was used to calibrate the

model and the observed streamflow between the period of 2002-2007 was used to validate the model. During the model calibration, the Parameter Estimator Tool (PEST) combined with a manual approach was employed. Some parameters in the model was adjusted manually while others were modified using the PEST in order to get a representative streamflow for the basin. PEST is included in WEAP to aid the process of calibration. After the calibration, the validation process was performed to test the calibrated model. This was done by comparing the simulated streamflow to the observed streamflow for the period of 2002-2007. The performance of the calibrated model was measured by statistical measures of calibration: Nash-Sutcliff efficiency (NSE) and coefficient of determination (R^2) which measures the fit between the simulated and the observed streamflow. The statistical measures are explained in the following equations:

$$\boldsymbol{R^2} = \left[\frac{\sum_i (Q_{o,i}^t - \overline{Q_o})(Q_{s,i}^t - \overline{Q_s})}{\sqrt{\sum_i (Q_{o,i}^t - \overline{Q_o})^2 \sum_i (Q_{s,i}^t - \overline{Q_s})^2}}\right]^2 \qquad \text{Eqn. 3.2}$$

$$\boldsymbol{NSE} = 1 - \frac{\sum_i (Q_o - Q_s)^2}{\sum_i (Q_{o,i} - \overline{Q_o})^2} \qquad \text{Eqn. 3.3}$$

Where, *Q* is the discharge variable, *o* is the observed variable, *s* is the simulated variable, *t* is the time and *i* is the number of points.

Nash–Sutcliffe efficiency is a dimensionless coefficient ranging from 0 to 1. An efficiency of 1 (NSE = 1) indicates a perfect match between the simulated and observed data. Generally, the closer the efficiency coefficient to 1, the more accurate the model is (Nash & Sutcliff, 1970).

The climate data used in generating the baseline was obtained from the "Global Meteorological Forcing Dataset for land surface modeling" (Sheffield, Goteti, & Wood, 2006) at the Princeton data source (Princeton University, 2007)

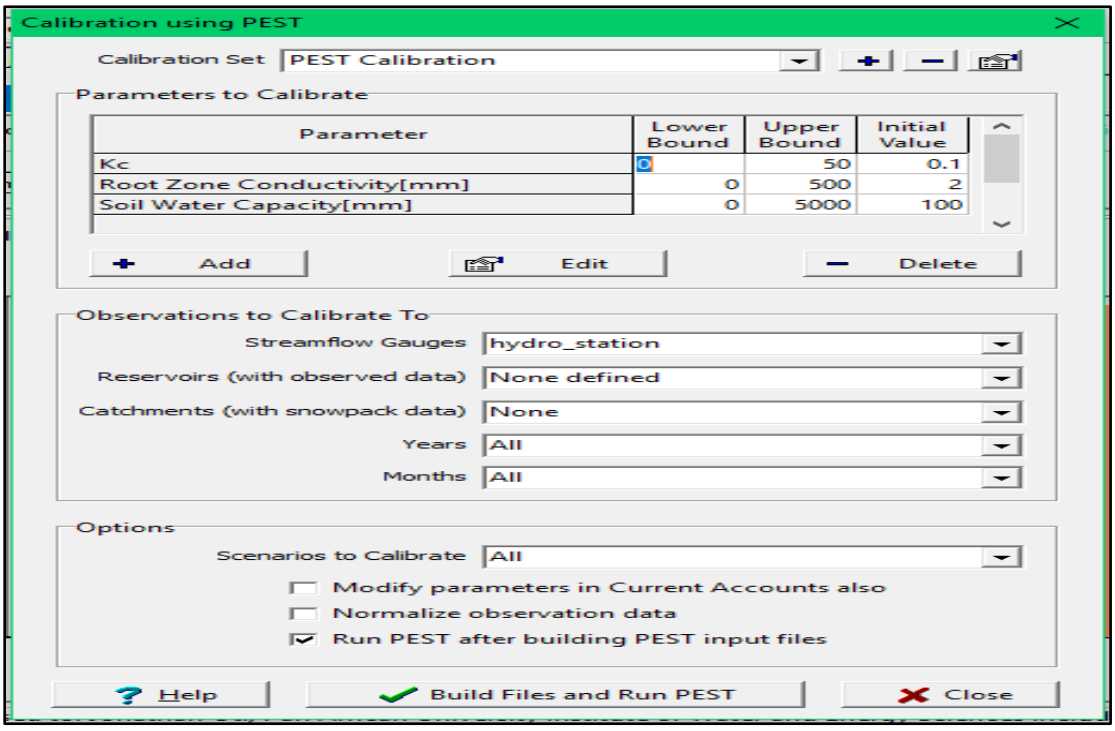

Figure 3.6: Setting up PEST tool for calibration

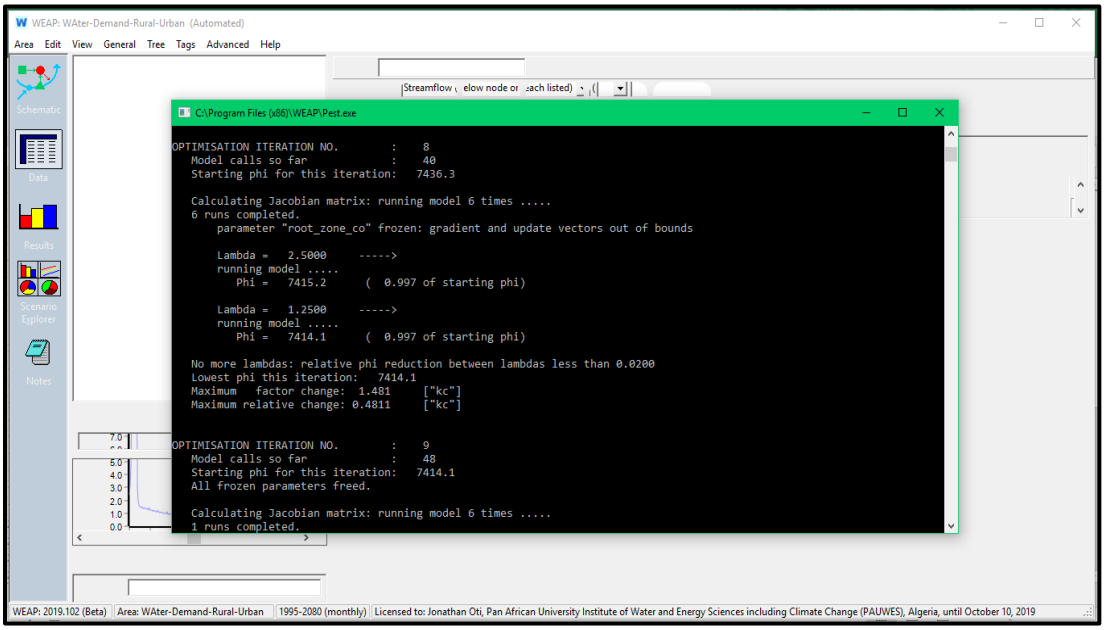

Figure 3.7: Running PEST to begin the calibration

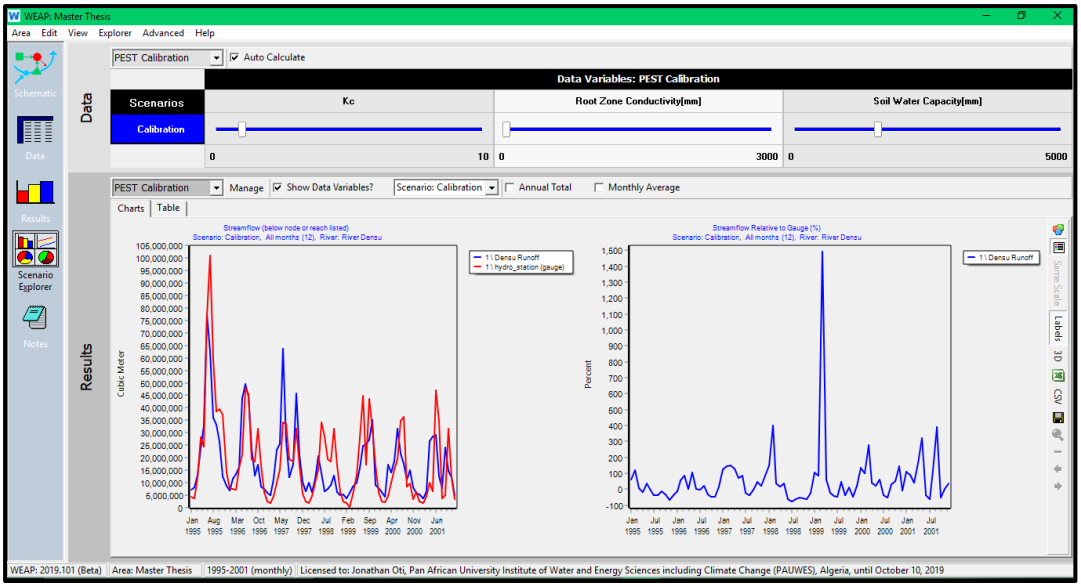

Figure 3.8: PEST calibration interface

3.4.3 Catchment simulations

The WEAP model contains four methods for simulating catchment processes. The methods include Irrigation Demands Only Method, Rainfall Runoff Method (Simplified Coefficient Method), Rainfall Runoff Method (Soil Moisture Method), and MABIA Method. These methods ranges from simple to complex and the choice of the method depends on the data availability and the purpose of the analysis. However, in this research, the Soil Moisture method was used.

The calculation process in WEAP is based on mass balance of water for every node and link and water allocation is subject to demand priorities, supply preferences, and water requirements. Calculation in the WEAP model is on a monthly time step beginning from the first month of the Current Account year to the last month of the last scenario year. The calculation for each month is independent of the previous months for all nodes with the exception of reservoirs, soil moisture or aquifer storage. Any amount of water that enters the system during a month will either be stored in the aquifer, reservoir or the catchment soils or leave the system by demand consumption or evaporation.

3.4.3.1 Soil moisture method calculation

The Soil Moisture method is one dimensional using the concept of two control volumes, called buckets, for soil moisture based on empirical functions for evapotranspiration, deep

percolation, surface runoff, and interflow for a catchment unit (Figure 3.9). The impact of land use/soil type on these processes can be characterized in this method. Deep percolation can be conveyed to surface water (e.g., baseflow) or to groundwater if there is an appropriate link between groundwater and catchment unit nodes. In this method, the catchment unit can be separated to N sub-catchments that signify land uses/soil types. For each fraction area, j of N, a water balance is computed assuming the climate is constant within each sub-catchment. The equation of the water balance is specified below (Seiber & Purkey, 2015).

$$Rd_j \frac{dZ_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5Z_{1,j}-2Z_{1,j}^2}{3}\right) - P_e(t)Z_{1,j}^{RRF_j} - f_j k_{s,j} Z_{1,j}^2 - (1-f_j)k_{s,j}Z_{i,j}^2 \quad \text{Eqn. 3.4}$$

Where $Z_{1,j}$ is relative storage [0, 1], based on the total effective storage of the root zone; Rd_j is the soil holding capacity of the land cover fraction j (mm); and P_e is the effective precipitation which includes snow melt from accumulated snowpack within each sub-watershed, and m_c is the melt coefficient. The melt coefficient is given by Eqn. 3.5.

P_e can be defined by a melt coefficient, snow accumulation, and melt rate (equation 3.5, 3.6, 3.7 and 3.8).

The melt coefficient computation is:

$$m_c = \begin{cases} 0 & T_i < T_s \\ 1 & if \quad T_i > T_1 \\ \frac{T_i - T_s}{T_1 - T_s} & T_s \leq T_i \leq T_1 \end{cases} \quad \text{Eqn. 3.5}$$

Where T_s and T_1 are temperature thresholds of melting and freezing while T_i is the measured temperature for month i. The Snow accumulation, Ac_i, is a function of m_c and the observed monthly total precipitation, P_i, and it is computed as:

$$Ac_i = Ac_{i-1} + (1 - m_c)P_i \quad \text{Eqn. 3.6}$$

The melt rate, m_r, is defined as:

$$m_r = Ac_i m_c \quad \text{Eqn. 3.7}$$

Then effective precipitation, P_e is computed as:

$$P_e = P_i m_c + m_r \quad \text{Eqn. 3.8}$$

The PET term is calculated using the modified Penman-Monteith reference crop potential evapotranspiration with the crop/plant coefficient defined by $k_{c,j}$ for each fractional land cover. The term RRF_j is the Runoff Resistance Factor of the land cover. Low and high values of RRF_j may cause more or less surface runoff respectively. Interflow and deep percolation

are defined by the fourth and fifth term of Eqn. 3.4 respectively. The term $k_{s,j}$ denotes the root zone saturated conductivity (mm/time) estimate and f_j is the partitioning coefficient that partitions water horizontally and vertically, based on the soil, type of land cover, and topography. The total surface and interflow runoff, RT, from each sub-catchment at time t is therefore computed as:

$$RT(t) = \sum_{j=1}^{N} A_j \left(P_e(t) z_{1,j}^{RRF_j} + f_j k_{s,j} z_{1,j}^2 \right) \qquad \text{Eqn. 3.9}$$

For situations where there is no link between the catchment and groundwater nodes, the baseflow from the second bucket is computed as:

$$S_{max} \frac{dz_2}{dt} = \left(\sum_{j=1}^{N} (1 - f_i) k_{s,j} z_{1,j}^2 \right) - k_{s2} z_2^2 \qquad \text{Eqn. 3.10}$$

where S_{max} is the deep percolation from the upper storage given in Eqn. 3.4, and K_{s2} is the saturated conductivity of the second storage (mm/time), which is given as a single value for the catchment.

When there is a link between the groundwater node and the catchment, the S_{max} relation (Eqn. 3.10) is ignored and the groundwater recharge, R (volume/time) is computed as:

$$R = \sum_{j=1}^{N} A_j (1 - f_i)\, k_s z_{1,j}^2 \qquad \text{Eqn. 3.11}$$

where A_j is the area of sub catchment j.

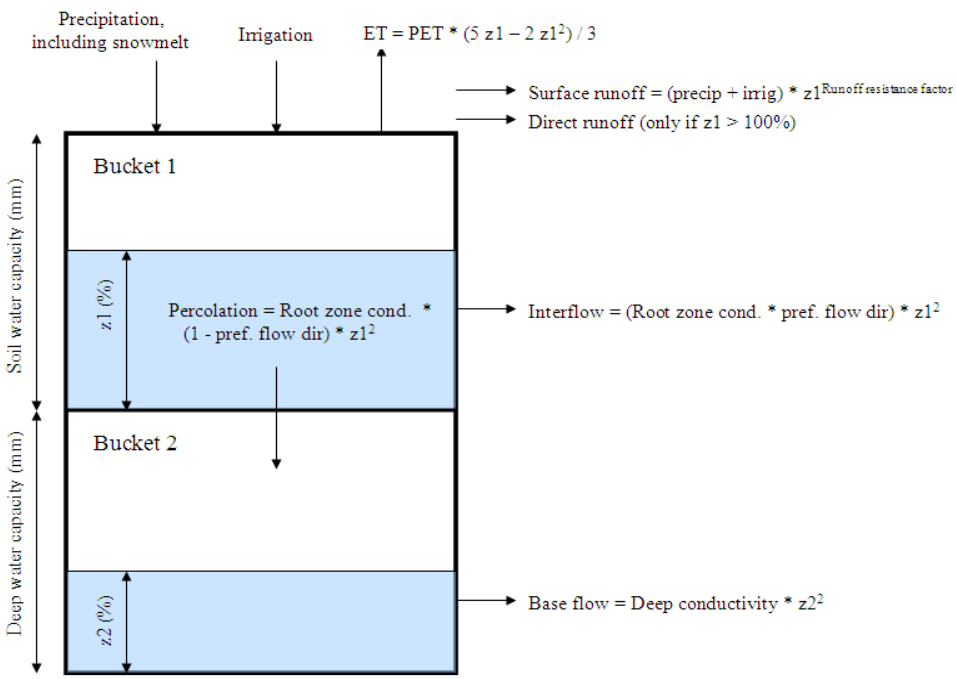

Figure 3.9: Concepts of Soil Moisture method and equations *(Seiber & Purkey, 2015)*

3.4.3.2 Water demand calculation

WEAP uses a disaggregated, end use approach to model water consumption so that at each node and for each time the demand is calculated from the lower level. WEAP is flexible in structuring the demand ranging from disaggregated to aggregated analysis. The structure in WEAP can include sectors such as municipal, hydropower, irrigation and industry. These sectors can be broken down to sub-sectors, depending on the data availability and desired analysis. WEAP calculate the water demand for each sector based on the various economic and social activities as well as the hectares of irrigated farmland. For instance, to calculate for the water requirement for irrigation sector, the water use rates of the irrigated farmlands are multiplied by the activity level (amount of hectares).

Overview of methods of demand calculation

In WEAP model, there are two options for demand calculation, Monthly Demand and Annual Demand with monthly variation.

1. The Monthly Demand option allows the user to input demands values month by month manually or the data can be read from a CSV file using a ReadFromFile function in WEAP.
2. The Annual Demand with Monthly Variation option can be used to express demand based on an annual level. Using it, the user can enter an activity level (e.g., population) and the water use rate (e.g., annual water consumption for each person) associated with that particular activity level. The Monthly Variation can be used to vary demand based on two options, weight per days for each month and user-defined expression.

Annual demand

The demand for each demand node is calculated by the sum of all demand site's bottom-level branches (Br). "A bottom-level branch is one that has no branches below it" (Seiber & Purkey, 2015). For example, in a single family home the bottom-level branches would include showers and toilets. The annual demand is calculated as:

$$Annual\ Demand = \sum_{Br} (TotalActivityLevel * WaterUseRates)$$

"The total activity level for a bottom-level branch is the product of the activity levels in all branches from the bottom branch back up to the demand site branch (where Br is the bottom

level branch, Br' is the parent of Br, Br'' is the grandparent of Br, etc.)" (Seiber & Purkey, 2015).

$$TotalActivityLevel_{Br} = ActivityLevel_{Br}\ x\ ActivityLevel_{Br'}\ x\ ActivityLevel_{Br''}$$

For example,

$$TotalActivityLevel_{showers} = ActivityLevel_{showers}\ x\ ActivityLevel_{singlefaamily}\ x\ ActivityLevel_{city}$$

which calculates the percent of people living in single family homes who have showers * percent of people who live in single family homes * number of people in the city (Seiber & Purkey, 2015).

Monthly demand

The monthly water demand is the month's fraction of the adjusted annual demand. For each month, the fraction is multiplied by the adjusted annual demand to give the demand (m) for that month.

$$MonthlyDemand_{DS,m} = MonthlyVariationFraction_{DS,m} x AdjustedAnnualDemand_{DS}$$

3.4.3.3 Hydrologic inflow (streamflow/runoff) simulation

WEAP can simulate and project water surface hydrology using four methods: the Water Year Method, Expressions, Catchments Runoff and Infiltration, and the ReadFromFile Method. Using these methods, one can model monthly inflows to appropriate surface and ground water locations (or nodes) in the study area. The catchment runoff/infiltration was used in this study to model the river flow for the study area.

Catchments runoff and infiltration

WEAP allows one to simulate catchment runoff using the Soil Moisture Method or using the Rainfall Runoff Method runoff. The simulated runoff is then directed to rivers and groundwater nodes using a Runoff/Infiltration link. This was the method used in this study. However, in this study, there was no link between the catchment and the groundwater so the simulated runoff was directed to the river. The simulated runoff was directed at the upstream of the river as the headflow of the river. The streamflow/runoff was generated from the climatic data after the calibration and validation of the model. It was assumed that the basic

characteristics of the watershed will not change for the projected period of analysis to 2080. Once a set of characteristics for the watershed was selected, there was a further assumption that the rainfall-runoff processes will stay reasonably constant under changing precipitation and temperature conditions. The changing temperature and precipitation conditions will impact the runoff simulation through increased evapotranspiration for example and reduction of baseflow. The runoff for the future was simulated under changing climate and compared to the baseline to assess the impacts of climate change on the Densu river.

3.4.4 Scenario creation

To assess the impacts of climate change on water resources in the study area, three scenarios were used. Scenario one and two were to assess the climate change impact on domestic water availability and scenario three was to assess the climate change impact on water availability for irrigation demands. Scenario one was generated to simulate the climate impact on the river basin with the assumption that the per capita water demand for the baseline period (1981-2010) will remain the same for the future under changing climate. Scenario 2 took into consideration the assumed water demand for 2051 in the era of changing climate and increasing population growth. The only difference between the scenarios was the water demand per person per day as both considered the population growth. Scenario three was generated with assumption that the irrigable land and the irrigation water demand will remain the same for the future as the climate changes. Scenarios in WEAP explore how a water system will respond to different conditions such as introduction of new technologies (drip irrigation system), change in population and climate change. Scenarios in the WEAP model are based on the current account year reference. The simulated results are compared to the baseline scenario to assess their impacts on the river basin. All scenarios were built and analyzed for the period 2051 to 2080 and compared to the baseline period 1981-2010. The water allocation in WEAP was based on the following criteria; domestic water demand (1) and irrigation water demand (2). The numbers 1 and 2 signifies the level of priority in the system. This is very important in allocating water to meet demands. In WEAP, a demand site with allocation priority 1 is considered the highest and hence considered first during the water demand allocation process.

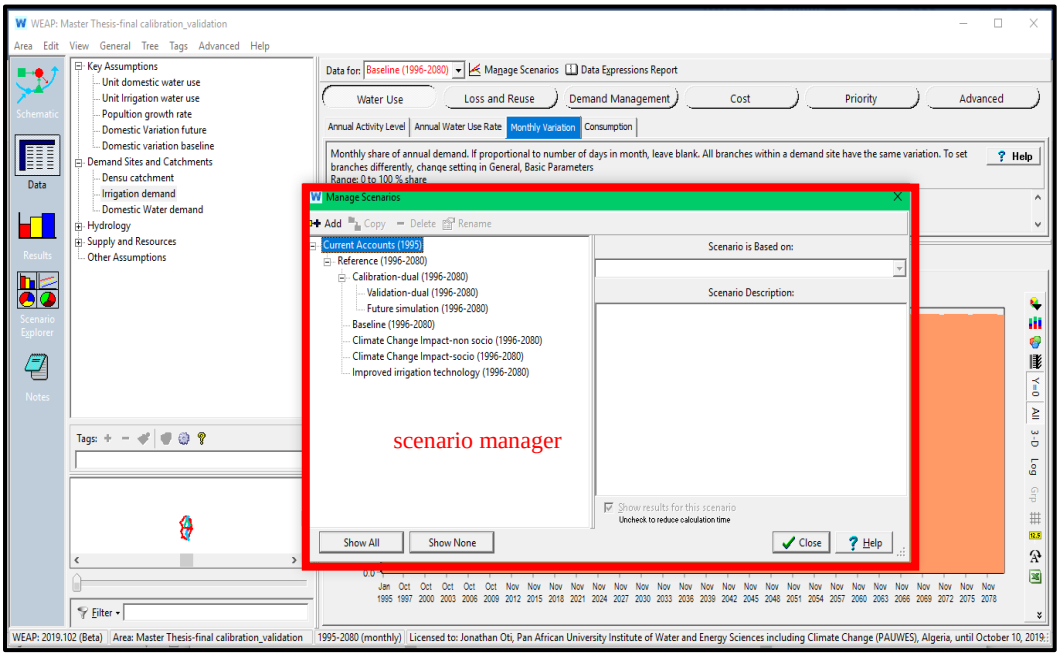

Figure 3.10: Scenario manager for creating and managing scenarios in WEAP

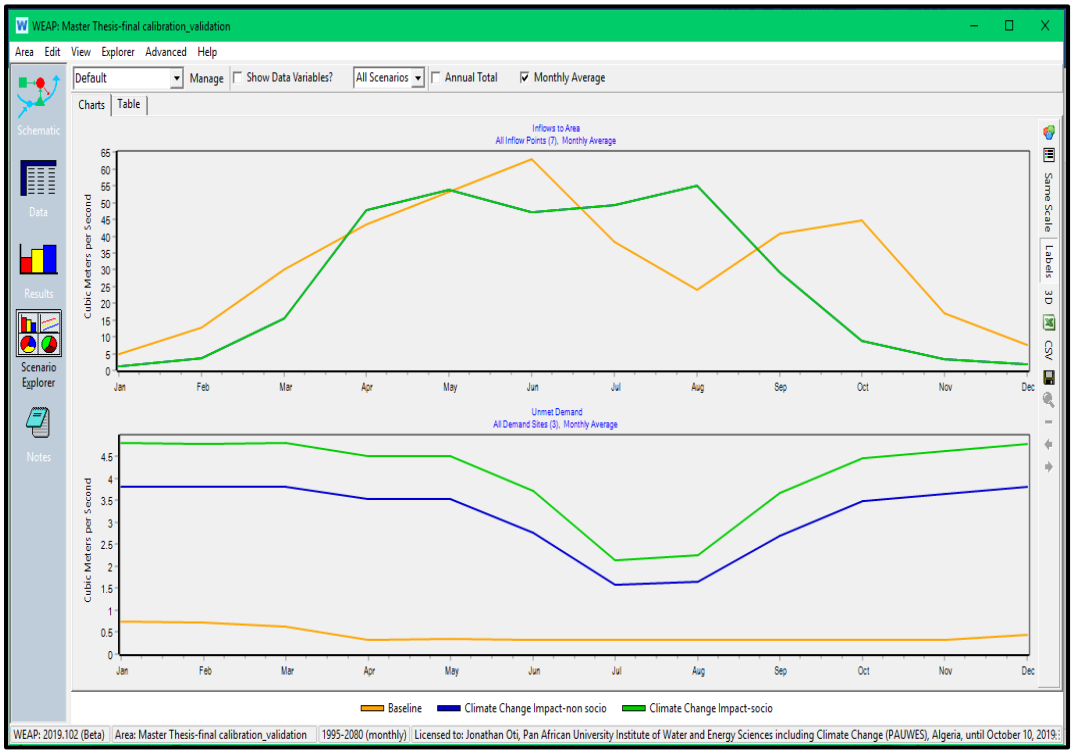

Figure 3.11: Scenario explorer for viewing and comparing the output of scenarios

Table 3.2: Key assumptions used in the WEAP model

Parameters	**Unit**
Domestic Demand	80l/c/d for baseline and scenario 1 (WRC, 2007) 100l/c/d for scenario 2 (assumed)
Irrigation Demand	15000m^3/ha/year for baseline and scenario 3 (WRC, 2007)
Population growth rate	2.2% annual growth (GSS, 2013)
%Population directly dependent on the river discharge	67% for baseline (WRC, 2007) 60% for scenario 1 and 2 (assumed)

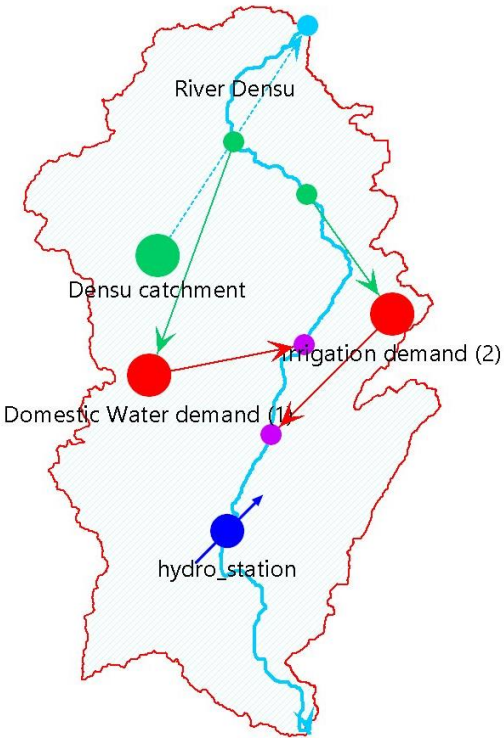

Figure 3.12: WEAP Schematic diagram of the study area

3.5 Reporting Phase

This is the final phase of the research. This involves the interpretation of the whole research process and outcomes into information. This phase is very important as it involves documentation of the research to communicate the outcome to the public.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

The results of changing climate and the impacts on the Densu River Basin are presented in this chapter. One GCM, (ICHEC-EC-EARTH) and RCM (RCA4) was used to project the change in climate under one Climate Change scenario, RCP 4.5 which represents moderate future emissions. The effect of these changes on water resources in the DRB was analyzed using the WEAP model.

4.1 Calibration and Validation Results

The WEAP model was calibrated before analyzing the scenarios. This was necessary to make sure the model is correctly representing the current situation in the study area. The streamflow data between the period of 1995-2001 was used in the calibration of the model whereas streamflow data between 2002-2007 was used in validation of the model. Overall, the model showed an efficient performance for both calibration and validation periods. The NSE value were 0.94 and 0.71 for calibration and validation respectively. The R^2 values were 0.997 and 0.799 for both calibration and validation periods respectively. Hydrographs in the Figure 4.1 and Figure 4.2 shows the performance of the model calibration and validation respectively. Evaluation of the hydrographs and the statistical analysis indicates that the model is reproducing the observed data reasonably well. The goal of calibrating the watershed rainfall runoff model in WEAP was not to exactly reproduce the historical runoff properties of the watershed but rather to develop a good representation of the existing streamflow that could serve as a base condition for the climate change analysis.

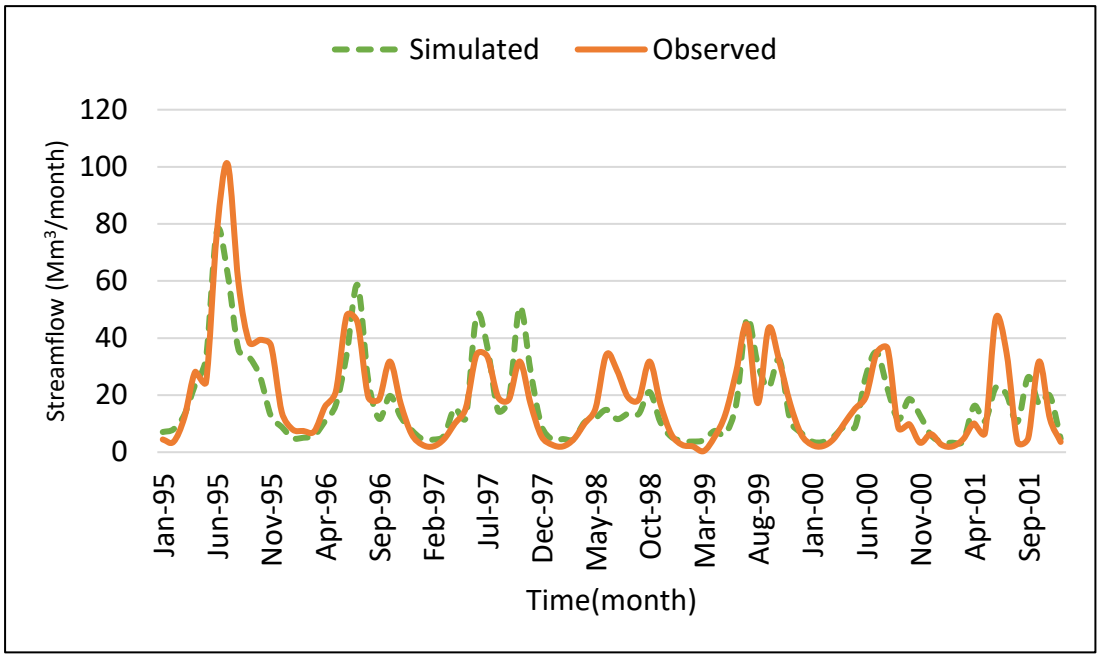

Figure 4.1: Graph of model calibration between 1995-2001

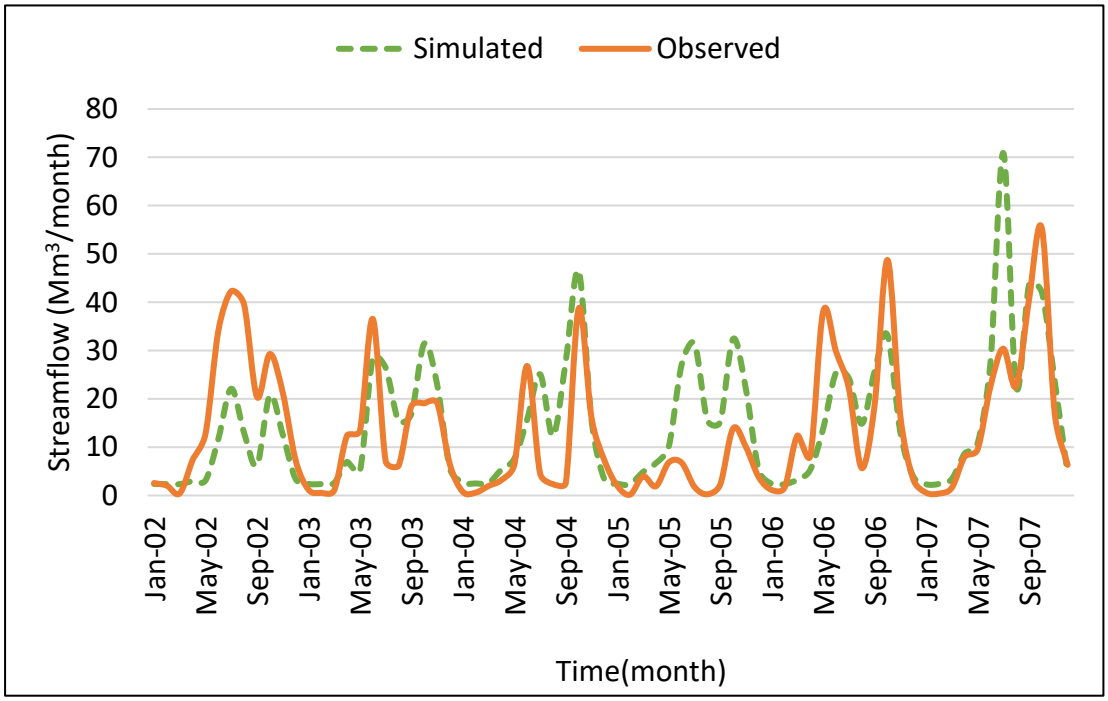

Figure 4.2: Graph of model validation between 2002-2007

4.2 Future Climatic Conditions for the DRB (2051-2080)

4.2.1 Change in temperature

The DRB is anticipated to be warmer Figure 4.3. The mean annual temperature for the study period in the DRB is projected to increase by 8.23% under the RCP 4.5 scenario (Table 4.1). The increase in temperature corresponds to the findings of Niang, et al., 2014, and Sylla, et al., 2016 which projects temperature increase across Africa and West Africa respectively as well as Ghana (McSweeney, New, & Lizcano, 2006). The temperature in the DRB is projected to increase for all the months for the study period as shown in Figure 4.3. The projected mean monthly temperature ranges between 25.9^{o}C to 29.9^{o}C with the highest recording in the month of March. August remains the coolest month with reference to the baseline as the projections showed the lowest mean temperature of 25.9^{o}C representing a percentage increase of 8.86%. Moreover, compared to the baseline, the month of July is projected to have the highest increase of 12.32% for the study period followed by June with an increase of 9.7%. The month of May is anticipated to have the minimum increase (5.13%) (Figure 4.3). The temperature increase could have an impact on the streamflow of the river as this will increase the rate of evapotranspiration in the basin.

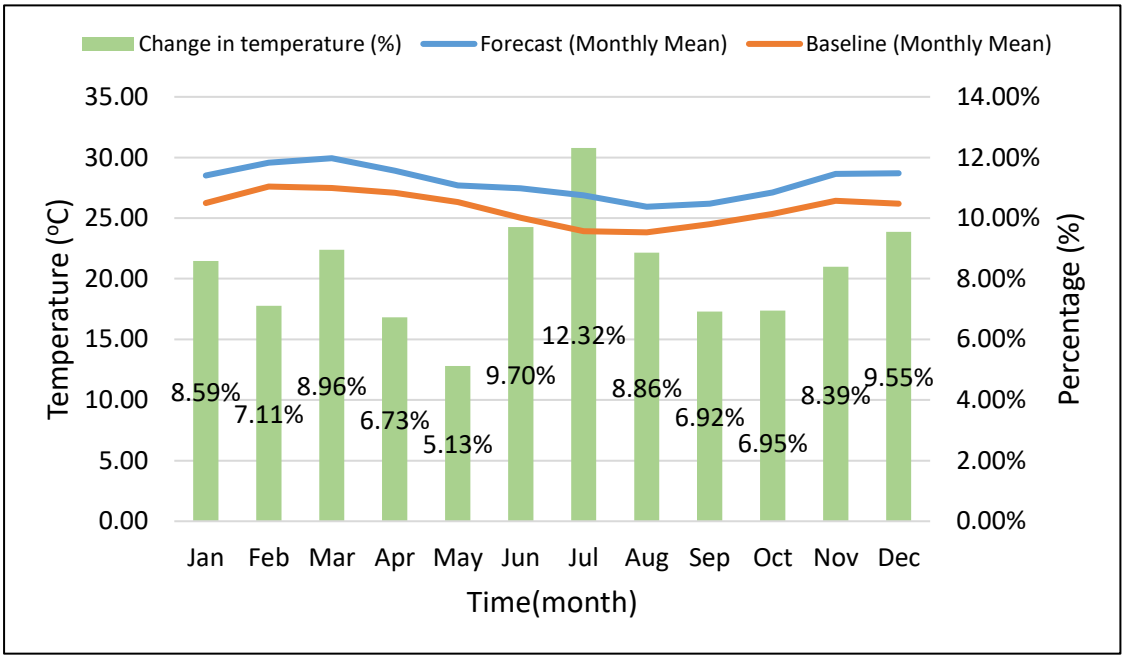

Figure 4.3: Pattern of occurrence and anticipated increase of the projected temperature (2051-2080) under scenario RCP4.5 against the baseline (1981-2010)

Table 4.1: Projected temperature changes in 2051-2080

Month	Forecast (ºC)	Baseline (ºC)	Change (ºC)	Change (%)
Jan	28.50	26.25	2.25	8.59%
Feb	29.57	27.60	1.96	7.11%
Mar	29.94	27.48	2.46	8.96%
Apr	28.92	27.10	1.82	6.73%
May	27.68	26.33	1.35	5.13%
Jun	27.45	25.02	2.43	9.70%
Jul	26.87	23.92	2.95	12.32%
Aug	25.94	23.83	2.11	8.86%
Sep	26.19	24.49	1.69	6.92%
Oct	27.12	25.35	1.76	6.95%
Nov	28.64	26.42	2.22	8.39%
Dec	28.69	26.19	2.50	9.55%
Annual mean	**27.96**	**25.83**	**2.13**	**8.23%**

4.2.2 Change in rainfall

The projected mean monthly rainfall for the DRB ranges between 3.14mm/month to 159.6mm/month. The projection shows a reduction in the rainfall over the study period compared to the baseline. Generally, Ghana is expected to experience variation in rainfall in the future (McSweeney, New, & Lizcano, 2006). A reduction in rainfall signifies a reduction in the streamflow of the river basin as the principal source of recharge is through rainfall. Compared to the baseline, the future mean annual rainfall will see a reduction of -17% (180.69mm/year) (Table 4.2) which fall within the projected range of -30% and 30% for rainfall variability in West Africa (Sylla, Nikiema, Gibba, Kebe, & Klutse, 2016). The decrease in rainfall will have a devastating impact on the river discharge especially with increasing temperature and evapotranspiration (Kankam-Yeboah, Obuobie, Amisigo, & Opoku-Ankomah, 2013). All the months is projected to experience a reduction in the mean rainfall with the exception April, May, July and August which will experience an increase in the mean monthly rainfall. Based on the projection, the DRB will still exhibit the bi-modal rainfall pattern, however, the monthly peak rainfall has shifted from June (baseline) to August (projected) (Figure 4.4). The month of August is not only projected to have the

minimum mean temperature over the period, it will be the wettest month as it records the highest rainfall over the study period. August is projected to have the highest increase in rainfall (135%) in the future as compared with the baseline (Figure 4.5). The month of November is projected to experience the highest reduction of rainfall for the study period as compared to the baseline.

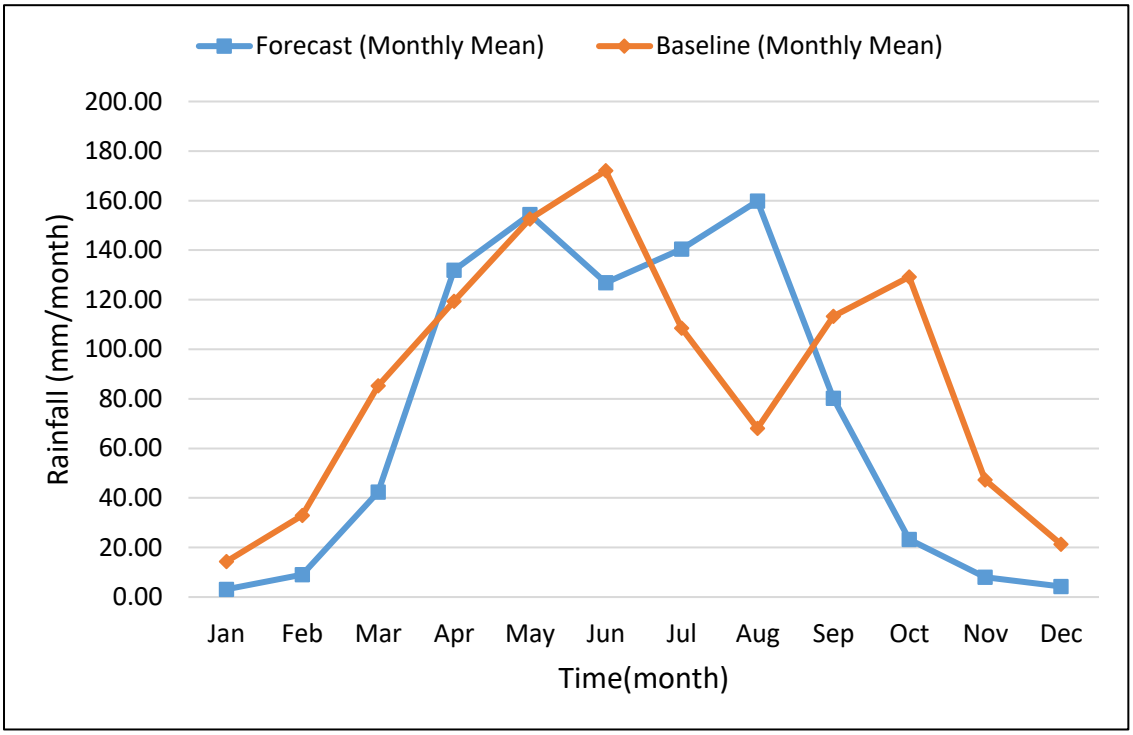

Figure 4.4: Pattern of occurrence of the projected rainfall (2051-2080) under scenario RCP4.5 against the baseline (1981-2010)

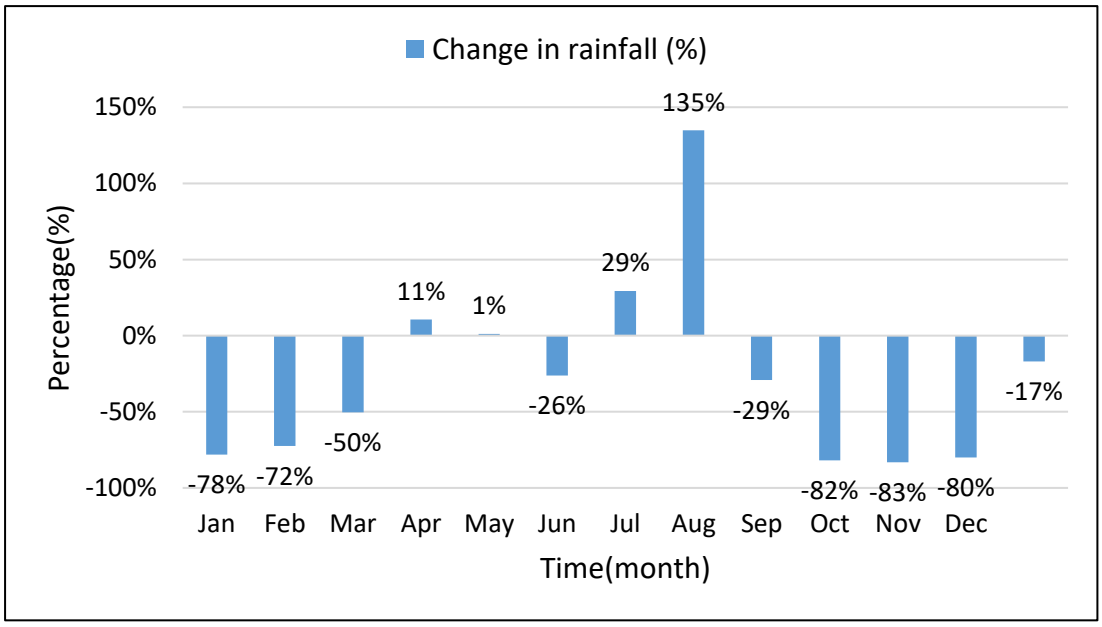

Figure 4.5: Graph showing the percentage change in projected rainfall between 2051-2080 for RCP4.5 scenario for CORDEX

Table 4.2: Projected rainfall changes in DRB (2051-2080)

Month	Forecast (mm)	Baseline (mm)	Change (mm)	Change (%)
Jan	3.14	14.34	-11.20	-78%
Feb	9.05	32.91	-23.86	-72%
Mar	42.33	85.34	-43.00	-50%
Apr	131.93	119.34	12.59	11%
May	154.37	152.64	1.73	1%
Jun	126.86	172.06	-45.20	-26%
Jul	140.49	108.57	31.92	29%
Aug	159.79	68.07	91.73	135%
Sep	80.30	113.38	-33.08	-29%
Oct	23.29	129.15	-105.86	-82%
Nov	7.95	47.29	-39.33	-83%
Dec	4.26	21.39	-17.13	-80%
Annual mean	**883.77**	**1064.47**	**-180.70**	**-17%**

4.3 Impact Analysis

The impact analysis was done using the scenario section of the WEAP model. The scenario analysis allows water managers to answer "what if" questions that are related to water management. The scenario analysis is a way of exploring the sensitivity of several drivers that affects water management. It supports the water manager in planning and implementing better policies. For this research, the scenarios were used to access the impact of climate change on streamflow and water demand (domestic and irrigation) due to socio-economic development driven by population growth in the study area.

4.3.1 Impact of climate change on streamflow

The projected mean annual streamflow for the study period (2051-2080) for the study basin shows significant decreases compared to the baseline condition. The mean annual streamflow reduction is estimated to be 58.3% by 2080 as shown in Table 4.3. Figure 4.6 indicates the mean monthly streamflow for the study period shifting from a bi-modal flow regime (baseline) to a uni-modal flow regime. However, the peak flow is anticipated in July which is same as the baseline. The results from the simulation indicate a projected decrease of the average monthly streamflow from the baseline scenario to the future scenario for all the months excluding August. August is anticipated to increase by 21.05%. The month of October will see the highest reduction of 90.03% at the end of the study period. The months of the dry period (November-March) will all experience a reduction of over 80% as it could be seen in Figure 4.7 and this might lead to water shortages. The streamflow reduction could be link to the reduction in rainfall over the basin for the study period. This can be explained by a tight correlation between the changes in projected rainfall and streamflow. To statistically determine this, a correlation coefficient between the rainfall changes and the streamflow changes was calculated. The correlation coefficient was calculated to be 0.93 which represent a positive correlation between the two variables. Any change in rainfall appends a change in the streamflow accordingly. A graphical representation of the correlation is shown in Figure 4.8. Streamflow reduction in September and October will likely exacerbate water shortage in the months ahead (dry season). The reduction of the Densu river streamflow has been predicted in previous research (Kankam-Yeboah, Obuobie, Amisigo, & Opoku-Ankomah, 2013; Kasei, Barnabas, & Ampadu, 2014).

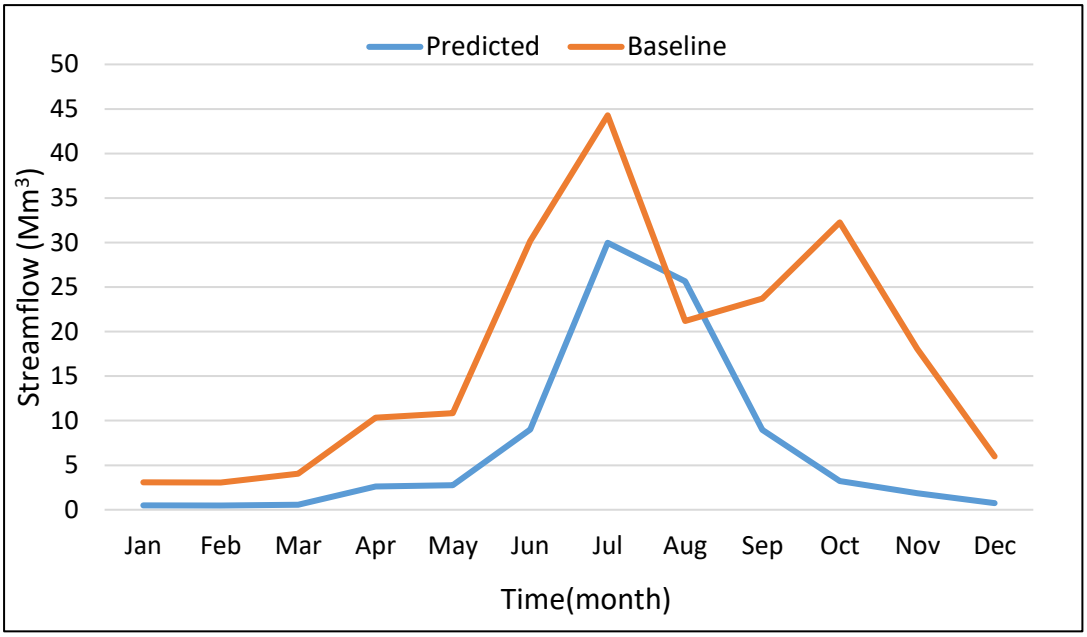

Figure 4.6: Pattern of occurrence of the projected streamflow (2051-2080) under scenario RCP4.5 against the baseline (1981-2010)

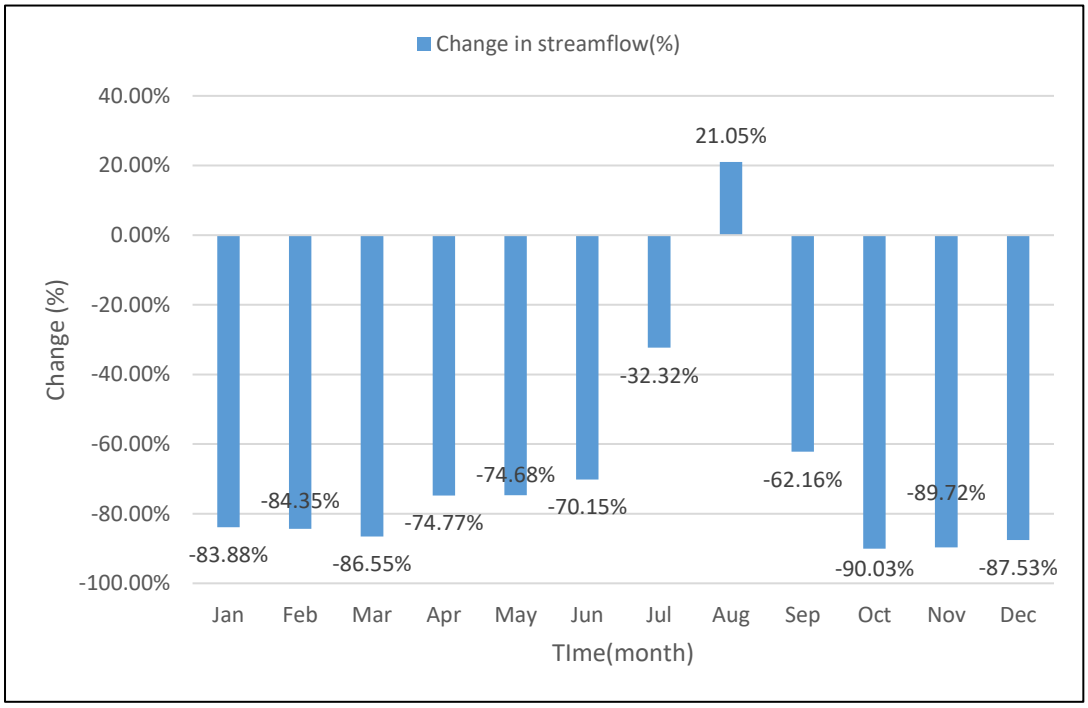

Figure 4.7: Graph showing the percentage change in projected streamflow between 2051-2080 for RCP4.5 scenario

Table 4.3: Projected streamflow changes in DRB (2051-2080)

Month	Predicted (Mm^3)	Baseline (Mm^3)	Change (Mm^3)	Change (%)
Jan	0.49	3.06	-2.57	-83.88%
Feb	0.48	3.06	-2.58	-84.35%
Mar	0.55	4.07	-3.52	-86.55%
Apr	2.61	10.34	-7.73	-74.77%
May	2.75	10.86	-8.11	-74.68%
Jun	9.00	30.16	-21.16	-70.15%
Jul	29.97	44.28	-14.31	-32.32%
Aug	25.65	21.19	4.46	21.05%
Sep	8.98	23.72	-14.74	-62.16%
Oct	3.22	32.28	-29.06	-90.03%
Nov	1.86	18.07	-16.21	-89.72%
Dec	0.75	5.99	-5.24	-87.53%
Annual mean	**7.19**	**17.26**	**-10.06**	**-58.32%**

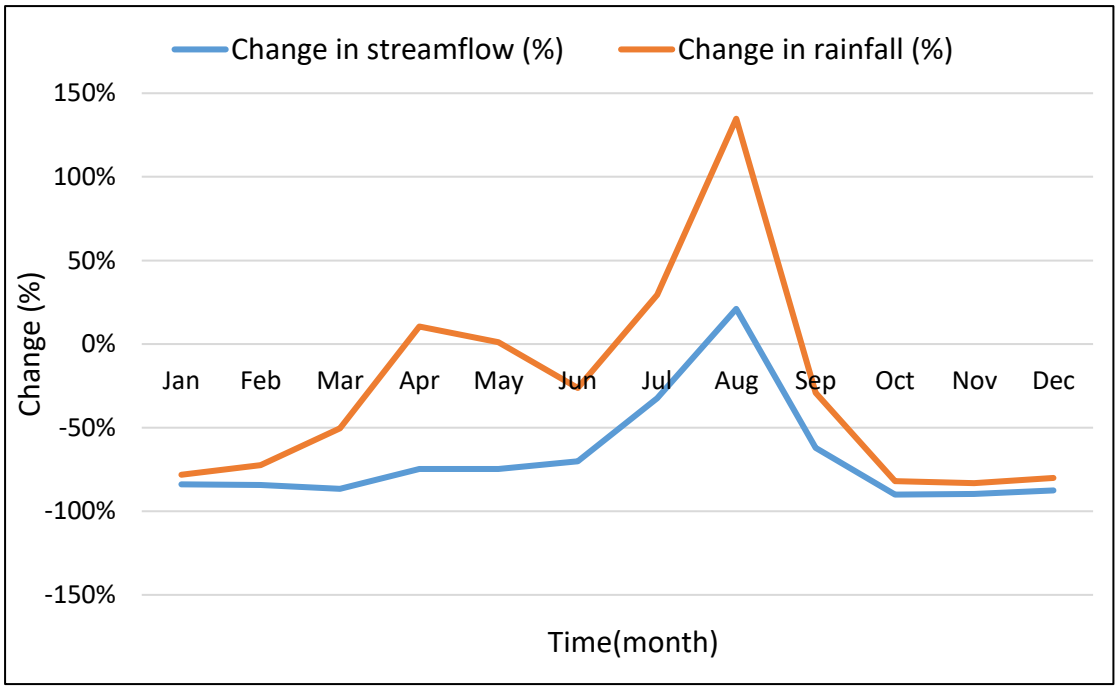

Figure 4.8: Correlation between the changes in the projected rainfall and the streamflow

The change in streamflow was determined with the relation below:

$$Change\ in\ Streamflow\ (\%) = \frac{MAS_p - MAS_b}{MAS_b} x100 \qquad \text{Eqn. 4.1}$$

Where MAS is the mean annual streamflow, p is the projected streamflow and b is the baseline streamflow. The reduction in the river discharge for the period projects severe conditions in the future as far as water resources availability in the basin is concerned.

4.3.2 Impact of climate change on water demand coverage

The climate change impact on water demand coverage was analyzed for domestic and irrigation water uses. In this study, it was assumed that the river utilized by only the people in the basin. In total, three scenarios were used in this section to assess the impact of climate change on water demand coverage in the future. Scenario one is about climate change impact on domestic water coverage using baseline water demand rate of 80l/c/day. The socio-economic activities are assumed to be constant for the study period. Scenario two also analyzed the climate change impact on domestic water demand coverage with increasing water demand rate due to increasing socio-economic activities. The assumed water demand rate was 100l/c/day for the year 2051 through the study period. However, few general assumptions were made for the two scenarios under the domestic water demand coverage. According to the Water Resource Commission, 2007, 67% of the Basin population were relying on the river flow for their domestic water use. The remaining 33% were using water from other sources including rainwater harvest and groundwater. So in this study, it was assumed that by the year 2051, only 60% of the total population will rely directly on the river discharge for their domestic water use for both scenarios (1 and 2) as there will be a lot of education and training on water management and the use of alternate source to supplement their water needs. The population was projected in the WEAP model with an annual basin growth rate of 2.2%. WEAP projected the population to increase from 3,467,481 people in 2010 to 15,906,607 by the end of the study period. Scenario three which was about irrigation water demand was built on the annual water demand rate with the assumption that due to increasing rate of urbanization, the irrigation land will not be extended with the small scale farmers practicing rain fed irrigation.

For all these scenarios, the climate data for the future (2051-2080) was used. The impacts are described in the next sections.

4.3.2.1 Water demand coverage under scenario one

The DRB is projected to experience water shortages in the future: water availability is expected to decrease. The total water demand increases with increasing population growth (Figure 4.9). Compared to the baseline period (1981-2010), the total demand for the future is projected to increase by 4695.96Mm^3 which represent 311% increase. The increasing trend in the water demand is attributed to the increase in population growth. Though the socio-economic activities and the per capita water demand rate remained unchanged for this scenario, the water demand in the basin will not be met in the future (Figure 4.10). The total projected unmet demand for the study period amounts to 4275.58Mm^3. This represent up to 69% of the total water demand for the study period. The water shortage will be much severe in the dry periods with demand coverages below 5% from December to March (Figure 4.11). However, only July and August is projected to meet the highest water demand at 99.3% and 97.1% in the future respectively (Figure 4.11).

The high rate of unmet demand in the basin is associated with the reduction in river discharge which is driven by the changing climate. From the baseline data, the DRB is water-stressed and this situation will be extremely severe in the future due to climate change (Rosenzweig, et al., 2004).

4.3.2.2 Water demand coverage under scenario two

The projected demand situation under this scenario is consistent with the scenario one. However, the demand is much higher under this scenario due to increased socio-economic activities which will require much more water (Figure 4.9). The total water demand by the end of the study period is projected to be 7758.56Mm^3. Compared to the baseline, the total demand is anticipated to increase by 414%. The dry months are projected to experience severe water shortages. The water shortages under this scenario is projected to amount up 5624.8Mm^3 by the end of the study representing 72% of the total water demand. The demand coverage under this scenario is displayed in Figure 4.11. From the figure, July and August are projected to be the month with high demand coverage at 93.1% and 91.9% respectively. January will experience minimum coverage of 2.2% by the end of the study period. The total demand coverage is 28% which is 56% lower than the demand coverage for the baseline. The high water shortages occur as the population and per capita water use rate increases with decreasing river discharges as a result of climate change. Though the baseline indicates water-stressed basin, there is an abstraction of water from the Volta Basin to support the

water issues in the DRB basin. However, the Volta Basin has been projected to experience reductions in its streamflow due to climate change impacts (Gyau-Boakye & Tumbulto, 2006; Kankam-Yeboah, Obuobie, Amisigo, & Opoku-Ankomah, 2013).

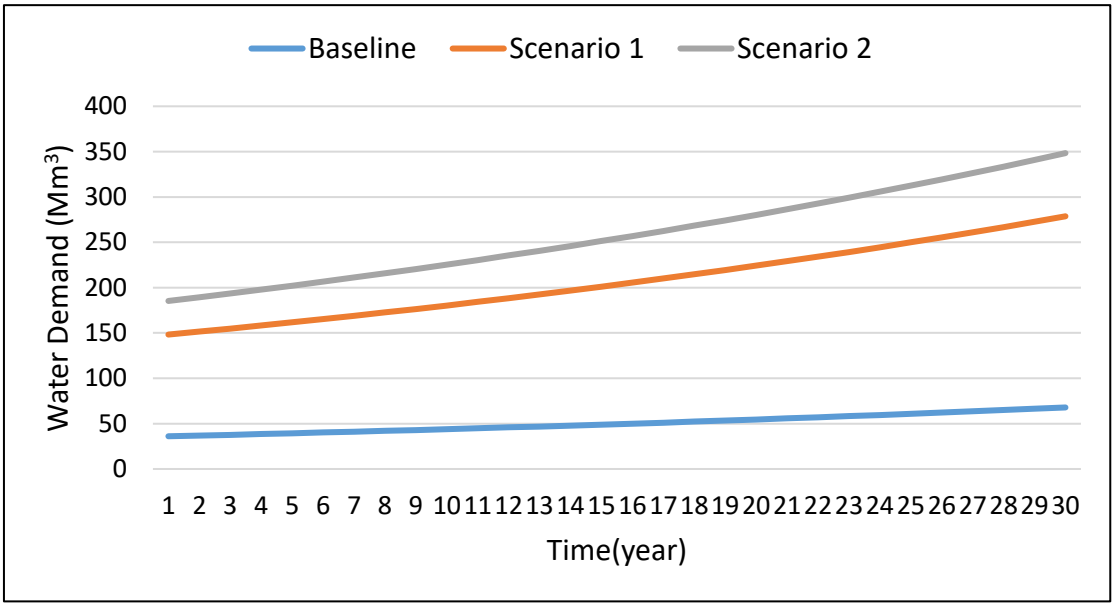

Figure 4.9: Domestic Water Demand for the baseline(1981-2010) and the future scenarios (2051-2080)

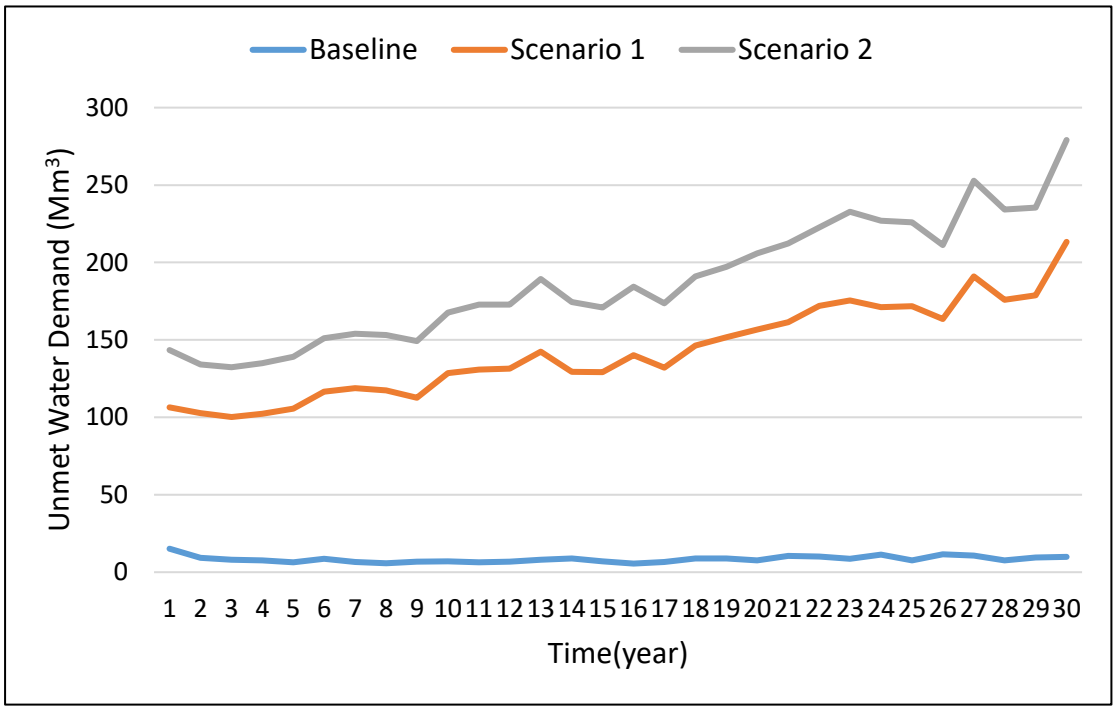

Figure 4.10: Unmet domestic water demands for the future scenarios (2051-2080) compared to the baseline (1981-2010)

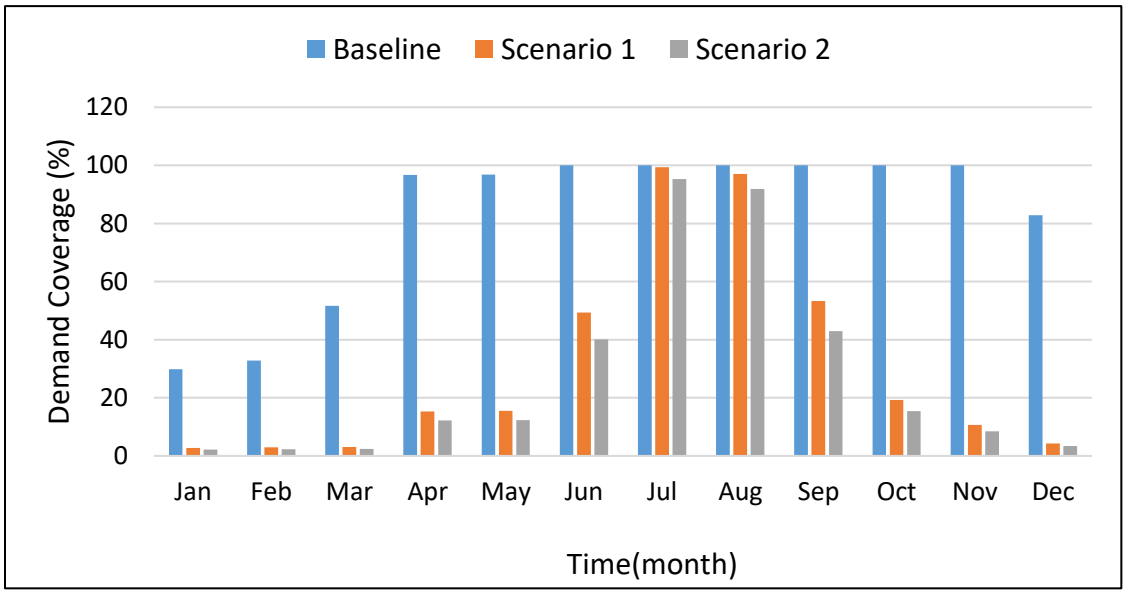

Figure 4.11: Domestic water demand coverage for the baseline (1981-2010) and the future scenarios (2051-2080)

4.3.2.3 Water demand coverage under scenario three

The irrigation water demand projected remains same as the baseline demand. However, the projected demand coverage is lower than the baseline which is attributed to the low flow of the river. The total irrigation demand sums up to 99Mm^3 with a total irrigated area of 220ha. The total unmet demand projected for the study period is 52.49Mm^3. The unmet irrigation demand is projected to be high with a coverage of 19% at the end of 2080. Compared to the baseline, the unmet demand is anticipated to increase by 172% by the end of 2080. The annual water shortages for the baseline and the future is shown in Figure 4.12. This increase in water shortage is an effect of the climate change as it will reduce rainfall amounts and increase surface temperatures as well as evapotranspiration. The combined effect of these hydrological parameters will lead to the reduction of the river streamflow. The irrigation water shortages imply a future with high food insecurities and therefore requires proper measures to avoid hunger in the future.

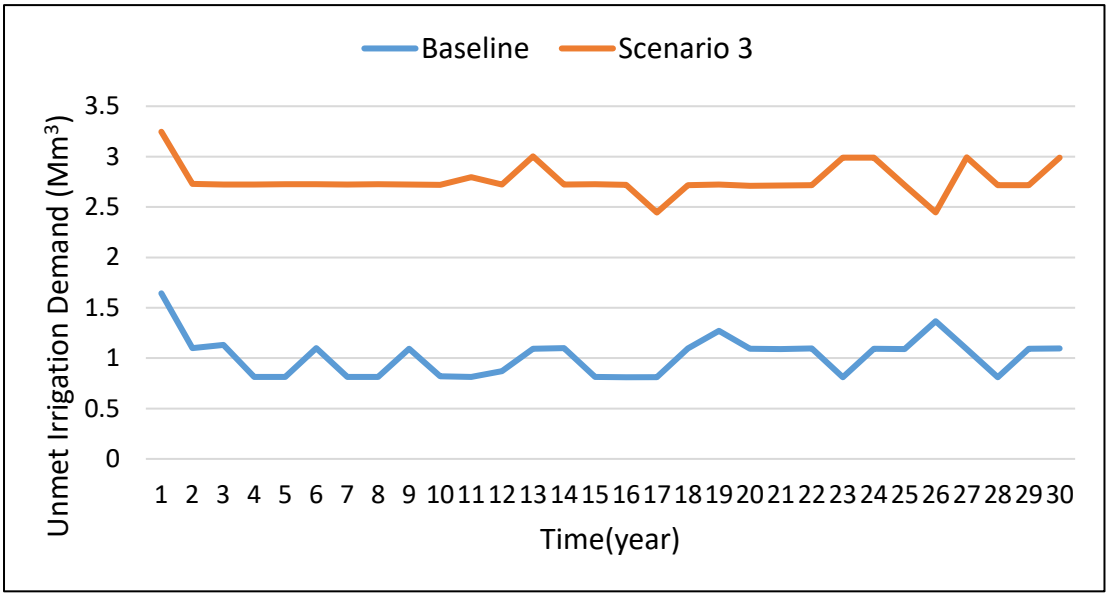

Figure 4.12: Unmet irrigation water demand for the study period (2051-2080) compared to the baseline (1981-2010)

4.4 Limitations of Study

Though this study presents important information regarding the impact of climate change on water resources in the Densu River Basin, it also has some limitations. Generally, climate change impact studies are associated with two key uncertainties: uncertainty related to the input data (e.g. climate data which is based on GCMs and RCMs models), and uncertainty related to the impact hydrological model. Application of hydrological model to assess the impact of climate change on streamflow involves a range of uncertainties (Fowler, Blenkinsop, & Tebaldi, 2007; Abdo, Fiseha, Rientjes, Gieske, & Haile, 2009; Thompson, Green, Kingston, & Gosling, 2013).

Various sources of climate change studies uncertainties are ranked in several studies (Wilby & Harris, 2006; Chen, Brissette, Poulin, & Leconte, 2011). One of the greatest sources of climate change studies uncertainties is the selection of GCM model (Wilby & Harris, 2006; Chen, Brissette, Poulin, & Leconte, 2011; Zyang, Xu, & Fu, 2014). A significant source of uncertainty in the disparity between different GCM models over regional climate change studies has been reported (Wilby & Harris, 2006; Wilby & Dawson, 2013). The application of dynamic and statistical downscaling methods could result in large difference in future climate data (Wood, Leung, Sridhar, & Lettenmaier, 2004; Wilby & Harris, 2006; Qiao, Zou, Gaitán, Hong, & McPherson, 2017) due to the difference in the spatial domains, predictor

variables and predictands (Fowler, Blenkinsop, & Tebaldi, 2007; Qiao, Zou, Gaitán, Hong, & McPherson, 2017).

The second source of uncertainty in climate change studies is associated with hydrological models. The hydrological models are used to interpret the impact of future climate data to hydrological response (e.g., Climate impact on streamflow). Model structure, data scarcity and parameter uncertainty results in hydrological uncertainties (Brigode, Oudin, & Perin, 2013).

The results of this study however, is limited to the GCMs, RCMs, emission scenarios and the hydrological model used.

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this research, the Water Evaluation and Planning system (WEAP21) was used to assess the climate change impact on the water resources in the Densu River Basin between 2051-2080 period. Future downscaled climate data were obtained from the WCRP CORDEX data archives. One GCM and one RCM were used to downscale the data under RCP 4.5 scenario. The climate data was used to calculate the streamflow using the WEAP model. Finally, three potential scenarios were simulated to assess the potential impacts of climate change on water demand in the basin.

The basin is projected to be warmer in the future with expected mean temperature increase of 8.23% over the study period. The projected rainfall at the end of the study period is anticipated to see a drastic decline of -17%. However, the months of April, May, July and August will see an increase in rainfall.

The impact of the climate change on the water resources in the Densu River Basin was assessed in the WEAP model. The projected mean streamflow is anticipated to experience a drastic decline of -58.32% by the end of the study period. This reduction implies a potential water-stressed basin and this was further assessed in WEAP using 3 scenarios. Scenario one which uses baseline per capita water use rate with increasing population projected an increase in demand for domestic uses compared to the baseline. Scenario two projected a much higher demand compared to the baseline and scenario two due to the increase in per capita water use rate. The percentage coverage for scenario two is 28% by the end of the study period. Scenario three which is about irrigation demands projected a future of food insecurities with water demand coverage of 19%. The projected unmet demands for the study period are 69%, 72% and 81% for scenario 1, scenario 2 and scenario 3 respectively. The results from this research anticipate water shortages in the future as a result of climate change.

This indicates that global warming is a potentially very serious problem for water management in the Densu River Basin.

5.2 Recommendations

The results of this research have led to the recommendation for future research on climate change adaptation for water management in the Densu River Basin. This research also recommends the fully utilization of specific demand management strategies such as groundwater resources, rainwater harvesting at household levels, grey water reuse and the use of artificial wetlands in the basin to meet the increasing water demands through conjunctive water management. There must be policy strategies targeting these interventions to ensure efficient and effective implementation.

Further research on climate change impact using different GCMs and RCMs is recommended to ascertain the potential future climate change impact on the river basin.

6 REFERENCES

Abdo, K. S., Fiseha, B. M., Rientjes, T. H., Gieske, A. S., & Haile, A. T. (2009). Assessment of climate change impacts on the hydrology of Gilgel Abay catchment in Lake Tana basin, Ethiopia. *Hydrological Processes, 23*, 3661–3669. doi:10.1002/hyp.7363

Abouabdillah, A., Oueslati, O., Maria De Girolamo, A., & Porto, A. L. (2010). MODELING THE IMPACT OF CLIMATE CHANGE IN A MEDITERRANEAN CATCHMENT (MERGUELLIL, TUNISIA). *Fresenius Environmental Bulletin, 19*(10a), 2334-2347.

Akpoti, K., Antwi, E., & Kabo-bah, A. (2016). Impacts of Rainfall Variability , Land Use and Land Cover Change on Stream Flow of the Black Volta. *Hydrology, 3*(26).

ALAMEDDINE, I., FAYYAD, A., NAJM, M., & EL-FADEL, M. (2018). SUSTAINABILITY OF BASIN LEVEL DEVELOPMENT UNDER A CHANGING CLIMATE. *Int. J. Sus. Dev. Plann., 13*(3), 394-405.

Alemayehu, T., McCartney, M., & Kebede, S. (2010). The water resource implications of planned development in the Lake Tana catchment, Ethiopia. *Ecohydrology and Hydrobiology, 10*(2-4), 211-222. doi:10.2478/v10104-011-0023-6

Al-zubari, W., El-sadek, A., Al-aradi, M., & Al-mahal, H. (2018). Climate Risk Management Impacts of climate change on the municipal water management system in the Kingdom of Bahrain : Vulnerability assessment and adaptation options. *Climate Risk Management, 20*, 95-110.

Amisigo, B. A., McCluskey, A., & Swanson, R. (2015, May). Modeling Impact of Climate Change on Water Resources and Agriculture Demand in the Volta Basin and other Basin Systems in Ghana. *Sustainability, 7*, 19. Retrieved from www.mdpi.com/journal/sustainability

Amoako , J., Karikari, A. Y., Ansa-Asare, O. D., & Adu-Ofori, E. (2010). Water quality characteristics of Densu River basin in south-east Ghana. *Water Science and Technology, 61*(6), 1467-1477. Retrieved from https://doi.org/10.2166/wst.2010.012

Arndt, C., Asante, F., & Thurlow, J. (2015). Implications of Climate Change for Ghana's Economy. *Sustainability, 7*, 7214-7231. doi:10.3390/su7067214

Arsisoa, B. K., Tsidua, G. M., Stoffberg, G. H., & Tadesse, T. (2017). Climate change and population growth impacts on surface water supply and demand of Addis Ababa, Ethiopia. *Climate Risk Management, 18*, 21-33. doi:10.1016/j.crm.2017.08.004

Ashiagbori, G., Forkuo, E. K., Laari, P., & Aabeyir, R. (2014). Modelling Soil Erosion in the Densu River Basin Using RUSLE and GIS Tools. *Journal of Environmental Science & Engineering, 56*(3), 247-245.

Ayivor, J. S., & Gordon, C. (2012). Impact of land use on river systems in Ghana. *West African Journal of Applied Ecology, 20*(3), 83-95.

Bates, B., Kundzewicz, Z., Wu, S., & Palutikof, J. E. (2008). *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change.* Geneva: IPCC Secretariat.

Beck, L., & Bernauer, T. (2011). How will combined changes in water demand and climate affect water availability in the Zambezi river basin? *Global Environmental Change*. doi:10.1016/j.gloenvcha.2011.04.001

Berredjem, A.-f., & Hani, A. (2017). Modelling current and future supply and water demand in the northern region of the Seybouse Valley. *Journal of Water and Land Development, 33*(IV-V), 31-38.

Beyene, T., Lettenmaier, D. P., & Kabat, P. (2010). Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios. *Climatic Change, 100*, 433-461. doi:10.1007/s10584-009-9693-0

Brigode, P., Oudin, L., & Perin, C. (2013). Hydrological model parameter instability: A source of additional uncertainty in estimating the hydrological impacts of climate change? *J. Hydrol., 476*, 410-425.

CGIAR-CSI. (2018, November). *SRTM 90m DEM Digital Elevation database*. Retrieved December 24, 2018, from CGIAR-Consortium for Spatial Information: http://srtm.csi.cgiar.org

Chen, J., Brissette, F. P., Poulin, A., & Leconte, R. (2011). Overall uncertainty study of the hydrological impacts of climate change for a Canadian watershed. *Water Resour. Res., 47*.

Daily, G. C., Polasky, S., Goldstein, J., Kareiva, P. M., Mooney, H. A., Pejchar, L., . . . Shallenberger, R. (2009). Ecosystem Services in decision making: Time to deliver. *Frontiers in Ecology and the Environment, 7*, 21-28.

Dale, V., & Polasky, S. (2007). Measures of the effects os agricultural practices on ecosystem services. *Ecol. Econ., 64*, 286-296.

Dams, J., Woldeamlak, S. T., & Batelaan, O. (2008). Predicting Land--use change and its impact on the groundwater system of the Kleine Nete catchment, Belgium. *Hydrology and Earth System Sciences, 12*, 1369-1385.

Deng, X., Zhao, C., Lin, Y., Zhang, T., Qu, Y., Zhang, F., . . . Wu, F. (2014). Downscaling the Impacts of Lage-Scale LUCC on Surface Temperature along with IPCC RSPs: A Global Perspective. *Energies, 7*, 2720-2739.

Dole, L., Gironas, J., & Vicuna, S. (2015). GC51E-1134 : Analysis of Future Streamflow Regimes under Global Change Scenarios in Central Chile for Ecosystem Sustainability. *2015 AGU Fall Meeting.* San Francisco.

Droogers, P., Immerzeel, W. W., Terink, W., Hoogeveen, J., Bierkens, M. F., van Beek, L. P., & Debele, B. (2012). Water resources trends in Middle East and North Africa

towards 2050. *Hydrology and Earth System Sciences, 16*, 3101–3114. doi:10.5194/hess-16-3101-2012

Elshamy, M. E., Seierstad, I. A., & Sorteberg, A. (2009). Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. *Hydrology and Earth System Sciences, 13*, 551–565.

Fant, C., Gebretsadik, Y., & Strzepek, K. (2013). *Impact of climate change on crops, irrigation and hydropower in the Zambezi River Basin.* The United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki.

Faramarzi, M., Abbaspour, K. C., S., A. V., Farzaneh, M. R., Zehnder, A. J., Srinivasan, R., & Yang, H. (2013). Modeling impacts of climate change on freshwater availability in Africa. *Journal of Hydrology, 480*, 85-101. Retrieved from https://doi.org/10.1016/j.jhydrol.2012.12.016

Fathian, F., Dehghan, Z., & Eslamian, S. (2016). Evaluating the impact of changes in land cover and climate variability on streamflow trends (case study : eastern subbasins of Lake Urmia , Iran). *Int. J. Hydrology Science and Technology, 6*(1).

Fianko, J. R., Donkor, A., Lowor, S. T., Yeboah, P. O., Glover, E. T., Adom, T., & Faanu, A. (2011). Health Risk Associated with Pesticide Contamination of Fish from the Densu River Basin in Ghana. *Journal of Environmental Protection, 2*(2), 115-123. doi:10.4236/jep.2011.22013

Fowler, H., Blenkinsop, S., & Tebaldi, C. (2007). Linking climate change modelling to impacts studies: Recent advances in downscaling techniques for hydrological modelling. *Int. J. Climatol., 27*, 1547-1578.

Gao, J., Christensen, P., & Li, W. (2017). Application of the WEAP model in strategic environmental assessment : Experiences from a case study in an arid / semi-arid area in China. *Journal of Environmental Management, 198*, 363-371.

Geng, X., Wang, X., Yan, H., Zhang, Q., & Jin, G. (2015). Land Use/Land Cover Change Induced Impacts on Water Supply Service in the Upper Reach of Heihe River Basin. *Sustainability, 7*, 366-383.

Genxu, W., Lingyuan, Y., Lin, C., & Ku, J. (2005). Impacts of Land use changes on Groundwater resources in the Heihe River Basin. *Journal of Geophysical Sciences*, 405-414.

Ghana Statistical Service. (2013). *2010 Housng and Population Census-National Analytical Report.* Ghana Statistical Service.

Gordon, C., & Ansa-Asare, O. D. (2012). Water Quality Assessment of Densu, Birim and Ayensu Rivers in the Okyeman Area. *West African Journal of Applied Ecology*.

Guettaf, M., Maoui, A., & Ihdene, Z. (2017). Assessment of water quality: a case study of the Seybouse River (North East of Algeria). *Applied Water Science, 7*, 295-307. doi:10.1007/s13201-014-0245-z

Gyau-Boakye, P., & Tumbulto, J. (2006). Comparison of rainfall and runoff in the humid south-western and the semiarid northern savannah zone in Ghana. *African Journal of Science and Technology: Science and Engineering Series, 7*(1), 64-72.

Hagan, I. (2007). *MODELLING THE IMPACT OF SMALL RESERVOIRS IN THE UPPER EAST REGION.* Lund University, Division of Water Resources Engineering: Department of Building and Environmental Technology.

Hoff, H., Bonzi, C., Joyce, B., & Tielbörger, K. (2011). A Water Resources Planning Tool for the Jordan River. *Water, 3*(3), 718-736. doi:10.3390/w3030718

Hoyer, R., & Chang, H. (2014). Assessment of freshwater services in the Tualatin and Yamhill basins under climate change and urbanization. *Appl. Georgr., 53*, 402-416.

Hrdinka, T., Vlasák, P., Havel, L., & Mlejnská, E. (2015). Possible impacts of climate change on water quality in streams of the Czech Republic. *Hydrological Sciences Journal, 60*(2), 192-201. doi:10.1080/02626667.2014.889830

Huang, J.-C., Lee, T.-Y., & Lee, J.-Y. (2014). Observed magnified runoff response to rainfall intensification under global warming. *Environmental Research Letters, 9* (3), 34008.

IPCC. (2007). *Climate Change: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* UK: Cambridge University press.

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* (R. K. Pachauri, & L. A. Meyer, Eds.) Geneva, Switzerland: IPCC.

Jarvis, A., Reuter, H. I., Nelson, A., & Guevara, E. (2008). Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT). Retrieved from http://srtm.csi.cgiar.org.

Joyce, B. A., Mehta, V. K., Purkey, D. R., Dale, L. L., & Hanemann, M. (2011). Modifying agricultural water management to adapt to climate change in California's central valley. *Climatic Change, 109*(1), 299-316. doi:10.1007/s10584-011-0335y

Kabo-bah, A. T., Anornu, G. K., Ofosu, E., Andoh, R., & Lis, K. J. (2014). Spatial-temporal estimation of evapotranspiration over Black Volta of West Africa. *International Journal of Water Resources and Environmental Engineering, 6*(12), 295–302. Retrieved from https://doi.org/10.5897/IJWREE2013.0530

Kankam-Yeboah, K., Obuobie, E., Amisigo, B., & Opoku-Ankomah, Y. (2013). Impact of climate change on streamflow in selected river basins in Ghana. *Hydrological Sciences Journal, 58*(4), 773-778. doi:10.1080/02626667.2013.782101

Karikari, A., & Ansa-Asare, O. (2006). Physico-chemical and microbial water quality assessment of Densu River of Ghana. *West African Journal of Applied Ecology, 10*(1).

Kasei, R. A., Barnabas, A., & Ampadu, B. (2014). The Nexus of Changing Climate and Impacts on Rainfed Water Supply and Fresh Water Availability for the Inhabitants of Densu Basin and Parts of Accra - Ghana, West Africa. *Journal of Environment and Earth Science, 4*(20), 84-96.

Ki, B., Mengistu, G., & Hendrik, G. (2017). Climate Risk Management Climate change and population growth impacts on surface water supply and demand of Addis Ababa , Ethiopia. *Climate Risk Management, 18*, 21-33.

Kishtawal, C., Niyogi, D., Tewari, M., Pielke, R., & Shepherd, J. (2010). Urbanization signature in the observed heavy rainfall climatology over India. *International Journal of Climatology, 30*, 1908-1916.

Kumar, P., Masago, Y., Kumar, B., & Fukushi, K. (2018). Groundwater for Sustainable Development Evaluating future stress due to combined e ff ect of climate change and rapid urbanization for Pasig-Marikina River , Manila. *Groundwater for Sustainable Development, 6*(October 2017), 227-234.

Kundu, P., Mathivha, F., & Nkuna, T. (2015). *The Use of GIS and Remote Sensing Techniques to Evaluate the Impact of Land use and Land Cover Change on the Hydrology of Luvuvhu River Catchment in Limpopo Province.* Department of Hydrology and Water Resources: University of Venda.

Kunstmann, H., Jung, G., Wagner, S., & Clottey, H. (2008). Integration of atmospheric sciences and hydrology for the development of decision support systems insustainable water management. *Physics and Chemistry of the Earth, 33*, 165-174.

Lettenmaier, D., Major, D., Poff, L., & Running, S. (2008). *Water Resources. In: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.* Washington, DC: U.S. Department of Agriculture.

Li, Z., Deng, X., Huang, J., Zhang, R., & Huang, J. (2013). Critical Studies on Tntegrating Land-Use Induced Effects on Climate Regulation Services into Impact Assessment for Human Well-Being. *Advances in Meteorology*. doi:10.1155/2013/831250

Limantol, A., Afouda, A., Lenartz, B., & Agyare, W. (2015). GC43B-1201 : Impact of climate change on Vea Catchment and irrigation scheme in Upper East Region of Ghana. *AGU FALL MEETING.* San Francisco.

Mahe, G., Lienou, G., Descroix, L., Bamba, F., Paturel, J., Laraque, A., . . . Khomsi, K. (2013). The rivers of Africa : witness of climate change and human impact on the environment. *Hydrological Processes, 27*, 2105-2114.

Mahmood, R., Pielke, R., Hubbard, K., Niyogi, D., Dirmeyer, P., McAlpine, C., . . . Beltrán-Przekurat, A. (2014). Land cover and their biogeophysical effects on climate. *Int. J. Climatol, 34*, 929-953.

Maliehe, M., & Mulungu, D. (2017). Assessment of water availability for competing uses using SWAT and WEAP in South Phuthiatsana catchment , Lesotho. *Physics and Chemistry of the Earth, 100*, 305-316.

Marquès, M., Bangash, R., Kumar, V., Sharp, R., & Schuhmacher, M. (2013). The impact of climate chnge on water provision under a low flow regime: A case study of the ecosystems services in the Francoli river basin. *Journal of Hazardous Materials, 263*, 224-232.

McCartney, M. P., & Girma, M. M. (n.d.). Evaluating the downstream implications of planned water resource development in the Ethiopian portion of the Blue Nile River. *Water International, 37*(4), 362–379. doi:10.1080/02508060.2012.706384

McCartney, M., Forkuor, G., Sood, A., Amisigo, B., Hattermann, F., & Muthuwatta, L. (2012). *The Water Resource Implications of Changing Climate in the Volta River Basin.* Colombo, Sri Lanka: International Water Management Institute(IWMI). doi:10.5337/2012.219

McSweeney, C., New, M., & Lizcano, G. (2006). *UNDP Climate Change Country Profiles: Ghana.* Retrieved July 22, 2019, from UNT Digital Library: https://digital.library.unt.edu/ark:/67531/metadc226664/

Mehta, V. K., Haden, V. R., Joyce, B. A., Purkey, D. R., & Jackson, L. E. (2013). Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California. *Agricultural Water Management, 117*, 70-82.

Milzow, C., Burg, V., & Kinzelbach, W. (2010). Estimating future ecoregion distributions within the Okavango Delta Wetlands based on hydrological simulations and future climate and development scenarios. *Journal of Hydrology, 381*, 89-100.

Murray-Hudson, M., Wolski, P., & Ringrose, S. (2006). Scenarios of the impact of local and upstream changes in climate and water use on hydro-ecology in the Okavango Delta, Botswana. *Journal of Hydrology*, 73-84.

Mylopoulos, N., Fafoutis, C., Sfyris, S., & Alamanos, A. (2017). Impact of water pricing policy and climate change on future water demand in Volos , Greece. *European Water, 58*, 473-479.

Nash, J. E., & Sutcliff, J. V. (1970). River flow forecasting through conceptual models part I - A discussion of principles. *Journal of Hydrology, 10*(3), 280-290. doi:10.1016/0022-1694(70)90255-6

Ncube, S., Makurira, H., Kaseke, E., & Mhizha, A. (2011). Reservoir operation under variable climate: Case of Rozva Dam, Zimbabwe. *Physics and Chemistry of the Earth, 36*, 1112–1119.

Niang, I., Ruppel, O., Abdrabo, M., Essel, A., Lennard, C., Padgham, J., & Urquhart, P. (2014). *Africa. In: Climate Change 2014: Impacts, Adaptation and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* (V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, E. T. Bilir, . . . L. L. White, Eds.) Cambridge, United Kingdom and New York, USA: Cambridge University Press.

Nicholson, S., & Grist, J. (2001). A CONCEPTUAL MODEL FOR UNDERSTANDING RAINFALL VARIABILITY IN THE WEST AFRICAN SAHEL ON

INTERANNUAL AND INTERDECADAL TIMESCALES. *INTERNATIONAL JOURNAL OF CLIMATOLOGY, 21*, 1733-1757.

Ofosu, E. (2011). *Sustainable Irrigation Development in the White Volta sub-Basin.* UNESCO-IHE.

Okyereh, S., Ofosu, E., & Kabobah, A. (2019). Modelling the impact of Bui dam operations on downstream competing water uses. *Water-Energy Nexus, 2*, 1-9.

Olsson, T., Kämäräinen, M., Santos, D., Seitola, T., Tuomenvirta, H., Haavisto, R., & Lavado-casimiro, W. (2017). Regional Studies Downscaling climate projections for the Peruvian coastal Chancay- Huaral Basin to support river discharge modeling with WEAP. *Journal of Hydrology: Regional Studies, 13*, 26-42.

Peterson, D. F., & Keller, A. A. (1990). Effects of Climate Change on U.S. Irrigation. *Journal of Irrigation and Drainange Engineering, 116*(2), 194-210.

PHAM, B. Q., YU, P.-S., YANG, T.-C., KUO, C.-M., & TSENG, H.-W. (2017). ASSESSMENT OF CLIMATE CHANGE IMPACTS ON HYDROLOGICAL PROCESSES AND WATER RESOURCES BY WATER EVALUATION AND PLANNING (WEAP) MODEL: CASE STUDY IN THAC MO CATCHMENT, VIETNAM. *Proceedings of the 37th IAHR World Congress.* Kuala Lumpur, Malaysia: International Association for Hydro-Environment Engineering and Research(IAHR).

Pielke, R., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., & Goldewijk, K. (2011). Land use/land cover changes and climate: Modeling analysis and observational evidence. *Wiley Interdisciplinary Reviews: Climate Change, 2*, 828-850.

Princeton University. (2007). *Global Meteorological Forcing Dataset for land surface modeling*. Retrieved May 2, 2019, from Terrestrial Hydrology Research Group: http://hydrology.princeton.edu/getdata.php?dataid=1

Psomas, A., Panagopoulos, Y., Konsta, D., & Mimikou, M. (2016). Designing water efficiency measures in a catchment in Greece using WEAP and SWAT models. *2nd EWaS International Conference.* Chania.

Psomas, A., Panagopoulos, Y., Stefanidis, K., & Mimikou, M. (2017). Assessing future water supply and demand in a water-stressed catchment after environmental restrictions on abstractions. *Journal of Water Supply: Research and Technology*, 1-12.

Purkey, D. R., Huber-Lee, A., Yates, D. N., Hanemann, M., & Herrod-Julius, S. (2007). Integrating a climate change assessment tool into stakeholder-driven water management decision-making processes in California. *Water Resources management, 21*, 315-329. doi:10.1007/s11269-006-9055-x

Qiao, L., Zou, C. B., Gaitán, C. F., Hong, Y., & McPherson, R. A. (2017). Analysis of precipitation projections over the climate gradient of the Arkansas Red River basin. *J. Appl. Meteorol. Climtol., 56*, 1325-1336.

Reuter, H. I., Nelson, A., & Jarvis, A. (2007). An evaluation of void filling interpolation methods for SRTM data. *International Journal of Geographic Information Science, 21:9,*, 983-1008.

Riepl, D. (2013). *Knowledge-Based Decision Support for Integrated Water Resources Management with an application for Wadi Shueib, Jordan.* Karlsruher Institut für Technologie (KIT), Bauingenieur-, Geo- und Umweltwissenschaften.

Rosenzweig, C., Strzepek, K. M., Major, D. C., Iglesias, A., Yates, D. N., McCluskey, A., & Hillel, D. (2004). Water Resources for Agriculture in a Changing Climate: International case studies. *Global Environmental Change, 14*, 345-360.

Roudier, P., Ducharne, A., & Feyen, L. (2014). Climate change impacts on runoff in West Africa : a review. *Hydrology and Earth System Sciences, 18*, 2789-2801.

Ruelland, D., Ardoin-Bardin, S., Collet, L., & Roucou, P. (2012). Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. *Journal of Hydrology, 424–425*, 207–216.

Santikayasa, I. P., Babel, M. S., & Shrestha, S. (2015). Assessment of the Impact of Climate Change on Water Availability in the Citarum Rive Basin, Indonesia: The use of Statistical Downscaling and Water Planning Tools. *Managing Water Resources under Climate Uncertainty*. doi:10.1007/978-3-319-10467-6_3

Santikayasa, I., & Basit, R. (2017). Water allocation for agriculture complex terrain under changing climate. *IOP Conference Series: Earth and Environmental Science, 54*.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., . . . Leetmaa, A. (2007, May 25). Model projections of an imminwnt transition to a more arid climate in southwestern North America. *Science, 316*(5828), 1181-1184. doi:10.1126/science.1139601

Seiber, J. (n.d.). *Water Evaluation and Planning (WEAP) System, Software version: 2019.0.* Somerville: Stockholm Environmental Institute. Retrieved from https://www.weap21.org

Seiber, J., & Purkey, D. (2015). *Water Evaluation and Planning System User Guide.* Somerville, M.A.: Stockholm Environmental Institute.

Sharma, K. D., Sorooshian, S., & Wheater, H. (2008). *Hydrological Modelling in Arid and Semi-Arid Areas.* New York: Cambridge University Press.

Sharma, P., Gupta, G., Prabhakar, P., Tiwari, S., Kathait, P., Pathak, Y., . . . Kumar, S. (2017). LAND USE LAND COVER CHANGE IMPACT ON WATER RESOURCES-A REVIEW. *International Journal of Advances in Engineering & Scientific Research, 4*(2), 7-14.

Sheffield, J., Goteti, G., & Wood, E. F. (2006, July 1). Development of a 50-yr high-resolution global dataset of meteorological forcings for land surface modeling. *Journal of Climate, 19*(13), 3088-3111. doi:10.1175/JCLI3790.1

Stanturf, J. A., Warren, M. L., Charnley, S., Polasky, S. C., Goodrick, S. L., Armah , F., & Nyako, Y. A. (2011, June). GHANA CLIMATE CHANGE VULNERABILITY AND ADAPTATION ASSESSMENT.

Steynor, A. C., Hewitson, B. C., & Tadross, M. A. (2009). Projected future runoff of the Breede River under climate change. *Water SA, 35*(4), 433-440.

Sun, G., McNulty, S. G., Cohen, E., & Myers, J. M. (2005). Modeling the Impacts of Climate Change, Landuse Change, and Human Population Dynamics on Water Availability and Demands in the Southeastern U.S. *2005 ASAE Annual International Meeting.* Tampa, Florida: The Society for Engineering in Agricultural, food and bilogical systems.

Sylla, M. B., Nikiema, P. M., Gibba, P., Kebe, I., & Klutse, N. A. (2016). Climate Change over West Africa: Recent Trends and Future Projections. In J. Yaro, & J. Hesselberg (Eds.), *Adaptation to Climate Change and Variability in Rural West Africa* (pp. 25-40). Springer International Publishing. doi:DOI 10.1007/978-3-319-31499-0_3

Tay, C., & Kortatsi, B. (2008). Groundwater Quality Studies: A Case Study of the Densu. *West African Journal of Applied Ecology, 12*. Retrieved from http://dx.doi.org/10.4314/wajae.v12i1.45760

Thompson, J., Green, A., Kingston, D., & Gosling, S. (2013). . Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. *J. Hydrol., 486*, 1-30.

Toure, A., Diekkrüger, B., Mariko, A., & Cissé, A. (2017). Assessment of Groundwater Resources in the Context of Climate Change and Population Growth : Case of. *Climate, 5*(45), 1-15.

Trenberth, K. E., & Shea, D. J. (2006). Atlantic hurricanes and natural variability in 2005. *Geophysical Research Letters, 33*(L12704). doi:10.1029/2006GL02689

Tshimanga, R., & Hughes, D. (2012). Climate change and impacts on the hydrology of the Congo Basin: The case of the northern sub-basins of the Oubangui and Sangha Rivers. *Physics and Chemistry of the Earth, 50–52*, 72–83. doi:10.1016/j.pce.2012.08.002

UNFCCC. (2007). *Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries.* United Nations Framework Convention on Climate Change.

Wagner, P., Kumar, S., & Schneider, K. (2013). An assessment of land use change impacts on the water resources of the Mula and Mutha Rivers catchment upstream of Pune , India. *Hydrology and Earth System Sciences, 17*, 2233-2246.

Water Resources Commission. (2007). *DENSU RIVER BASIN - Integrated Water Resources Management Plan.* Accra: Water Resources Commission.

Water Resources Commission. (2018). *Basins*. Retrieved October 9, 2018, from Ghana Water Resources Commission: https://www.wrc-gh.org/basins/densu

Wilby, R. L., & Harris, I. (2006). A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. *Water Resour. Res., 42*(W02419). doi:10.1029/2005WR004065

Wilby, R., & Dawson, C. W. (2013). The statistical downscaling model: Insights from one decade of application. *Int. J. Climatol, 33*, 1707-1719.

Wolski, P., Todd, M., Murray-Hudson, M., & Tadross, M. (2012). Multi-decadal oscillations in the hydro-climate of the Okavango River system during the past and under a changing climate. *Journal of Hydrology, 475*, 294-305.

Wood, A. W., Leung, L. R., Sridhar, V., & Lettenmaier, D. (2004). Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Clim. Chang., 62*, 189-216.

Yan, T., Bai, J., LEE ZHI YI, A., & Shen, Z. (2018). SWAT-Simulated Streamflow Responses to Climate Variability and Human Activities in the Miyun Reservoir Basin by Considering Streamflow Components. *Sustainability, 10*, 941.

Yates, D., Sieber, J., Purkey, D., & Huber-Lee, A. (2005). WEAP21 - A Demand-, Priority-, and Preference-Driven Water Planning Model, Part 1: Model Charactristics. *Water International, 30*(4), 487-500. doi:10.1080/02508060508691893

Zhang, W., Ricketts, T., Kremen, C., Carney, K., & Swinton, S. (2007). Ecosystem services and dis-service to agriculture. *Ecol. Econ., 64*, 253-260.

Zyang, X., Xu, Y.-P., & Fu, G. (2014). Uncertainties in SWAT extreme flow simulation under climate change. *J. Hydrol., 515*, 205-222.