MODELING THE CLIMATE AND HYDROLOGY OF THE TONO BASIN IN GHANA, WEST AFRICA

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"If dams are to live up to expectations in the face of a changing climate, there will be the need for a robust hydrologic data analysis coupled with rigorous risk assessment of how climate change might affect runoff in the future" (Lamptey, 2009).

ABSTRACT

The study focused on the Tono basin in the Kessena municipality in the Upper East Region of Ghana. Due to poor data collection at the basin, there has not been any hydrological and climatic assessment of the basin. To address these challenges the study explored the potential of using a state of the art hydrological model (WRF-Hydro) in a coupled mode to assess these water resources, particularly the Tono basin in Ghana. A 2-domain configuration was chosen: an outer domain at 25 km horizontal resolution encompassing the West African Region and an inner domain at 5 km horizontal resolution centered on the Tono basin. The infiltration partition parameter (kdtref) and Manning's roughness parameter (MannN) of the hydrological model were calibrated to fit the simulated discharge with the observed one. The simulations were done from 1999-2007, using 1999 as a spin-up period. The results were compared with TRMM precipitation, CRU temperature and available observed hydrological data. A standalone WRF model was run for the same period to assess whether the coupled model (WRF/WRF-Hydro) provides an improvement in estimating climate variables, e.g. precipitation and temperature. The forcing data used to drive the model runs were, ERA interim reanalysis and ECHAM6. The WRF/WRF-Hydro forced with ERA-I demonstrated a precipitation pattern of correlation with observed (TRMM) data of about 0.91 and its centered RMS error of 2.4 mm/day, whereas WRF-only forced with ERA-I produced a precipitation pattern of correlation of about 0.82 and a RMS error of 3.6mm/day. For temperature, WRF/WRF-Hydro produced a pattern of correlation with observed (CRU) data of about 0.94 and a RMS error of 0.6 ^{0}C, whereas WRF-only produced a pattern of correlation of about 0.87 and a RMS error of 1.2 ^{0}C. Similar characteristics were demonstrated by ECHAM6 model data; however, ECHAM6 produced the worst results especially for the coupled approach. These variations in model performance can be attributed to

the optimum physics option chosen, which may not be the optimum in the Tono basin (microscale effect) and also applying the same calibration for different models (coupled or uncoupled). The WRF-Hydro model demonstrated strong signal of streamflow estimate; with Nash-Sutcliff efficiency (NSE) of 0.78 and Pearson's correlation of 0.89. Further validation of model results was based on driving the output from the WRF-Hydro to a water balance model to simulate the dam levels. The model-derived dam levels were in good agreement with the observed dam levels with a correlation (R^2) of 0.71. The deficiency in the modelled dam levels could be attributed to the models' over estimation of evaporation. Regarding climate change impact on the Tono dam, two climate change emission scenarios were applied (i.e. RCP4.5 and RCP8.5). Both scenarios did not agree on the signal of change with respect to precipitation but both indicated a warmer condition. RCP4.5 indicated an annual rainfall projection increase of +7%, which implies a future increase in flows of about 14% and RCP8.5 indicated rainfall projection decrease by -9.6%, implying about 20% reduction in flows. There is therefore the need to put in place adaptation measures to ensure the sustainability of the Tono dam in the face of climate change.

CERTIFICATION OF ORIGINALITY

a) By the student:
I declare that this is my own work and that it has not been submitted previously as dissertation or thesis elsewhere at any other university for the award of a degree.

Candidate's Name: Edward NAABIL

Signature:…………………………………… Date: 27th May, 2016

b) By the Supervisor(s):
This is to certify that this work was carried out by Mr. NAABIL Edward under my supervision and that to the best of my knowledge, it has not been submitted elsewhere for the award of a degree.

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DEDICATION

This work is dedicated to my wife, Sarah K. Weyori, who endured my absence for the period of this study while providing support and encouragement to me.

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I am very grateful to God, the almighty, maker of heaven and earth and that is in him I have the strength and well-being that enabled me to complete this research.

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LIST OF ACRONYMS

ACLHFLX	Accumulated Latent Heat Flux
AEJ	African Easterly Jet
AEW	African Easterly Wave
AWJ	African Westerly Jet
AGCM	Atmospheric Global Circulation Model
AGRHYMET	Agriculture, Hydrology, Meteorology centre
AOGCM	Atmospheric-Ocean General Circulation Model
AIM	Asia-Pasific Integrated Model
BWR	Basic Water Requirement
BCM	Billion Cubic Meters
CRU	Climate Research Unit
CIN	Convective Inhibition
CU	Cumulus
DEM	Digital Elevation Map
DHSVM	Distributed Hydrology Soil Vegetation Model
DSS	Decision Support System
FAO	Food and Agriculture Organisation
GCAM	Global Change Assessment Model
GCM	Global Circulation Model
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GIDA	Ghana Irrigation Development Authority

LIST OF ACRONYMS

GIS	Geographic Information System
GNA	Ghana News Agency
GSS	Ghana Statistical Service
ICOLD	International Commission on Large Dams
ICOUR	Irrigation Company of Upper Region
IS	Irrigation Scheme
ITCZ	Inter-Tropical Convergence Zone
ITD	Inter-Tropical Discontinuity
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
JGCRI	Joint Global Change Research Institute
JICA	Japan International Cooperation Agency
LSM	Land Surface Model
MCM	Million Cubic Meters
MCS	Mesoscale Convective System
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MP	Microphysics
NCAR	National Center for Atmospheric Research
NAO	North Atlantic Oscillation
NDHMS	NCAR Distributed Hydrologic Modeling System

LIST OF ACRONYMS

NNI	Natural Neighbor Interpolation
NIES	National Institute for Environmental Studies
NSE	Nash-Sutcliffe Efficiency
NWP	Numerical Weather Prediction
OCS	Organised Convective System
PBIAS	Percentage Bias
PBL	Planetary boundary layer
PD	Peak Decline
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
RMSE	Root Mean Square Error
SDSM	Statistical Downscaling Method
SL	Squall Line
SRES	Special Representative Emission Scenarios
TEJ	Tropical Easterly Jet
TRMM	Tropical Rainfall Measuring Mission
TRWR	Total Renewable Water Resource
UN	United Nations
UNESCO	United Nations Educational Scientific and Cultural Organisation
USGS	United States Geological Survey
WA	West Africa
WAM	West Africa Monsoon

LIST OF ACRONYMS

WASCAL	West Africa Science Service Center on Climate Change and Adapted Land Use
WAWJ	West Africa Westerly Jet
WB	Water Balance
WRF	Weather Research and Forecast
WSM5	WRF single-moment 5-class scheme
WPS	WRF Preprocessing System
WWAP	World Water Assessment Program

CHAPTER ONE

INTRODUCTION

1.1 General

Water resources are a major source of economic development for most West African (WA) countries. These resources are depended on for agriculture, power generation and fisheries. Though most of the agriculture is rain-fed, some regions strongly depend on irrigation to complement the rain-fed agriculture. The increasing demand for food due to increasing population has increased irrigation schemes by way of land size or number of operating schemes to boost agriculture output. The climate characteristic of Northern Ghana is that of a short rainy season (May-September) and a long dry season (November-April). This variability in climate does not support adequate agricultural activities. The Tono irrigation scheme in Northern Ghana was developed to provide dry season agriculture (irrigation) in order to supplement food production and to improve incomes of farmers. Irrigation uses the largest proportion of water in most developing countries where it is practiced; this constitutes about 70% of freshwater (Cai, *et al.*, 2001). However, the demand for water for industrial and domestic use over time outstrips its demand for irrigation in developing countries due to increasing economic development and urbanization. As a result, most water meant for irrigation is being allocated to urban-industrial use, resulting in increasing water stress (Rosegrant and Ringler, 2000).

Stream flows are a major source of water resources, these flows are affected by a number of drivers such as land use changes, water withdrawals and climate variations. As outlined above, variability of West Africa climate, particularly Northern Ghana with respect to rainfall plays a major role in flow variations. Rivers in WA generally display strong relationships with rainfall and temperature variability; with rainfall accounting for around 60-70% of river flow variability (Conway *et al.*, 2008). In the light of global warming (IPCC, 2014) and the increasingly varying rainfall and temperature, changes in hydrological regimes could become even more important in the future (Wuebbles and Ciuro, 2013). West Africa in recent decades has been observing decreases in rainfall and its antecedent effect on the availability of surface and sub-surface water. The combined effect of increasing demographic pressure and low adaptive capacity could cause these changes to have significant impacts on people and sectors that depend on the availability of water in WA.

In order to improve the modelling of climate and hydrology over the region to support water resources management, adequate and quality observational data are required. Hydrological and climate observation data availability and measurements in most developing countries like Ghana are a major challenge. The unavailability of these data is attributed to; inadequate funding to acquire measuring instruments, inadequate skilled staff to take measurements, destruction of equipment by the local people among other reasons. These data are required by hydrologists and modelers to facilitate understanding the hydrological dynamics of a catchment and to develop programs for the purposes of water resources management, flood control, drainage design, water supply and irrigation design. The hydrology of river basins and lakes of various regions has been studied, particularly for the purpose of understanding the hydrological dynamics and water resources management of those rivers. Examples of such studies are; the development of hydrological models for water resources utilization (Legesse *et al.*, 2004, Kunstmann et al., 2006), modeling lake levels or outflows with the objective to quantitatively interpret historical lake level records in terms of past rainfall or climate variations (Lamb *et al.*, 2002; Kumambala, 2010). The use of physics-based, hydrometeological systems that combine hydrological models with atmospheric models either in a coupled or standalone ("offline") mode in generating streamflow of river basins are now being applied in many regions (Kunstmann and Stadler, 2005; Dale *et al.* 2012; Yucel *et al.* 2015; Gochis *et al.*, 2015; Arnault *et al.*, 2015). Coupling high-resolution hydrological models with fine-scale atmospheric models in some cases reduces uncertainties associated with the spatial distribution and timing of heavy rainfall (Yucel *et al.* 2015). This is particularly important for complex terrain. Fine-scale, coupled Hydrometeorological models have been shown to have the potential to adequately predict runoff, streamflow and forecast flood when operating at effective grid resolutions of a few kilometers or less (e.g. Yucel *et al.* 2015, Gochis *et al.* 2015, Arnault *et al.* 2015, Senatore *et al.* 2015). However, the use of coupled atmospheric-hydrological models has not been applied as an operational tool in assessing water resources especially in the WA region.

Considering the economic significance of water resources, there is the need to study the hydrological dynamics and the impacts of climate change on runoff regimes and to assess the uncertainty of such projections and its implications for future water resources. This study applied the coupling approach of atmosphere-hydrological modeling to investigate the impact of climate change on the sustainability of the Tono Irrigation Dam; which will involve the reproduction of the historical dam levels and the projection of future dam levels. The method could then be used as a water resource tool for long-term water sustainability or management decisions.

1.2 Research Aim and Objectives

The study is aimed at assessing the sustainability of the Tono Irrigation scheme taking into account the impact of climate change. Specifically the research seeks to achieve the following objectives;

1. To assess the performance of coupling physics-based (or a process-based) hydrological model with atmospheric model in reproducing the current dam levels.
2. Assess the effect of climate change on future flow regime at the Tono basin based on the recent climate emission scenarios by the IPCC (i.e. RCPs).
3. Assess the sustainability of the Tono Irrigation scheme based on the projected climate and possible adaptive measures for water resources management.

1.3 Statement of the Problem/Justification

Agriculture is the driving force of Ghana's economy. It accounts for about 65% of the workforce, about 40% of the gross domestic product, and about 40% of foreign currencies earned through exports (Namara *et al.*, 2011). However, the performance of agriculture in Ghana is largely influenced by droughts and other types of variable weather which pose a risk to farmers. Under these conditions, irrigation development offers the promise of greater food security and the development of rural areas by ensuring year-long agricultural production (Namara *et al.*, 2011). It has, however, been noted that the performance and productivity of existing irrigation schemes are generally low (GIDA/JICA, 2004).

The construction of the Tono irrigation scheme (IS) by the Government of Ghana, started in 1975 and was completed 1985. The objectives were to improve production of food crops by small-scale farmers, enhance household incomes, food security, and standard of living in the communities. The irrigation scheme lies in the Guinea Savannah ecological zone of Ghana. It has a potential area of about 3840 ha with an irrigable area of about 2490 ha. The Tono Dam has a storage capacity of about 92.6 million cubic meters. Over the years, the scheme has engaged a lot of farmers within its catchment area and some farmers from other towns and villages in the Upper East Region. Recent figures show that more than 6,000 farmers are involved in irrigation farming within the catchment area (GSS, 2012). Nevertheless, this figure is below the number of farmers involved in the inception of the project. The main reason for the decrease in numbers is attributed to the low levels of the dam over time. There have been events of the dam levels falling below the minimum levels required for irrigation activities and the Irrigation Company of Upper Region (ICOUR) had to shut the release of water from the dam.

A November 2014 Ghana News Agency (GNA) Report which was attributed to the Director of the ICOUR, said at the time that, the company was going to shut down the outflow from the dam, with effect from 21st November 2014. The Ghana News Agency quoted him as saying that, "The irrigation dam was in its dead storage water level, which posed a threat to fishes in the dam". As at the time he was interviewed, the level of the Tono dam stood at 173.6m as against its maximum operating level of 179.2m above sea level. The shutting down of the dam was expected to affect over 6000 farmers. Thus, the usual dry season farming could not take place. Considering that the Upper East Region has a poor rainfall pattern, closing the dam would adversely affect food security and income levels of farmers in 8 communities in the Kassena-Nankana district.

The existence of the Tono dam over the past 30 years has made some gains, in terms of food security and improving the income of the farmers. However, the dam has also been faced with some challenges which include; the deterioration of the facilities, especially the canal systems and drains. The major challenges are low rainfall, high evaporation rate and sedimentation that have reduced the water holding capacity of the dam.

The justification for this research is the socio-economic importance (viz: livelihood and food security) of the Tono Irrigation scheme to the rural farmers. Knowing how sustainable the Tono irrigation scheme is, especially the effect of climate change on the dam levels, will inform the decisions to be made.

1.4 Research Questions

1. Does coupled atmospheric-hydrologic modeling improve climate and hydrological modeling of river basins?
2. Does the dam level variation affect agricultural irrigation?
3. Does climate change affect the sustainability of the Tono irrigation scheme?

1.5 Scope of Study

The study is designed to examine the hydrological dynamics and climate of a region with limited observational data. The approach was to examine the strength of a coupled atmospheric-hydrological model used in an operational way to support water resources studies and management. The focus was on the Tono basin in Ghana, West Africa, with observational data covering the period 2000 to 2007.

1.6 Limitations of Study

Inadequate observed hydrological (e.g. streamflow) data to verify the WRF-Hydro parameters calibrated is a limitation. Another limitation is the lack of streamflow gauges at the proposed streamflow stations to measure flows for a considerable length of time to allow further verification of WRF-Hydro model. The ability to run WRF-Hydro with RCPs forcing data sets to simulate future stream flows was yet another limitation. This could be due to numerical challenges in the WRF-Hydro model since there is no available study to suggest that such modeling approach has been used.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Water resources are a key to socio-economic empowerment for developing countries, especially for Ghana. However these resources recently are facing treat by way of flooding, drought, and low water levels or urban water shortage as well as water pollution. Particularly, the Tono dam, which is being used for irrigation activities, has in recent years been faced with flooding and low water levels (drought). This situation which is unpredictable in nature tend to affect downstream irrigation activities, hence affecting the socio-economic livelihoods of the rural communities. Water is a resource that has no substitute. Therefore, its limited reserves demand a thoughtful and sensible approach to its utilization. Often times we regard water as unlimited natural resources that could be used 'carelessly' because it is freely available through rainfall. However, this assertion does not hold any more in the face of climate variability and climate change.

Agricultural food production mainly based on rainfall is no more enough to meet the needs of growing population. Therefore water resources are mostly depended on to supplement food production. However these water resources apart from the impact of climate, is also under competition for various uses. Water resources managers will therefore need to find sustainable ways to manage these resources such that is available for irrigation and water supply in the face of these challenges. This therefore requires knowledge on the hydrological characteristics of the water resources and a tool to assess the sustainability of the resource.

The research work presented in this thesis includes developing a water balance model for assessing the variability of the Tono dam levels, hence the sustainability of the Tono IS in the face of climate change. The end product of the research is to provide a tool for water resources managers in planning and decision making regarding the water resource initially at the Tono Irrigation Scheme and eventually to adopt the tool for water resources managers in general. The review of works related to this study will start with a section on water resources availability; Global perspective, followed by water resources in WA, Water resources sustainability and management, climate change and its implication on water resources, water resources used for irrigation and its implication on climate, climate change impact assessment, numerical modeling of water resources and climate. All these feed into water resources strategy and sustainability of Tono irrigation scheme and will reflect in the results and discussions aspects of the study.

2.2 West African Climate Systems

West Africa (WA) lies within a range of climate zones. The position of the latitude and its influence on precipitation and temperature is one that can be noticed as the main geographic parameter in determining climate. In respect to rainfall distribution, WA can be categorized into five ecological zones (ENDA, 2007):

a. Saharan zone, mostly less than 150 mm of rainfall per year,
b. Sahelian zone (arid), average of 150-400 mm of rainfall per year,
c. Sudanese-Sahelian (semi-arid) zone, average annual rainfall in the range of 400-900 mm,
d. Sub-humid Sudanese zone, has an average annual rainfall of 600-900 mm and
e. Humid Sudanese-Guinean and Guinean zone, the annual average rainfall varies between 900-1500 mm, could be more in some places.

The distribution of rainfall is mostly associated with the Northward and -Southward migration of the Intertropical Convergence Zone (ITCZ). This is described as the region where the southern humid air mass meets the northern dry air mass. It has been shown that the movement of the

ITCZ is unsteady and that the Sahel rains are principally convective in their source (Taupin *et al.*, 2000).

2.2.1 Major air mass systems and rainfall variability

The climate system of West Africa is mainly influenced by two major air mass systems at low-level; the south-west maritime air called the monsoon and the north-east continental air. It has been established that interannual variability of WA rainfall is linked to changes in higher-level circulation features (Wang and Gillies, 2011). These large scale circulations are characterized by the African Easterly Jet (AEJ), the Tropical Easterly Jet (TEJ) [Grist and Nicholson, 2001; Nicholson and Grist, 2001), the African Easterly Waves (AEWs) [Thorncroft and Hodges, 2001; Grist, 2002) and the West African monsoon (Saha and Saha, 2001, 2002). Two other low-level westerly jets have been identified to be involved in the processes, the African Westerly Jet (AWJ) over the continent and the West African Westerly Jet (WAWJ) over the Atlantic (Pu and Cook, 2010, 2012; Nicholson, 2013). Studies conducted by Wang and Gillies (2011), suggested that the observed rainfall increase over the Sahal is accounted for by enhancements in both the Tropical Easterly Jet and the African Easterly Jet. They also stated that, positional shifts in the AEJ and the AEWs accompany the northward migration of the Sahel rainband. Some studies have also indicated that organized convective systems generate about 90% of the Sahel seasonal rainfall (Omotosho, 1985, Mathon *et al.*, 2002). Such convective systems are frequently initiated by AEWs, south of the AEJ (Reed *et al.*, 1988). It is also established that about 50% of the June-September rainfall in West Africa occurs under the influence of AEWs (Chen and Wang, 2007). Whereas the dry season is mainly influenced by the northeast trade winds known as Harmattan, the wet season is mainly influenced by the southwest monsoon, with the changing position of the Intertropical Discontinuity (ITD).

2.2.2 Precipitation types in West Africa

Different types of precipitation systems cause rainfall over West Africa. These systems are; organized mesoscale convective systems (MCSs), monsoon rains, and unorganized local thunderstorms or showers. The MCSs comprise squall line systems (SLs) [Rowell and Milford 1993, Fink *et al.*, 2006], organized convective systems (OCSs) [Mathon *et al.*, 2002], and mesoscale convective complexes (Laing *et al.*, 2008). A case study examined by Mathon *et al.*, (2002) in the southwest of Niger reveals that OCSs which appear to have similar characteristics to those of SLs produce about 90% of the estimated rainfall. In the semi-humid Sudanian climate zone, this fraction of rainfall produced by SL activity reduces to about 50% (Omotosho 1985, Fink *et al.*, 2006) and further decreases to between 16% and 32% at the Guinean coast (Omotosho 1985, Fink *et al.*, 2006). Along the coastal line in Ghana, 50% of the annual rainfall is related to monsoonal rains (Acheampong 1982). However the monsoon contributes about 40% to the annual rainfall total in the Sudanian zone of Nigeria. The major squall lines (SL) originate mostly over the highland of central Nigeria (e.g. Jos Plateau) (e.g. Omotosho, 1985) while the Dahomey Plains in Benin Republic is found to be a less-favorable zone for SL genesis (Aspliden *et al.*, 1976). These observations could be attributed to orographic effects (e.g. Jos Plateau); since it is generally assumed that enhanced diurnal heating and reduced convective inhibition (CIN) over the orography increase the likelihood of the release of potential instabilities (Barrett *et al.*, 2014). This mechanism may cause the strong organization and downstream development of OCSs originating over central Nigeria highland.

2.3 Water Resources Availability; Global Perspective

Water is the driving element for any living creature on earth. The industrialization of the world is also dependent on water. Basically our development on earth depends on water resources.

Unfortunately, this important resource (fresh water) is increasingly becoming less available (Shiklomanov, 1997; Gleick, 2004). This situation is considered by many to pose a major environmental threat of the 21^{st} century as described by UNESCO at the 1998 Pan's international conference on "World Water Resources at the beginning of the Twenty-first Century" (UNESCO, 1998). Climate change, increased population resulting in increase in water abstraction, land-use and water degradation due to industrial and agricultural pollution has resulted in water scarcity (UN, 2009). The earth's surface is covered with 70% of water, however only 3% of the earth's water is available as freshwater for human use, the remainder is salt water (WWAP, 2003). It is estimated that two thirds of this freshwater is "locked in glaciers and permanent snow cover" (WWAP, 2003). Accessibility of freshwater in lakes, rivers, aquifers and, man-made reservoirs (dams) also contribute about 70% of freshwater (WWAP, 2003).

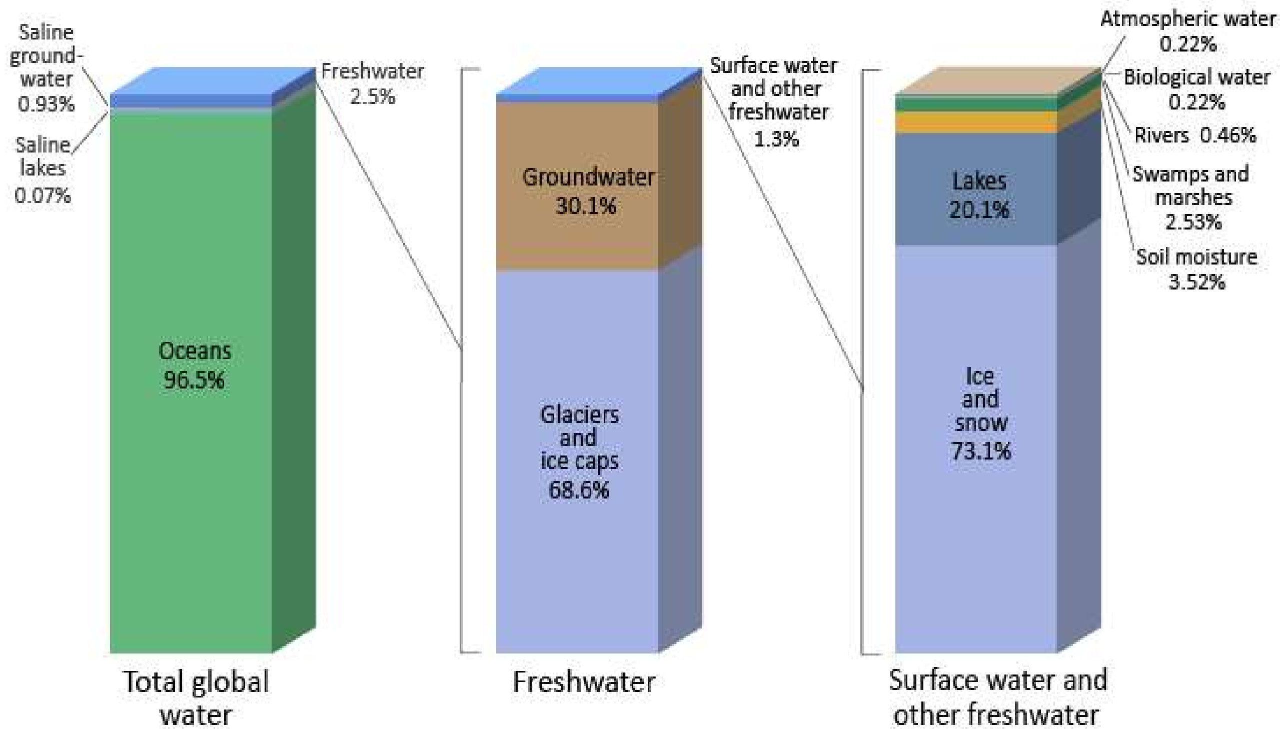

Figure 2.1 Distribution of earth freshwater

Source (Igor Shiklomanov's in Gleick, 1993)

2.3.1 Climate Change and Global Water Scarcity

Freshwater resources (especially surface water) are highly susceptible to variations in weather and climate. " The changes in global climate that are occurring due to accumulation of greenhouse gases in the atmosphere will affect patterns of freshwater availability and will affect the frequencies of floods and droughts" (IPCC, 2007; UN, 2009).

The precise impact of climate change on water resources is still uncertain (WWAP, 2003). It is noted that precipitation is likely to increase from latitudes 30^0 N to 30^0 S, but many tropical and sub-tropical regions will probably experience lower and more erratic rainfall. With an increasing trend towards more frequent extreme weather conditions, the chances are that, floods, droughts, mudslides, typhoons and cyclones will increase. Climate model simulations and other analysis suggest that, stream flows at low-flow periods are likely to decrease and water quality are certain to worsen, because of increased pollution loads and concentrations and higher water temperatures (WWAP, 2003; IPCC, 2007; Kundzewicz *et al.*, 2008). Recent estimates suggest that climate change will account for about 20% of the increase in global water scarcity. Growing interest on climate change and modelling has given better estimates of climate change impacts on water resources.

The threat of global water scarcity and pollution is not limited to human beings. In fact species in freshwater ecosystem are the most vulnerable of this threat (WWAP, 2003). It is further suggested that, half of the world wetlands have been destroyed in the last century due to conversion of wetlands to other uses, such as agriculture, industry, dams and canals. The sustainability of water resources is very important to address in the light of what has been discussed above. Since water spans every aspect of our human existence, addressing the crisis related with it, will help reduce poverty, hunger, water related illness and intrinsically improve education. Addressing sustainability ensures that the scarce resources are also available for future generations. The development and management of our water resources in a sustainable manner is therefore very critical going forward into the future.

2.3.2 Characteristics of West Africa water resources

The water resources of WA are comprised of surface water and sub-surface water (ground water). Surface flows are governed by local rainfall. The characteristics of these flows are influenced by local runoff and infiltration conditions which are determined by the state of surface soils. Areas with high rainfall (humid zones), usually have river levels rising; however during the dry season most of these rivers completely dry-out.

The WA region is transected by a number of rivers; viz:

1. The Niger River with its source in Guinea is within the Foutah Djallon range. It cuts across Mali, Niger and Nigeria and it is the most important shared river in WA, with a length of 4200 km.
2. The Volta River with a length of 1, 600 km, takes its source from Burkina Faso and cuts across, Togo, Benin, Ghana, Cote d'Ivoire and Mali.
3. The Senegal River also takes its source in Guinean Foutah Djallon mountain range and cuts across Mali, Mauritania, and Senegal, with a length of 1,800 km.
4. The Gambia River has a length of 1,120 km; it cuts across Senegal and Gambia.

Apart from these major river basins, there are several smaller rivers which are located in the coastal areas (Figure2.2). In WA these rivers play an important role in the socioeconomic activities (e.g. drinking water, power, irrigation, fishing) of the countries they cross (ENDA, 2007).

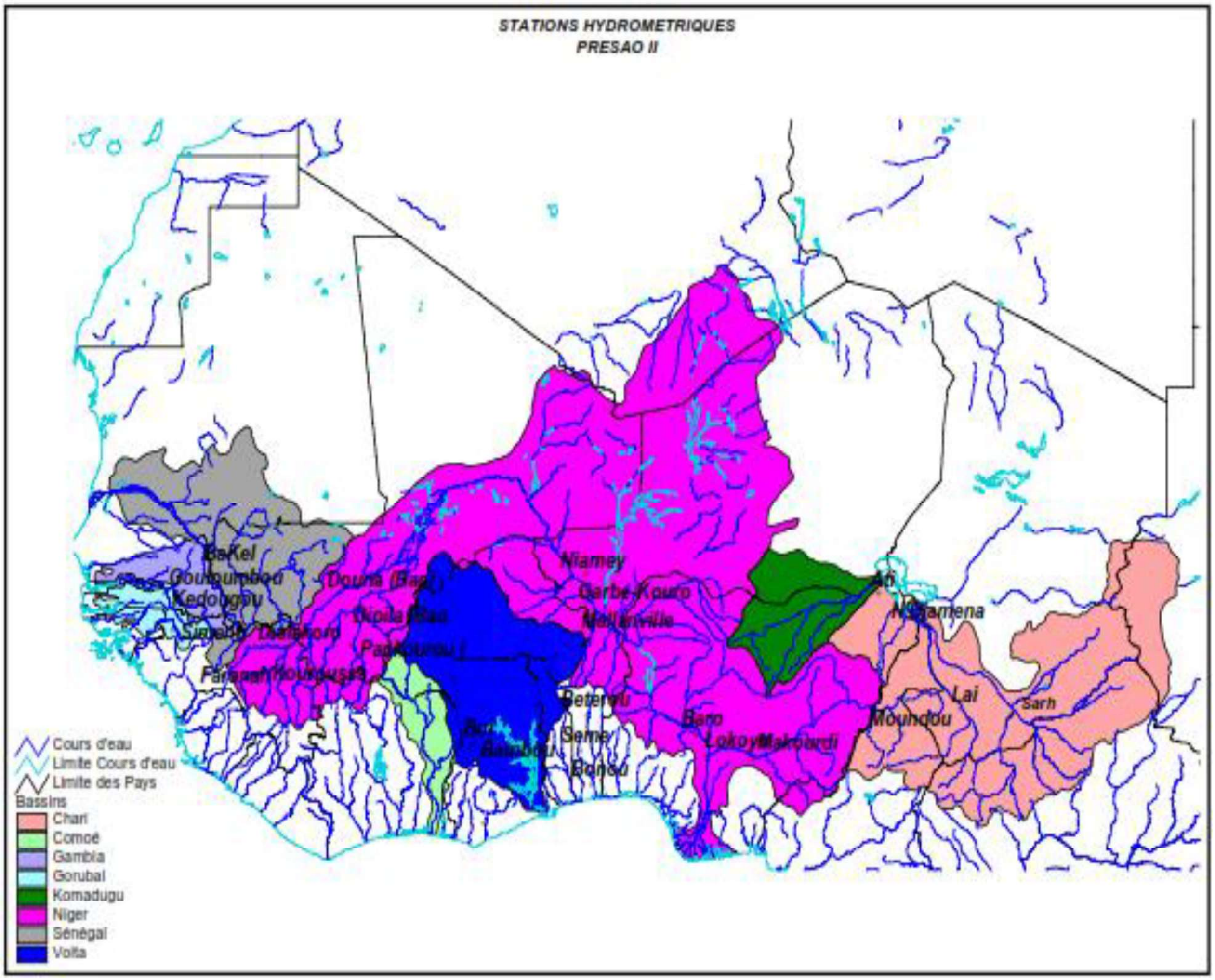

Figure 2.2 Main Rivers and hydrographic watersheds in the WA region

Source (AGRHYMET)

Subsurface water to a greater extent is governed by climate and geology. The water in this location is mostly found in sedimentary settings and also in crystalline rock. The availability of subsurface water depends on the storage capacity and the degree of recharge of the aquifers. The region contains several local hydro-geological basins and major cross-border aquifer systems (ENDA. 2007); viz:

a) Chad basin (Niger, Nigeria, Chad, Cameroon),
b) The Lullemeden basin (Niger, Nigeria, Mali, Algeria and Benin),
c) Taoudeni basin (Mauritania, Algeria, Mali, Burkina Faso).
d) Mourzouk-Djado basin (Niger, Algeria, Libya, and Chad)
e) Senegal-Mauritanian basin (Senegal, Mauritania, Gambia, Guinea-Bissau).

The geological basins are made up of groundwater where recharge rate is low relative to the volume.

2.3.3 Climate change impact on West Africa water resources

The effects of greenhouse gases on hydrological changes associated with rainfall are more speculative than temperature projections, especially at the regional and local geographic scales of interest to water planners (Kenneth, *et al.*, 1997). ENDA, (2007) indicates that in recent decades, the West African climate is that of one that has seen chronic large-scale upsets characterized by;

a) Rainfall shortages of the order of 20%, in some cases above 25% in humid climate areas and above 30% in areas noted to be drier climate.
b) Recurrent droughts due to the decline in rainfall, uncertainties in its distribution, resulting in decrease in river flows in the range of 20-60%.

The effect of these changes based on long-term hydrological observations by ENDA, (2007), indicates;

1. Changes in annual average river flows reflecting a drop in rainfall between 1968 and 1972.
2. Depletion of surface water resources in the major basins (from 40 to 60%); this is more severe than precipitation,
3. A drastic fall in water volumes cutting across the major rivers,
4. Increasingly severe low water-level situations with frequent cessations of flow in the rivers,
5. An increase in the runoff coefficient for the small basins,
6. A failure to fill most of the dam reservoirs during rainy seasons, with socioeconomic consequences,
7. Disturbances in hydroelectric dam operations due to flooding and low water situations,
8. A substantial depletion in the rate of recharge of major aquifers,
9. A drop in the water table and discharge coefficient, reducing the contribution of groundwater to the major rivers.

2.4 Global Climate Change Observations

The IPCC defines climate change, as change in climate over time, which could be attributed to natural variability or as a result of human activity (Traeger, 2009). The change must be statistically significant. The climate system is an interactive system, which is composed of 5 major components. These components are; the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere. Among these components, the atmosphere is regarded as the most unstable and rapidly changing part of the system (Le Treut *et al.* 2007).

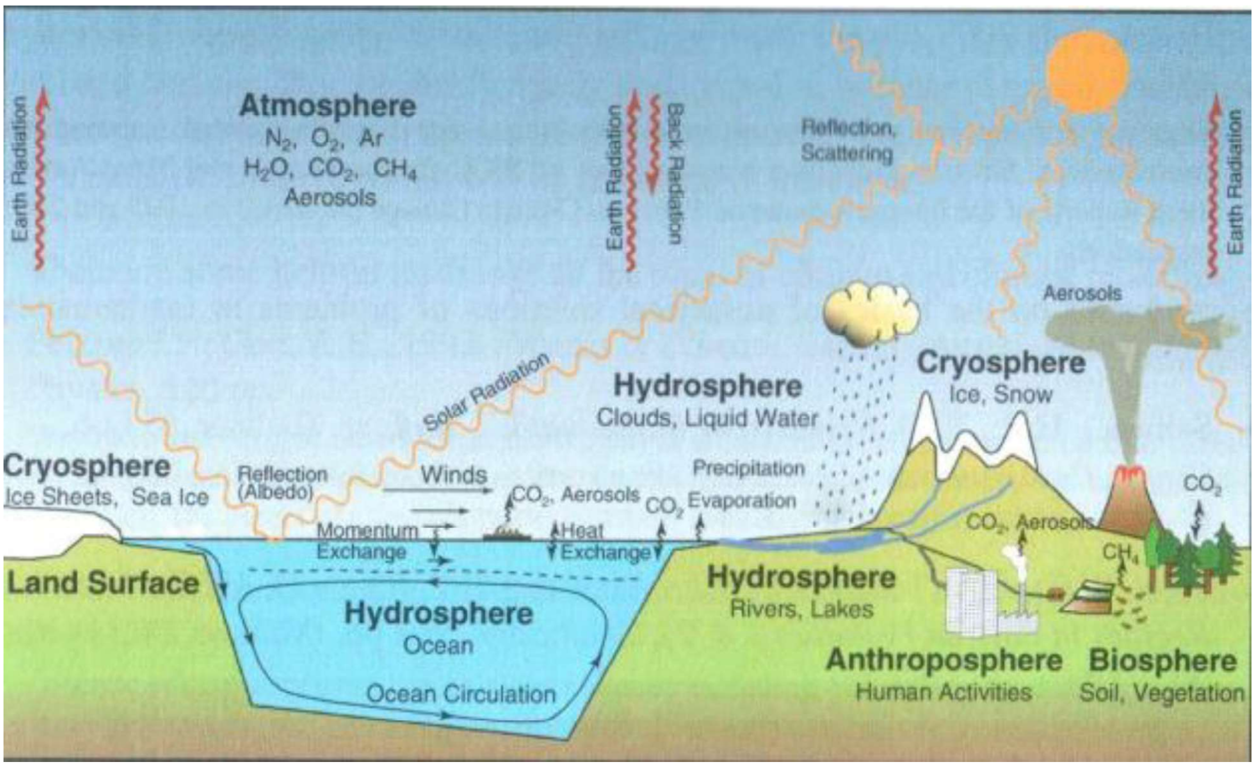

Figure 2.3 Interaction of components of the land, ocean, and atmosphere

Source: Stocker, (2011)

The extent of interactions or the behavior of the climate system is influenced by various external forcing mechanisms, such as anthropogenic (human) and non-anthropogenic (e.g. sun) activities. The most important linkage of the climate sub-systems is the hydrological cycle. This describes the energy and water fluxes between the atmosphere, biosphere and the land (figure 2.3).

The increase in (annual, seasonal or monthly) temperature is widespread over the globe and is more predominant in the northern latitudes as shown in Figure 2.4 and Figure 2.5. The increase over the period, 1961 to 1990 is twice the global average rate in the past 100 years. Temperature observations for the period 1970 to 2004 have indicated that land surfaces have warmed rapidly than the oceans (Figure 2.7). The IPCC, 2007 report shows that global average sea level rise has been increasing at a rate of 1.8mm per year with a range of 1.3 to 2.3mm per year over the period of 1961 to 2003 (IPCC, 2007). The rise in annual temperature by about 3 ^{0}C has resulted in a decline of mountain glaciers and snow cover in both hemispheres (see Figure 2.4 and figure 2.5).

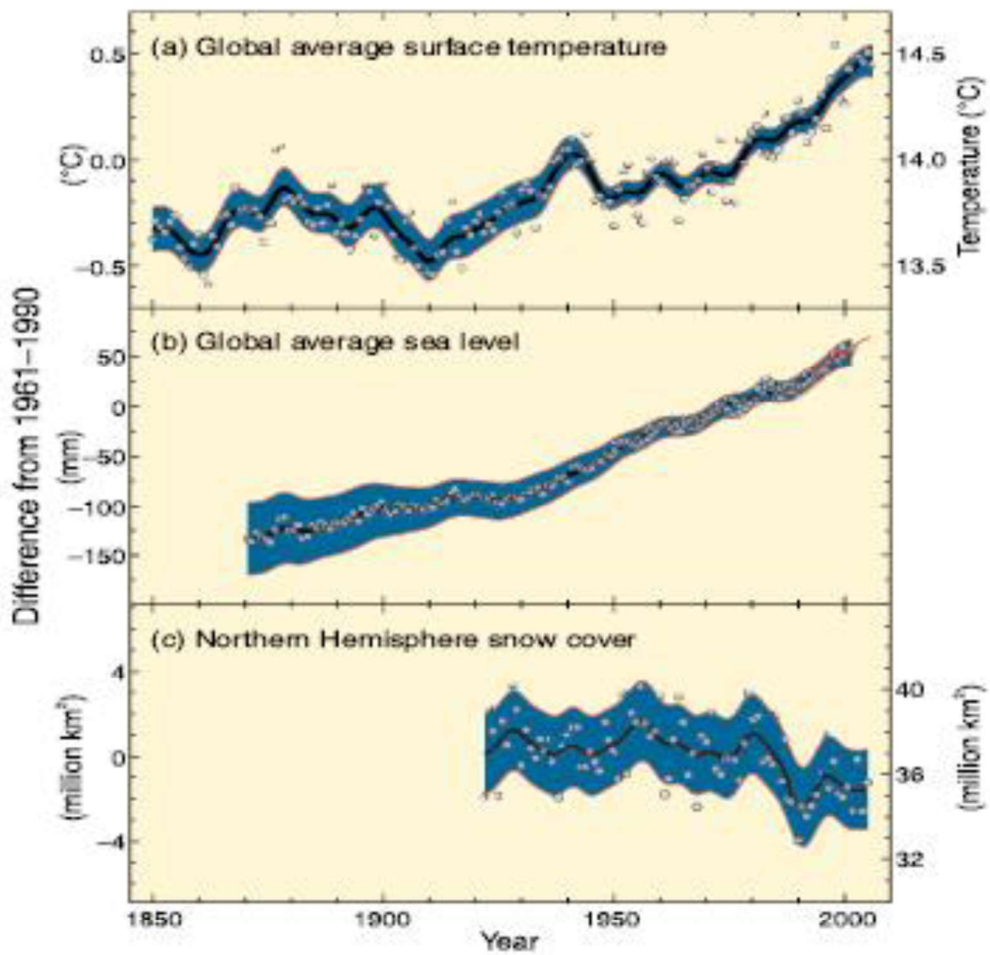

Figure 2.4 (a) Observed changes in annual global average surface temperature global average sea level (b) and (c) Northern hemisphere snow cover for March-April. Source: IPCC, (2007)

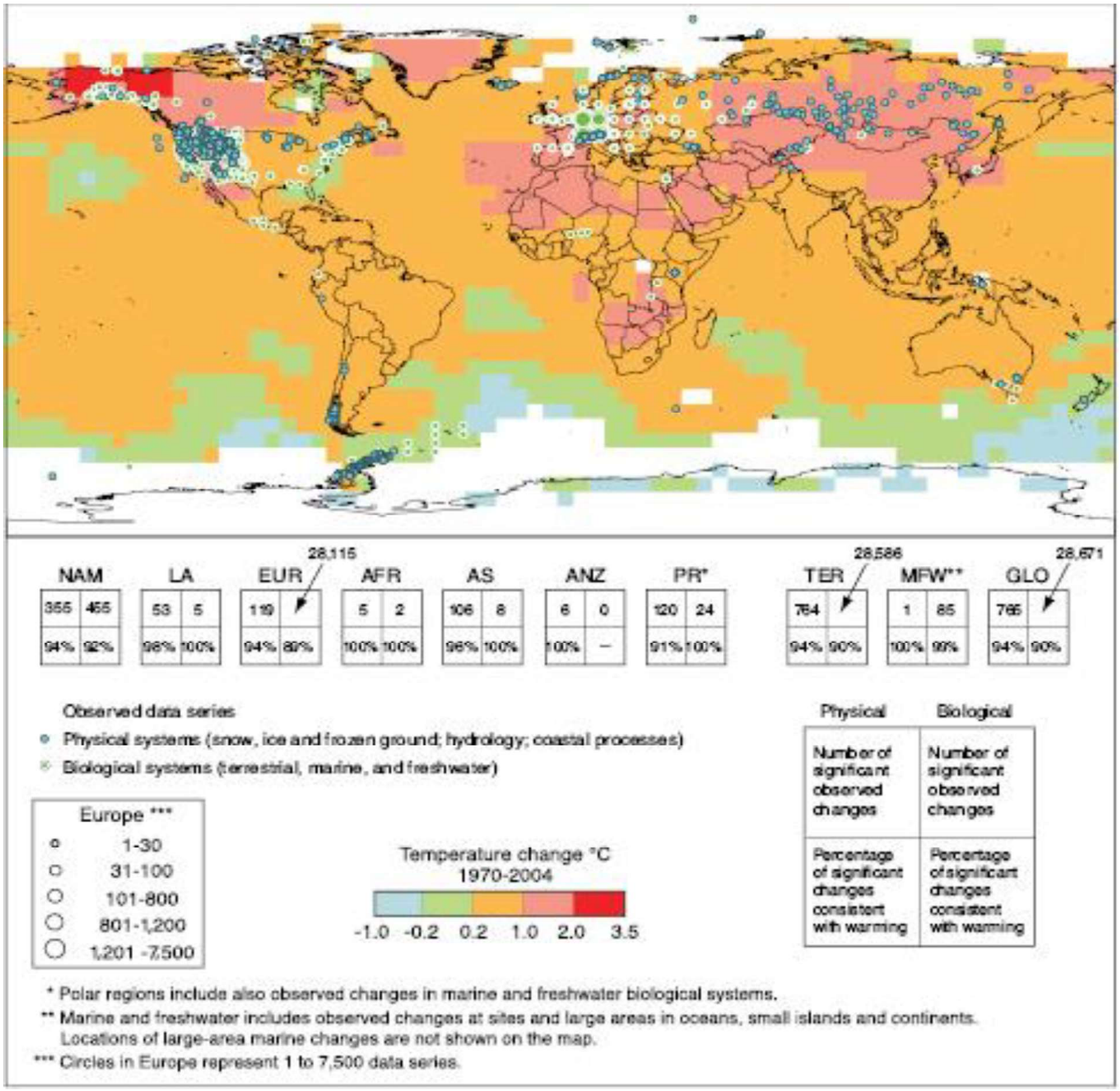

Figure 2.5 Changes in physical and biological systems and surface annual temperature, 1970-2004. Source: IPCC, (2007)

Regional observations have been focused on changes in precipitation amounts and patterns. It has been observed that, over the period 1900 to 2005 precipitation increased significantly in eastern parts of North and South America, Northern Europe and Northern and Central Asia, whereas in the Mediterranean, Sub-Saharan Africa, parts of Southern Asia experienced a decrease in precipitation (IPCC, 2007).

Ghana is already experiencing the effect of climate change; it is most predominant in the Northern part. The observed climate changes in Ghana are evident by the changes in the rainfall season, pattern and temperature. These changes are also observed in the frequency of droughts and floods as well as significant variations in the White Volta; rivers and dams who take their source from it (Jung *et al.*, 2012).

Drought situations have not been well documented. The changes in rainfall and temperature could have far reaching consequences on the water resources of Ghana, especially the Tono Dam from the indications of Figure 2.6 and Figure 2.7. Since the observations show a decreasing rainfall and increasing temperature, this will result in open water bodies decreasing in volume as a result of evaporation. This will consequently have an effect on the country's economy, since Ghana's economy is primarily driven by agriculture.

2.4.1 Causes of Climate Change

The earth's climate is influenced by a couple of factors which can be distinguished into natural (e.g. sun) and anthropogenic (human induced) factors (IPCC, 2001). Understanding the climate and the factors that influence it has generated a lot of scientific interest since the 20th century. Recent studies, shows more of anthropogenic influence on the climate. The changes in the concentrations of greenhouse gases (GHGs) in the atmosphere, aerosols, land-use change and solar radiation alter the energy balance of the climate system. These are the main causes of climate change (Le Trent *et al.*, 2007). The non-anthropogenic climate will vary due to variations in the earth's orbital characteristics, that are variations in the energy emitted by the sun, interaction between the ocean and atmosphere and volcanic eruptions (Le Trent *et al.* 2007). Anthropogenic activities are; burning of fossil fuels (e.g. coal, oils, and gas), forest destruction and agriculture (e.g. rice field cultivation and the rearing of livestock). These activities result in the emission of greenhouse gases (GHGs). The earth has a natural greenhouse effect where certain gases in the atmosphere allow the sunlight to enter but absorb the heat radiation (IPCC, 2014). As a result, these gases absorb the heat, while keeping the average surface temperature on earth around 14 ^{0}C. Without the natural greenhouse effect, the earth's average surface temperature could be around -19 ^{0}C (IPCC, 2014). Since the industrial age, human activity has increased the amount of greenhouse gases in the atmosphere. The increasing amount of gases which absorb heat, has directly resulted in more heat being retained in the atmosphere and consequently increase in global average surface temperatures (IPCC, 2014). The gases that make up the greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons (a group of gases made up of fluorine, chlorine or bromine) [IPCC, 2007]. Among these gases, carbon dioxide is the major component (Figure 2.6). The emission of carbon has increased by 80% between 1970 and 2004 from 21 to 38 Gt representing 77% of total GHG emission of 2004. The largest increase in GHG emissions between 1970 and 2004 has been contributed by energy supply, transport and industry, while waste and wastewater treatment, residential and commercial buildings, forestry (including deforestation) and agricultural sectors had rather seen a lower rate (Kumambala, 2010).

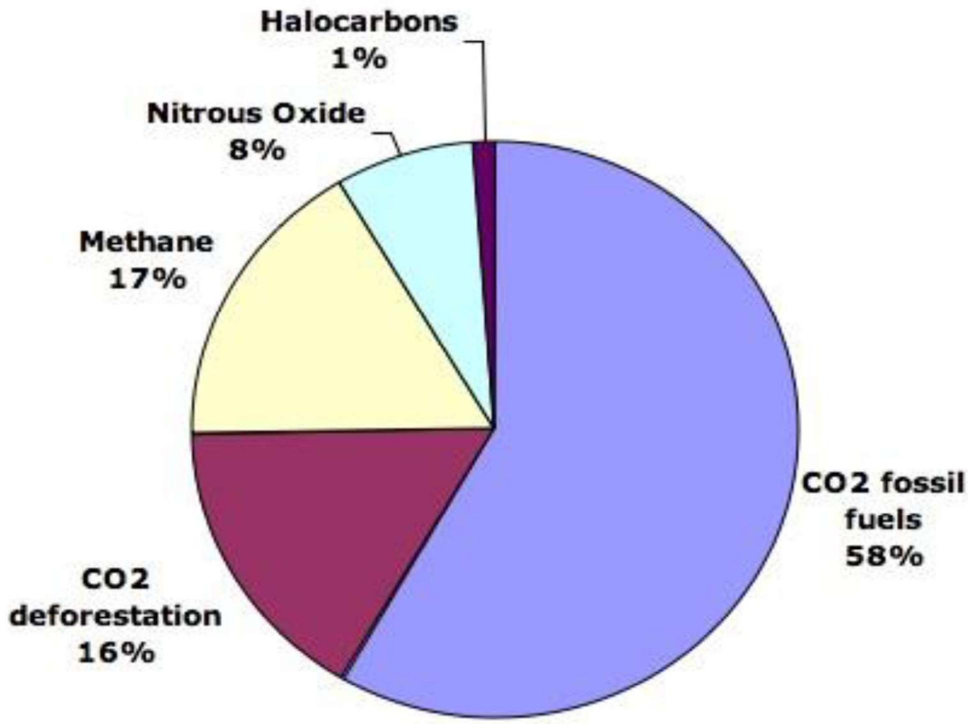

Figure 2.6 Major sources of greenhouse gases (GHG)

The buildup of greenhouse gases in the atmosphere absorbs the outgoing terrestrial energy, thus trapping it near the earth's surface, which results in increase in global average surface temperatures at a rate faster than the natural greenhouse effect. This faster change in temperature (i.e. enhanced greenhouse effect) is referred to as global warning. Scientific reports confirm an increase in annual average global temperature of 0.15 – 0.3 ^{0}C per decade as predicted by general circulation models (GCMs), as long as the concentrations of greenhouse gas continue to increase at the present rate (IPCC, 2007). This phenomenon will lead to an increase in precipitation in some regions while other regions will experience decreased precipitation. The phenomenon could also lead to the extinction of some species on the planet since they will not be able to cope with the changes (IPCC, 2007). Temperature and precipitation are thus the critical aspects for investigating the effect of climate change on the water resources.

2.4.2 Representative Concentration Pathways (RCPs)

Climate change scenarios are used in climate research to provide plausible explanation of how the future may evolve with respect to a number of variables including socioeconomic change, technological change, energy and land-use, and emissions of greenhouse gasses and air pollutants (Van Vuuren *et al.* 2011). These scenarios are used as inputs for climate model runs and as a basis for assessment of possible climate impacts and mitigation options and related costs. As time evolved in climate research, a lot of interest from different scientific communities has been expressed towards the need for;

a) more detailed information in running the current generation of climate models than that provided by previous scenarios sets.
b) scenarios that explicitly explore the impact of different policies in addition to the no-climate policy scenarios explored so far (e.g. SRES) [Moss *et al.*, 2010].

The need for new scenarios alerted the IPCC to request the scientific community to develop a new set of scenarios to facilitate future assessment of climate change (IPCC, 2007). The research community subsequently designed a process of three stages (Moss *et al.*, 2010):

1. Development of a scenario set containing emission, concentration and land-use trajectories, referred to as "representative concentration pathways" (RCPs).
2. A parallel development phase with climate model runs and development of new socio-economic scenarios,
3. A final integration and dissemination phase.

Based on design criteria and discussions at an IPCC meeting in 2007, four (4) RCP radiative forcing levels were selected (table 2.1), [Moss *et al.*, 2008].

The RCPs are named with respect to radiative forcing target level for 2100 (Van Vuuren *et al.,* 2011). The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents. The four RCPs selected were considered to be representative of existing scenarios. This includes one mitigation scenario leading to a very low forcing level (RCP2.6), two medium stabilization scenarios (RCP4.5/RCP6) and one very high baseline emission scenarios (RCP8.5). The first scenario (RCP2.6) has also been referred to as RCP3PD, a name that emphasizes the radiative forcing trajectory (First going to a peak forcing level of 3W/m^2 followed by a decline (PD = Peak-Decline), (Van Vuuren *et al.*, 2011). The RCP8.5 was developed using the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) model and the Integrated Assessment Framework by the International Institute for Applied System Analysis (IIASA), Austria (Van Vuuren *et al.* 2011).

Table 2.1 Overview of Representative Concentration Pathways (RCPs)

RCPs	Description*	Publication	IA Model
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100.	(Riahi *et al.*, 2007)-	MESSAGE
RCP6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization 2008) after 2100	(Fujino *et al.* 2006; Hijioka *et al.*	AIM
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100	(Clarke *et al.* 2007; Smith and Wigley 2006; Wise *et al.* 2009)-	GCAM
RCP2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100).	(Van Vuuren *et al.*, 2007a; Van Vuuren *et al.* 2006)	IMAGE

*Approximate radiative forcing levels were defined as ±5% of the stated level in W/m^2 relative to pre-industrial levels. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents

This RCP is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the previous studies that led to high greenhouse gas concentration levels (Riahi *et al.* 2007). The Asia-Pacific Integrated Model (AIM) group developed the RCP6 at the National Institute for Environmental Studies (NIES) in Japan. It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshoot, by reducing greenhouse gas emissions (Fujino *et al.* 2006; Hijioka *et al.* 2008). Whereas the RCP4.5 was developed by the Global Change Assessment Model (GCAM) modeling group at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) in the United States. It is a stabilization scenario in which total radiative forcing target level is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level (Clark *et al.* 2007; Smith and Wigley, 2006; Wise *et al.* 2009). The RCP2.6 was developed by the IMAGE modeling group of the PBL Netherlands Environmental Assessment Agency (Van Vuuren *et al.* 2011). The emission pathway is representative of scenarios in previous studies that resulted in very low greenhouse gas concentration levels.

The RCPs were selected from existing studies on the basis of their emissions and associated concentration levels (Van Vuuren *et al.* 2011). Therefore the socio-economic assumptions of the different modeling groups were based on individual model assumptions made within the context of the original publication, and that there is no consistent design behind the position of the different RCPs relative to each other for these parameters (Van Vuuren *et al.* 2011). The population and GDP pathways underlying the four RCPs are shown in Figure 2.7. The figure indicates, as reference, the UN population projections and the 90th percentile range of GDP scenarios in the literature on greenhouse gas emission scenarios. Figure 2.7 also indicates the RCPs to be consistent with these two references.

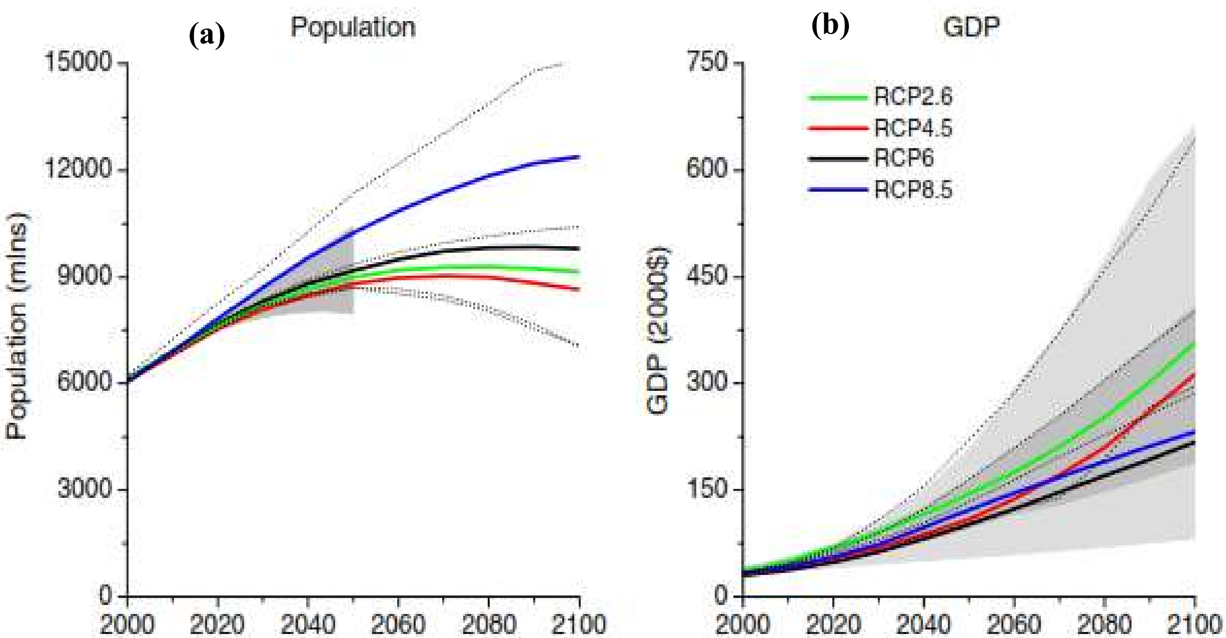

Figure 2.7 (a) Population and (b) GDP projections of the four scenarios underlying the RCPs. Source: Van Vuuren *et al.*, (2011)

However, with the exceptions of RCP8.5, the modeling groups deliberately made intermediate assumptions about the main driving forces (as illustrated by their position in Figure 2.7). In contrast, the RCP8.5 was based on a revised version of SRES A2 scenario; here the storyline emphasizes high population growth and lower incomes in developing countries (Van Vuuren *et al.* 2011).

In respect of energy use, the scenarios governing the RCPs are in line with previous studies, with RCP2.6, RCP4.5 and RCP6 again being representative of intermediate scenarios in literature (resulting in a primary energy use of 750 to 900 EJ in 2100, or about double the level of today). The RCP8.5, in contrast, is a highly energy-intensive scenario as a result of high population growth and a lower rate of technology development (Van Vuuren *et al.* 2011). With respect to the mix of energy carriers, there is a clear distinction across the RCPs given the influence of the climate target.

The future emission levels have been described by the Kaya Identity as a simple multiplicative function of population, income per capita, energy per unit of income (energy intensity) and emissions per unit of primary energy (Carbon factor), (Ehrlich, 1971, Kaya 1989) as illustrated in Figure 2.8. These factors are mostly used to provide insight into scenario trends. Figure 2.10 indicates all RCPs to be above average values in literature for energy intensity, which is attributed mostly to the inclusion of traditional fuels. Analysis done based on the Kaya factors indicates the influence of the radiative forcing targets, and indicates that the scenarios behind the RCPs cover the full range of possible values reasonably well (Van Vuuren *et al.* 2011). RCP2.6 achieves most of its emission reductions by reducing the carbon factor but is also the lowest scenario in terms of energy intensity.

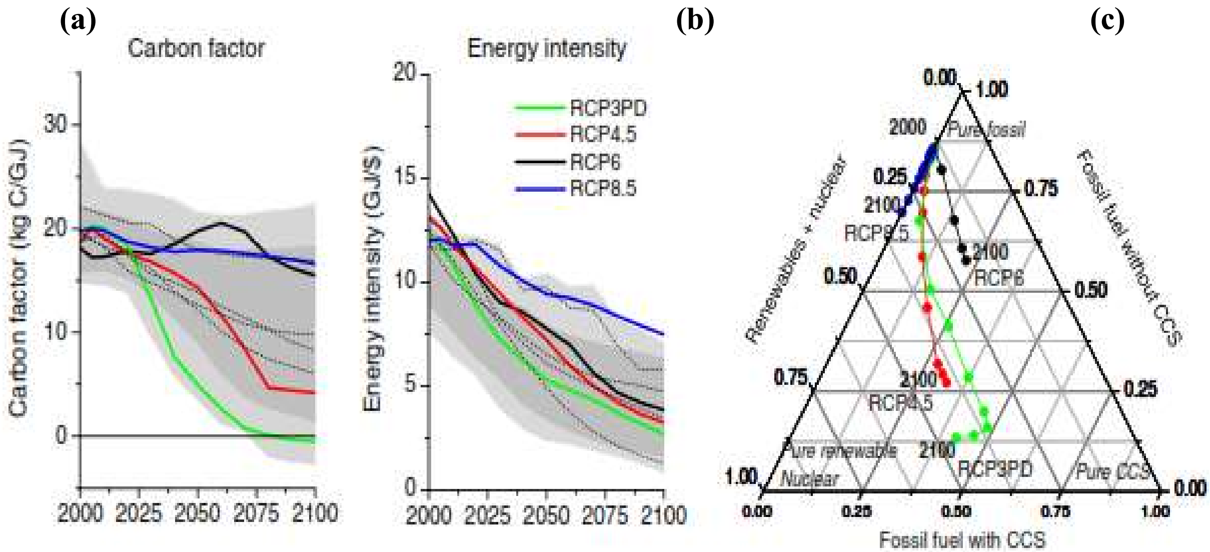

Figure 2.8 (a) Carbon and (b) energy intensities for the RCPs and (c) ternary graph representation of the fractions of different types of energy technologies
Source: Van Vuuren *et al.*, (2011)

RCP6 and RCP8.5 both show a rather constant trend for the carbon factor (heavy reliance on fossil fuel), but are very different in terms of development of energy intensity (high for RCP8.5 and intermediate for RCP6). However, RCP4.5 shows trends that are very similar to those in RCP2.6, but less extreme (Van Vuuren *et al.* 2011).

2.5 Water Resources for Irrigation and Implication on Climate

Irrigation is a human activity to improve crop production and quality and to decrease economic effects of drought. It is the artificial application of water to plants for their growth and maturity. Irrigation water is supplied to supplement the water available from rainfall and the contribution of soil moisture from groundwater. Irrigation is the most consumptive user of freshwater in the world (Kumambala, 2010). Due to increasing population, hence increasing demand for food, irrigated areas have increased rapidly over the last five decades, reaching its peak during 1970s and 1980s (Bhattarai *et al.*, 2007; Hussain, 2007). This has subsequently seen expansions of well over 160% (Sanmuganathan, 2000). A greater proportion of global irrigated cropland is in China and India with about 100 million hectares. This constitutes more than one third of the total irrigated land globally (Kumambala, 2010). The desire to support increasing irrigation activities led to the era of dam construction and development of new irrigation systems from 1950 to 1970 (Sanmuganathan, 2000). Irrigation activities require large volume of available freshwater in most countries where the activities occur. However, the irrigation agriculture sector is not without challenges in the face of increasing population growth, decreasing availability of land, and competition for freshwater demand from domestic, industrial, navigational and recreational uses (Ambast *et al.*, 2002; Hussain, 2007) and also decreasing runoff volumes due to climate change effect. This implies that the world's share of water in the irrigation sector is bound to reduce significantly; hence the need to develop sustainable policies in the management of water resources to satisfy all the competing areas.

2.5.1 Prospects of Irrigation

A reliable and sustainable irrigation water supply can result in vast improvements in agricultural production and assure the economic viability of a country. The benefits of irrigation are both direct (accrued to the farming community) and indirect (accrued to wider sectors of the economy) [Bhattarai *et al.* 2007; Hussain, 2007].

The benefits accruing to the farmer are derived from increases in crop yield, increase in cropping pattern and reduction in vulnerability to the seasonality of agriculture production and external shocks (Hussain and Hanjra, 2004). Crop production under irrigation is substantially higher than that of the same crops under rain fed conditions, increasing returns to farmers. Irrigation farming makes food available and affordable for the poor. It also enables crop-switching; selecting high yielding and more profitable crops which are also tolerant to drought. This implies a shift from subsistence farming to commercial production. Irrigation provides opportunity for all-year-round farming, which enables the farmer to spread risk more evenly over the course of the year (Hussain and Hanjra, 2004). The opportunity to diversify crop production assures income minimization and risk minimization (Hussain, 2007).

2.5.2 Disadvantages of Irrigation

In spite of the enormous contribution of irrigated agriculture to increasing food production and overall socio-economic development, irrigation has come under increasing criticism over the past decade; for concerns regarding social disruptions and environmental changes that are attributed to irrigation development and reservoir construction (FAO, 1997).

Large-scale irrigation development, which involves dam construction often, results in displacing people from the reservoir area. The extent of impact depends on the size of dam construction and the population density of the affected community. Often displacement exercise do not involve the local community in decision making processes of the people who actually will be displaced when running the irrigation scheme (IS) (Kumambala, 2010). A call is always made for the compensation and resettlement of communities affected by the construction of large-scale IS (Magadza, 2006). Irrigation activities come along with some health risk implications. Applying water to drier areas creates favorable environment for vectors and pathogens responsible for the transmission of water borne, and water based insect vector diseases such as malaria, cholera, schistosomiasis and diarrheas. There has been debates about the environmental impacts of developing large or smaller scale IS (FAO, 1997). One school of thought suggest that constructing larger scale IS will increase food production thereby meeting the demand of rapidly growing population (Bhattarai, *et al.*, 2007; Hussain, 2007) while the other school of thought advocates for smaller scale IS to reduce its negative effects on the environment and also reallocating more water for environmental needs (Kumambala, 2010). The environmental impact resulting from irrigation includes; land degradation in the form of water logging and soil salinization and degradation of water quality (Allen, 1998).

Irrigation can adversely impact quality of downstream water due to excessive use of water and pollution upstream from fertilizer application and agricultural chemicals (FAO, 1997). This could lead to loss of biodiversity and altering the natural environment downstream, resulting in adverse impact on the livelihoods of communities that drive a range of benefits from the river system downstream.

2.5.3 Irrigation Perspective in Ghana

Agriculture in Ghana accounts for about 37.4% of the gross domestic product (GDP) and provides employment to about 56% of the total economically active population. It is predominantly practiced in small holder, family-operated farms, which produce about 80% of Ghana's total agriculture output (Namara, *et al.* 2010). About 38.9% of the total agricultural land area is currently cultivated.

Ghana has adequate water resources, particularly given the country's current demographic situation. The country receives an average annual precipitation of 283.2 billion cubic meters (BCM). The total actual renewable water resources are 53.2 BCM per year, 43% of which originates outside of Ghana's international borders (Namara, *et al.* 2010).

The development of irrigation in Ghana can be traced to a little over a century ago (Smith, 1969). However to some extent the practice dates back to as early as 1880 in the Keta area on land above flood level between the lagoon and the sandbar separating it from the sea. The attention and development of irrigation by the government of Ghana has been a recent phenomenon, though some forms of irrigation existed a century ago. Agodzo and Bobobee, 1994, estimated Ghana's irrigation potential to range from 0.36 to1.9 million hectares (Mha). Valley bottoms and flood plains could add about 1.0 Mha to the irrigation potential.

The major crops grown under irrigation are; rice and vegetables such as tomatoes, okra, and exotic vegetables (cabbage & spring onions). The cultivated rice area under formal irrigation is about 40% of the total area, with vegetables making up the rest of the area. In most cases peri-urban is devoted to exotic vegetables.

Irrigation systems practiced in Ghana can be categorized into two groups based on their level of formalization. These are; the conventional systems, which are mainly initiated and developed by the government of Ghana or NGOs and the emerging systems (Namara, *et al.* 2010). The conventional systems are solely to meet a number of objectives including the attainment of food security, domestic water supply, livestock watering, etc. The emerging systems are mostly developed by individuals or groups of entrepreneurs and farmers, either autonomously or with little support from the government and/or NGOs (Namara, *et al.* 2010).

2.5.3.1 Conventional Irrigation Systems

Surface irrigation system is one of the major conventional irrigation systems. There are twenty-two (22) of such irrigation facilities practiced in Ghana. This form of irrigation can further be categorized depending on the source of water. Rivers (e.g irrigation activities along the White Volta), Lakes (e.g. irrigation activities at the Volta Lake) and dams (e.g. Tono irrigation scheme) are the sources of water for this form of irrigation.

The Tono irrigation scheme is categorized as a reservoir or storage-based gravity-fed irrigation system (plate. 2.1). This system of irrigation is developed by impounding river flows with the construction of Earth dam and formation of a reservoir. The impounded water is diverted to the fields by gravity through intake structures and canal systems. This form of irrigation is widely practiced in Northern Ghana. It is considered to be less expensive to construct, requires less skills and knowledge for farmers to apply compared to other modern forms of irrigation (e.g. sprinkler and drip). However the challenge with this form of irrigation is the high rate of evaporation leading to loss (low level) of water in the reservoir, hence less water available for extensive irrigation.

Plate 2.1: Tono irrigation scheme as an example of the surface irrigation by gravity-fed

2.5.3.2 Emerging Irrigation System

This category of irrigation has become prominent as a result of low level of surface water bodies. Thus, farmers seek to maximize other sources of water and efficiently utilize surface water bodies for irrigation. There are a number of sub irrigation systems under this category practiced in Ghana. Shallow groundwater irrigation is one of the major irrigation systems practiced under this category (plate. 2.2). It has been identified as one of the old tradition of irrigation systems, first practiced in the Keta strip and is increasingly becoming significant in the White Volta Basin at the Upper East Region (Namara, *et al.* 2010).

Plate 2.2: (a), (c) Shallow wells, (b) hand pump irrigation and (d) lined permanent shallow well in the upper east region
Source: Gumma, (2007); Van den Berg, (2008); Namara, *et al* (2010)

2.5.4 Irrigation Impact on West African Monsoon (WAM)

The potential impact of irrigation activities on the West African Monsoon (WAM) has been demonstrated by some recent studies (Marcella and Eltahir, 2013). Irrigation influences the soil moisture dynamics and its related effects could force significant changes in spatial distribution and magnitude of rainfall, depending on the latitudinal location of irrigation (Sorooshian, *et al.* 2011; Marcella and Eltahir, 2013). The variations in the wetness of the soil due to irrigation, leads to induced surface cooling. This cooling turns to suppress moist convection and rainfall, which in turn induces local subsidence and low-level anticyclonic circulation. These localized effects are dominated by a consistent reduction of local rainfall over the irrigation area, irrespective of its latitudinal location (Mercella and Eltahir, 2013). In the case of remote response of rainfall distribution to irrigation, it has been shown to exhibit a significant sensitivity to the latitudinal position of irrigation and the intra seasonal variation of supplied irrigation water. The northeasterly low-level airflow associated with an anticyclonic circulation positioned over the irrigated area, induced at optimal location and timing would influence the extent of low-level convergence areas, through interaction with the monsoon flow, which will lead to a significant increase in rainfall. Marcella and Eltahir, 2013, showed that, as the location of the irrigation area is moved from the coast northward, the regional rainfall change exhibits a significant decrease first, and then increases gradually to a maximum corresponding to irrigation centered around 20^0 N, before it declines again.

2.6 Climate Change Impact Assessment on Water Resources

2.6.1 Modelling Climate Change Impact on Water Resources

The earth's climate system is too large to allow controlled experiments. Therefore, it has become imperative for climate scientists to employ mathematical models, known as global climate models (GCM), to examine the processes known to occur and their possible interactions (Lazar, 2011). The models are used for estimation of climate parameters such as temperature, precipitation, cloud cover and relative humidity due to climate change for different emission scenarios (Kumambala, 2010). The results from the GCMs are not definite but still tentative and should not be accepted uncritically. Global Climate Models are numerical models representing physical processes in the atmosphere, ocean, cryosphere and land surface to simulate the response of the global climate system to increasing greenhouse gas concentrations (IPCC, 2007). This response is further assessed with Regional Climate Models (RCM) which are forced using boundary conditions generated by GCMs to consider impacts of climate forcing at the regional scale in relation to orography, large water bodies, ocean dynamics, ice and snow masses (Lazar, 2011).

The main problem associated with outputs from GCMs is that, they are too coarse in spatial resolution (about 0.5^0 x 0.5^0), thus are inadequate in assessing land surface impacts. It is therefore not sufficient to depend on GCMs for predicting the effect of climate change on river basins (Wilby and Dawson, 2007; Fujihara *et al.* 2008).

Improvement in technology has resulted in the development of high-speed computers in recent years for climate modeling. This has led to an increase in model complexity by including more climate components and high spatial resolution GCM data in model simulation of future climate.

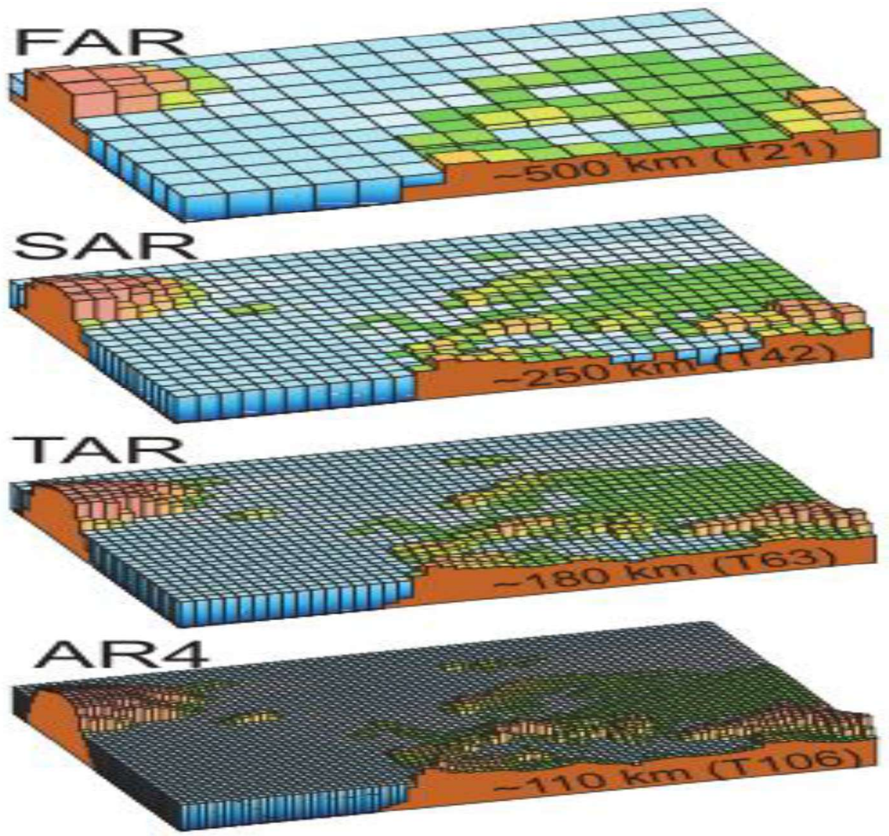

Figure 2.9 Spatial resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001a), and AR4 (2007). Adopted from Le Treut *et al.* 2007

These models have evolved in spatial resolution ranging from 500km grid size to 110km (Le Trent *et al.* 2007), as shown in Figure 2.9.

As a result of the coarse resolution of GCM outputs, downscaling methods are employed to associate GCM results to a particular catchment (Smiatek, *et al.*, 2012; Berg *et al.*, 2012).

2.6.2 Climate Downscaling

There have been enormous interest in understanding past, present, and future climate change and variability. The response and feedbacks from natural resources (including managed ecosystems) has generated the desire for the development and application of models and techniques that will provide climate data at the required spatial and temporal scales. Geologic records also provide an indirect assessment of climate changes in the past. Future estimates and assessment of climate, requires the development of climate models that will take into account the interactive changes in the global atmosphere and oceans which are driven by global boundary conditions, such as atmospheric trace-gas concentrations and aerosols, earth-sun geometry, sea ice, sea level, and continental ice sheets. Global climate simulations are conducted with general circulation models (GCMs). These models are designed to give a good representation of model resolution and physics with computation requirements and limitations. The limitations of GCMs are related to the output data from these models not been able to serve the needs for example of hydrologic models that require watershed-scale information. This is because GCMs are used for predicting future climate at grid space of hundreds of kilometers. The major objective of climate downscaling is to produce high-horizontal-resolution information about climates (Maraun, *et al.* 2010; Warner, 2011). Current climate downscaling uses global gridded data sets that are produced by the global-model-based data assimilation systems. In other to downscale both present and future climates two basic approaches have been identified. One approach is to use statistical (empirical) relationships that define the high resolution subgrid-scale variability based on resolved, grid-scale, using values from the global data set (Moriondo and Buidi, 2006; Kilsby *et al.* 2007; Kumambala, 2010; Warner, 2011). This approach is mostly referred to as statistical downscaling. The second approach uses regional climate models (RCM) whose boundary conditions are forced by the global data set or stretched-grid AGCM. This approach is referred to as dynamical downscaling. The dynamical downscaling is described by various methods, which include;

a) Limited-area-models (RCM), which are usually located over the a geographical region of interest and long simulations are produced by defining the local boundary conditions with output from an AOGCM or with a global analyses (Jiang *et al.* 2008). The nesting technique provides a high level of fidelity between the synoptic-scale GCM fields and the associated mesoscale resolution fields simulated by the RCM.

b) Global stretched-grid AGCMs, that uses enhanced horizontal resolution over a geographical region of interest, and is run for climate time scales. This application is able to bring out detailed information at spatial scales of 10- 20km at temporal scales of hours or less (Lorant and Royer 2001; Boé *et al.*, 2007).

As with the use of high resolution land surface atmospheric models for weather prediction, the benefits of the resolution for climate prediction are attributable to (1) the better representation of fine-scale local forcing such as from orographic or other landscape variability, (2) the ability to explicitly represent processes rather than parameterize them, (3) the nonlinear interactions permitted among a more-complete spectrum of waves and (4) greater compatibility between the model's vertical and horizontal resolutions. The challenge however with this kind of model is that, it is computationally demanding and expensive.

2.6.3 Models in Water Resources Assessment

2.6.3.1 Long-term Water Balance Models

The old approach in assessing water resources was based on the long-term average water balance equation over a basin in a form of

$$P = AE + Q \qquad (2.1)$$

Where P, AE, Q represent the long-term average annual precipitation, evapotranspiration and discharge respectively. To determine the available water resources, Q, from equation (2.1), the terms P, and AE, must be known. Areal precipitation is computed from a point measurement. The critical component or parameter in the long-term water balance of a large catchment or region is the value of the actual long-term evapotranspiration (AE). The linkage between actual evapotranspiration to precipitation and potential evapotranspiration were made in the early years of the last century on the basis of available measurements of catchment rainfall and runoff (Xu, 2002). The basic assumption applied in the mathematical relationship suggested for the long-term water balance of catchments is that, the ratio of actual to potential evapotranspiration may be expressed as a function of the ratio of precipitation (P) to potential evapotranspiration (PE). References to this formula include Schreiber (1904) and Dooge (1992);

$$\frac{AE}{PE} = \frac{P}{PE}\left[1 - exp\left(-\frac{PE}{P}\right)\right] \qquad (2.2)$$

Where AE is the actual evapotranspiration, PE is the potential evapotranspiration and P is the precipitation.

This was formulated on the basis of measured precipitation and runoff in a number of catchments in Europe (Xu, 2002). Ol'dekop (1911) suggested that;

$$\frac{AE}{PE} = tanh\left(\frac{P}{PE}\right) \qquad (2.3)$$

based on measurements carried out in Russia. A simple formula for the African catchment was proposed by Turc (1954) based on measurements. However, his approach was later modified by Pike (1964) on the basis of further measurements;

$$\frac{AE}{PE} = \frac{P/PE}{\sqrt{1 + (P/PE)^2}} \qquad (2.4)$$

The longer-term water balance approach for estimating water resources (e.g. river discharge) from meteorological data, though simplistic, has some inherent disadvantages. The approach does not give a time account of runoff estimation in arid and semi-arid regions. The other disadvantage is that it is impossible to estimate river discharge for seasons and months. These data are very important for modern planning of water resources management. The third limitation of this approach is that, it is incapable of estimating hydrological variables (e.g. river discharge, changes in storage) of the countries and regions located in the basins of international rivers.

2.6.3.2 Monthly Water Balance Models

Hydrologist and Agricultural Engineers have used simple water balance models that simulate hydrographs of streamflow based on available meteorological data and few physically relevant parameters in the assessment of regional water resources (Xu, 2002). These models were initially developed by Thornthwaite (1948), but have since been adopted, modified and applied to a wide range of hydrological problems (e.g. Kebede *et al.* 2006; Kumambala, 2010). The basic structure of all water balance models is similar and developing such models involves writing equations that relate the rates of change of water properties within the control volume to flow of those properties across the control surface (Xu, 2002). An expression of a simple soil water balance model for a control volume taken from a block of topsoil is given as:

$$S_{(t+1)} = S_{(t)} + P_{(t)} - AE_{(t)} - Q_{(t)} \quad (2.5)$$

Where $S_{(t)}$ represents the amount of soil moisture stored at the time t, i.e. at the start of the month, $S_{(t+1)}$ is the storage at the next month (time), t+1. The flow across the control surface during the interval [t, t+1], i.e. with respect to the month considered, consists of precipitation P(t), actual evapotranspiration, AE(t) and soil moisture surplus, Q(t), which supplies streamflow and groundwater recharge. Solving this equation requires dealing with time series of the four variables; S, P, AE, Q and some other related variables. The application of the water balance models differs in how AE and Q are conceptually considered and mathematically expressed. However, the monthly water balance model has limitations and as such its inability to adequately account for possible changes in individual storm runoff characteristics at the time steps they are applied (Xu, 2002).

2.7 Numerical Modeling of Water Resources and Climate

2.7.1 Coupled Atmospheric Models and Hydrological Models

Assessments of numerical weather prediction (NWP) models are based on variables that influence decision-making. However these meteorological variables do consequently influence other physical processes that also must be simulated before a weather-dependent decision can be made. Models that are coupled with atmospheric models are either referred to as special-applications models or secondary models. An example is River-discharge or flood models (Hydrological) used in this study.

In some situations, the secondary models are either embedded within the code of the atmospheric model or their coupling system is run concurrently. It is also possible in some cases that the models are run in 'offline' or uncoupled mode. When the secondary model is run with the atmospheric model, there may be an interaction between the secondary processes with the atmospheric simulation. The other situation will be a flow of data in one direction, where the atmospheric variables are used as input (forcing) data in the secondary model without feedback. However this is not the same for all secondary models, as some have storage feedbacks to the atmosphere; therefore there is the need to have a two-way exchange of information between the atmospheric and secondary models (Warner, 2011). The applications of these coupled models are on time scales of daily weather prediction, seasonal prediction, and multi-decadal climate prediction. The end product of coupling secondary models with atmospheric models is to provide information that can be used to make practical decisions, thus the output from the secondary model is often used an input to a formal Decision-Support Systems (DSSs). This DSSs processes data from the secondary model, and perhaps the driving atmospheric model, for the end-user to take decision on, whether to take an action to protect say a dam from reaching dead storage, or to evacuate a town that is threatened by flooding. This sequence of model software components is summarized in fig 2.10 (modified from Warner, 2011).

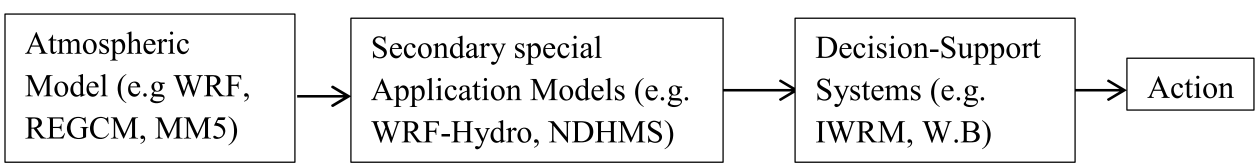

Figure 2.10 Sequence of model software components that are involved in providing the basis for a decision (action) that is weather dependent

The first step is to verify whether the coupling of the secondary model with atmospheric models generates the right values of the variables with respect to meteorological observations. The second step involves the use of historical cases to assess the accuracy of the model but the fully coupled model would be used to produce a forecast of the secondary variable. This would be compared with forecast from the secondary model that used meteorological input from observations or reanalysis (Warner, 2011). The third verification approach is that the coupled model is used for a retrospective forecast, but the forecast secondary variable is compared with observations.

2.7.2 Weather Research and Forecasting Model (WRF)

WRF model is a non-hydrostatic model (Skamarock, *et al.*, 2008). It is suitable for simulating a wide range of scales, from thousands of kilometers to a few meters. The model has a number of available options which relates to the model core and most physical parameterizations. This makes the model appropriate for a broad range of applications including: Idealized simulations (e.g. LES, Convective, baraclinic waves), Parameterization research, Data assimilation research, Forecast research, Real-time Numerical Weather Prediction (NWP), Regional climate research, Couple model applications.

The WRF modeling system consists of the following program; WRF Preprocessing System (WPS), WRF-DA, ARW Solver, Post-processing and Visualization tools, details of these components are presented in the WRF User guide V3.5 (Skamrock, *et al.*, 2008).

2.7.3 WRF Model Parameterization

Schwarz *et al.*, (2009), defined models as representations that explain and predict a natural phenomenon. In respect to atmospheric studies, accuracy of the model is directly related to how well it represents atmospheric processes and these processes can be adjusted by choosing the best parameterization schemes with respect to a research question. The choice of parameterizations scheme influence the outcome of the model simulations.

Parameterization options are in categories and mathematical formulae (derived from theoretical understanding of atmospheric processes) are used to calculate values of variables of interest. These schemes have been summarized into the categories of land surface, atmosphere interaction, water-atmosphere interaction, planetary boundary layer and turbulence, convection, microphysics and radiation (Stensrud, 2007). The WRF model consists of similar physical parameterizations that make it adaptable. Physical parameterizations are subroutines used to represent physical processes on scales too small or too complex to be represented physically in the model. The performance of any physics scheme depends largely on the main feature of atmospheric processes in the domain of interest, the model resolution and the appropriate choice of parameterization for the particular problem (Klein *et al.*, 2015).

2.7.4 Review of Hydrological Model Applied for Water Resources Assessment

This study applied the WRF-Hydro model to assess the water resources of the Tono basin. The WRF-Hydro model has been developed as a coupling extension module that provides an opportunity to couple hydrological components to atmospheric models and other Earth system modeling architecture (Gochis *et al.* 2013). Hitherto most hydrological models exit as standalone models. The underlying land surface model upon which the hydrological model is built is made up of a fully distributed, 3-dimensional, variably-saturated surface and sub-surface flow model previously referred to as 'Noah-distributed'. Terrain routing was the only routing function implemented in the Noah land surface model, however subsequently, channel and reservoir routing functions were added into the 1-dimensional Noah land surface model so as to account for the increased complexity in land surface states and fluxes and to provide physically-consistent land surface flux and stream channel discharge information for hydrometeorological applications (Gochis *et al.* 2013).

Gochis and Chan (2003) described the implementation of surface overland flow and subsurface saturated flow modules into the Noah land surface module. They employed a simple subgrid disaggregation procedure as a means of mapping land surface hydrological conditions from a coarsely resolved land surface model grid to a much more finely resolved terrain routing grid capable of adequately resolving the dominant local landscape gradient features responsible for gravitational redistribution of terrestrial moisture. The Noah-distributed model has been improved to include optional selection for 2-dimensional (in x and y) or 1-dimensional ('steepest descent' methodologies) terrain routing, a reservoir routing model, 2-reach based hydrologic channel routing models and a simple empirical baseflow estimation routine. The development of this hydrological land surface model is what is now referred to as the NCAR WRF-Hydro hydrological modeling extension package either fully coupled with WRF or used as a standalone ('uncoupled' or 'offline'). This provides the opportunity for a physics-based, fully coupled land surface hydrological regional atmospheric modeling capability for use in hydrometeorological and hydroclimatological research and applications (Gochis *et al.* 2013). The design of WRF-Hydro provides switch-activated option which allows the treatment of terrestrial hydrological physics, which has either been created or adopted from other existing distributed hydrological models. The schematic illustration of the conceptual structure of WRF-Hydro is shown in fig 2.11.

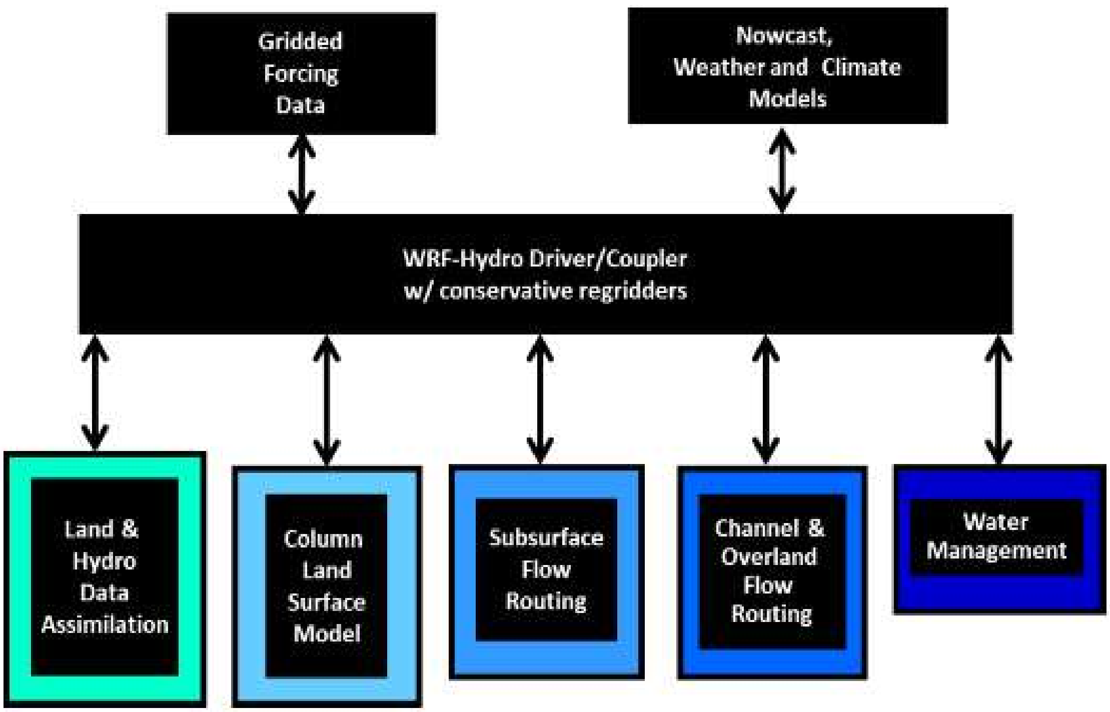

Figure 2.11 Conceptual Schematic WRF-Hydro architecture showing, various categories of model components (Gochis *et al.*, 2013)

The WRF-Hydro model requires both time-evolving (‘forcing’) and static input datasets for operation. The specification of these data depends on the selection of the model physics and component options to be used. The model physics options for the WRF-hydro include;

a) 1-dmensional (vertical land surface parameterization)
b) Surface overland flow
c) Saturated subsurface flow
d) Channel routing
e) Reservoir routing
f) Conceptual/empirical baseflow

In the situation where WRF-Hydro is coupled to the WRF regional atmospheric model, the forcing data is provided by the WRF atmospheric model with a frequency dictated by the land surface model time-step specified in WRF. When run in a standalone mode, these forcing data must be provided as gridded input time series. Geographical Information System (GIS) tools are used to delineate a stream channel network, open water (i.e. lake, dam, reservoir, and ocean) grid cells and baseflow basins. Water features are mapped onto the high-resolution terrain-routing grid and post-hoc consistency checks are performed to ensure consistency between the coarse resolution Noah land surface model grid and the fine resolution terrain and channel routing grid (Gochis *et al.* 2013).

The WRF-Hydro model calculates fluxes of energy and moisture either back to the atmosphere or also in the case of moisture fluxes, to stream and river channels and through reservoirs. The output variables of WRF-Hydro depending on the physics option selected are; surface latent heat flux, surface sensible heat flux, ground heat flux, ground surface and/or canopy skin temperature, soil moisture, deep soil drainage, soil temperature, surface runoff, stream channel inflow, channel flow rate, channel flow-depth

2.7.4.2 Model (WRF-Hydro) Physics Description

The 1D Noah LSM calculates the vertical fluxes of energy (sensible and latent heat, net radiation) and moisture (canopy interception, infiltration, infiltration excess, ponded water and soil thermal and moisture states. Infiltration excess, ponded water and soil moisture are subsequently disaggregated from the 1D Noah LSM grid, typically of 1-4km spatial resolution to a high resolution, of 30-100m routing grid using a time-step weighted method (Gochis and Chen, 2003). This is passed to the subsurface and overland flow terrain-routing modules.

The subsurface lateral flow in WRF-Hydro is calculated prior to the routing of overland flow to allow exfiltration from fully saturated grid cells to be added to the infiltration excess calculated from the LSM. The method used to calculate the lateral flow of saturated soil moisture is that of Wigmosta *et al.* (1994) and Wigmosta and Lettenmaier (1994), used in the Distributed Hydrology Soil Vegetation Model (DHSVM). It calculates a quasi-3D flow, which includes the effects of topography, saturated soil depth and varying saturated hydraulic conductivity values. Hydraulic gradients are approximated as the slope of the water table between adjacent grid cells in either the steepest descent or in both x-and y directions (Gochis *et al.* 2013). The flux of water from one cell to its down-gradient neighbor on each time-step is approximated as a steady-state solution. The saturated subsurface routing methodology of Wigmosta *et al.* (1994) has no explicit information on soil layers structure. It treats the soil as a single homogenous column. In WRF-hydro a minimum of four soil layers are used in a 2-meter soil column. In other to improve the resolution of a time-varying water table height, additional discretization is required.

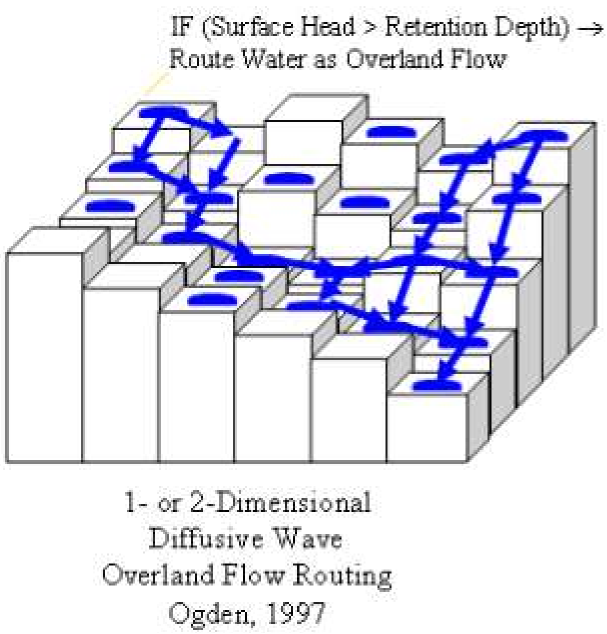

Figure 2.12 Overland flow routing modules in Noah-d

The fully unsteady, spatially explicit, diffusive wave formulation of Julien *et al.*, (1995) with later update by Ogden (1997) is the current option for representing overland flow, which is calculated when the depth of water on a model grid cell exceeds a specified retention depth. A schematic illustration of the grid-cell routing process is shown Figure 2.12.

The diffusive wave equation accounts for backwater effects and allows for flow on adverse slopes (Ogden, 1997). As it is in the case of Julien *et al.* (1995), the continuity equation for an overland flood wave is combined with the diffusive wave formulation of the momentum equation. Manning's equation is used as the resistance formulation for momentum and requires specification of an overland flow roughness parameter (Gochis *et al.* 2013). Values of the overland flow roughness coefficient used in the WRF-Hydro were obtained from Vieux (2001) and were mapped to the existing land cover classifications provided by the USGS 24-type, the same land cover classification dataset used in the 1D Noah LSM.

Additional modules have also been implemented to represent stream channel flow processes, lakes and reservoirs and stream baseflow. The current WRF-Hydro set-up indicates that stream network and lake inflow from the land surface is always positive to the stream or lake element. The current form of WRF-Hydro does not make provision for channel or lake loss functions, where water can move from channels or lakes back to the landscape (Gochis *et al.* 2013). Channel flow is accounted for by routing a 1d diffusive wave through a gridded channel network. Water flowing into and through lakes and reservoirs is routed by applying a simple level pool routing scheme. However baseflow to the stream network is represented using a simple empirically-based bucket model which obtains 'drainage' flow from the spatially-distributed landscape. Each of these process options described is activated with the specification of switches in the model namelist depending on the objective of the study. Further description of

WRF-hydro model physics are presented in WRF-Hydro technical description and User's guide (Gochis *et al.* 2013).

2.7.5 Hydrological Model Calibration

Hydrological models usually contain some unknown constants to represent the physical process. The parameters in the hydrological model must be assigned fixed numerical values before the model can be used to predict the runoff, therefore these parameters have to be estimated such that there is a best fit between modeled and observed runoff. The steps by which the parameters are selected are called "calibration". The focus here is the calibration of "conceptual" hydrologic model of streamflow.

2.7.5.1 Model Parameters

Most hydrological models are based on conceptual representation of the physical processes that control the flow of water through and over the soil (Xu, 2002). Such models usually have two types of parameters (Sorooshian and Gupta, 1995).

Physical Parameters: these represent physically measureable properties of the watershed e.g. the area of the watershed, the fraction of the watershed area that is impervious, the surface area of the streams and open water bodies, surface slopes.

Process Parameters: these represent watershed properties that are not directly measureable, e.g. the average or "effective" depth of surface soil moisture storage, the effective lateral interflow rate, the coefficient of nonlinearity controlling rate of percolation to the groundwater storage.

2.7.5.2 Methods of Parameter determination

There are basically two methods of parameter determination processes; parameter specification and parameter estimation.

Parameter specification: this process involves having prior knowledge about the watershed properties and behavior to specify initial estimates for the parameters of the model. In the case of "physical" parameters, estimates are made using measurements obtained from maps in the field. The parameters are then fixed at these measured values and not adjusted further unless it is found to be in error. However for the "process" parameters, estimates for the range (maximum and minimum values) of possible values for these parameters are determined based on judgment and understanding of the hydrology of the watershed (Xu, 2002).

Parameter Estimation: various techniques are designed to reduce the uncertainty in the estimates of the process parameters. In doing that, a first selection of the initial estimates for the parameters are made, somewhere within the ranges previously identified. The parameter values are then adjusted to more closely match the model behavior to that of the watershed. This process can either be done manually or automatically (computer-based). In this study the manual calibration is applied due to inadequate historical data.

2.7.5.3 Manual Calibration

To calibrate a model, some key aspects of the watershed behavior have to be selected to which the model is to be matched. The streamflow hydrograph at one or more locations of the river is selected for the assessment of the calibration process. The model parameters are adjusted to get the simulated streamflow hydrograph to resemble the observed hydrograph for some historical data period. Manual calibration is one of the trial-and –error process of parameter adjustment. After parameter adjustment is made, the simulated and observed hydrograph are visually compared to see if the match is improved. The major weakness of the manual calibration is the absence of generally accepted objective measures of comparison making it difficult to know when the process should be stopped (i.e. whether the “best” possible fit has been obtained), (Boyle *et al.*, 2000; Xu, 2002).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

Ghana is located on West Africa's Gulf of Guinea between latitudes 4 and 12 N. It has a total land mass of 238, 538 km^2. The country has boundaries with Cote d'Ivoire to the west, Burkina Faso to the north, Togo to the east and the Atlantic Ocean to the South. A half of the country lies less than 152 meters above sea level, and the highest point is 883 meters. The length of its coastline is about 537 km which is mostly a low sandy shore with plains and scrub. The climate is described as warm, humid with an annual temperature between 26 ^{0}C and 29 ^{0}C. The variations in major climate parameters of temperature, rainfall, and humidity are influenced by the movement and interaction of two air masses (Gordon, 2006). The rainfall seasons are controlled by the movement of the tropical rain belt (Inter-Tropical Convergence Zone, ITCZ), which oscillates between the northern and southern tropics over the course of a year. The dominant wind direction in regions south of the ITCZ is south-westerly, blowing moist air from the Atlantic onto the continent, but north of the ITCZ, the prevailing winds come from the northeast, bringing hot and dusty air from the Sahara desert (known as the 'Harmattan'). As the ITCZ migrates between its north and south positions over the course of the year, the regions between these those northern and southernmost positions of the ITCZ experience a shift between the two opposing prevailing wind directions. The West African Monsoon is the moist southwesterly winds blowing on to land with the northward migration of the ITCZ. This is due to a strong thermal gradient between the land and ocean. In northern Ghana, there is a single wet season occurring between May and November, when the ITCZ is in its northern position and the prevailing wind is south-westerly, and a dry season between December and March when the 'Harmattan' wind blows north-easterly. The southern regions of Ghana have two wet seasons, one in March to July, and a shorter wet season in September to November, corresponding to the northern and southern passages of the ITCZ across the region. The Northern Savanna receives an average rainfall of about 1,100mm annually (Figure 3.1).

Discharge from the various basins in most cases depicts rainfall trends. Most of the streams and rivers that discharge into these basins experience reduced flow during the dry seasons of the year and, flooding during the rainy seasons. Ghana is drained by a large number of streams and rivers. Most rivers and streams of the northern part of the country form part of the Volta system (White and Black Volta). These streams and rivers stretch to about 1,600 kilometers in length and draining an area of about 158,000 square kilometers in Ghana. There are 17 water bodies in Ghana which can be classified as large Dams (Gordon, 2006). Two of these water bodies (i.e. Akosombo and Kpong) are multipurpose (power supply, irrigation and water supply), while nine are irrigation dams (Golinga, Tono, Kplikpa, Okyereko, Dawhenya, Ashiaman, Vea, Botanga, Mankessim) and six (Barikese, Waija, Kwanyaku, Inchaban, Brimsu) are water supply dams.

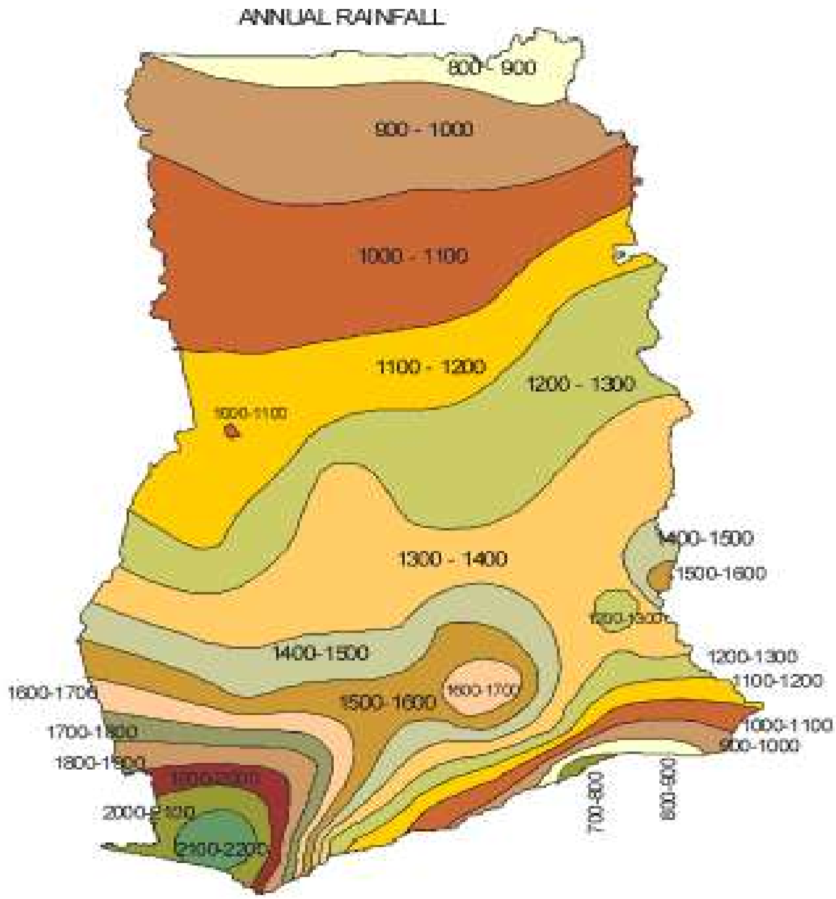

Figure 3.1 Annual rainfall distributions over Ghana

Source: Gordon, (2006)

The study focuses on the Tono basin located in the Kassena-Nankana Municipality of the Upper East Region of Ghana. The Kassena-Nankana Municipality lies within latitudes 10^0 30’ and 11^0 10’ N and longitude 1^0 01’ and 1^0 30’ W (Figure 3.2). The study area records lower annual rainfall values of about 950 mm than the average for the country. The rains, begin in May, reach a peak in August then drop sharply in October (Adams, *et al.*, 2014). Thereafter, there is a long dry period from November to the end of April. This area is characterised by high temperature and is seen to be one of the driest places in Ghana. The period of March-April, records the highest mean monthly temperature of 33 ^{0}C, whereas the peak harmattan season of December and January records the lowest mean monthly temperature of 26.5 ^{0}C. The vegetation of this geographical area, which is the longest vegetation zone in Ghana, is mainly interior wooded savannah (Anim-Gyampo, *et al.*, 2013). The basin is mainly for the purpose of irrigation. Figure 3.2 shows rivers draining into the dam and ungauged stations.

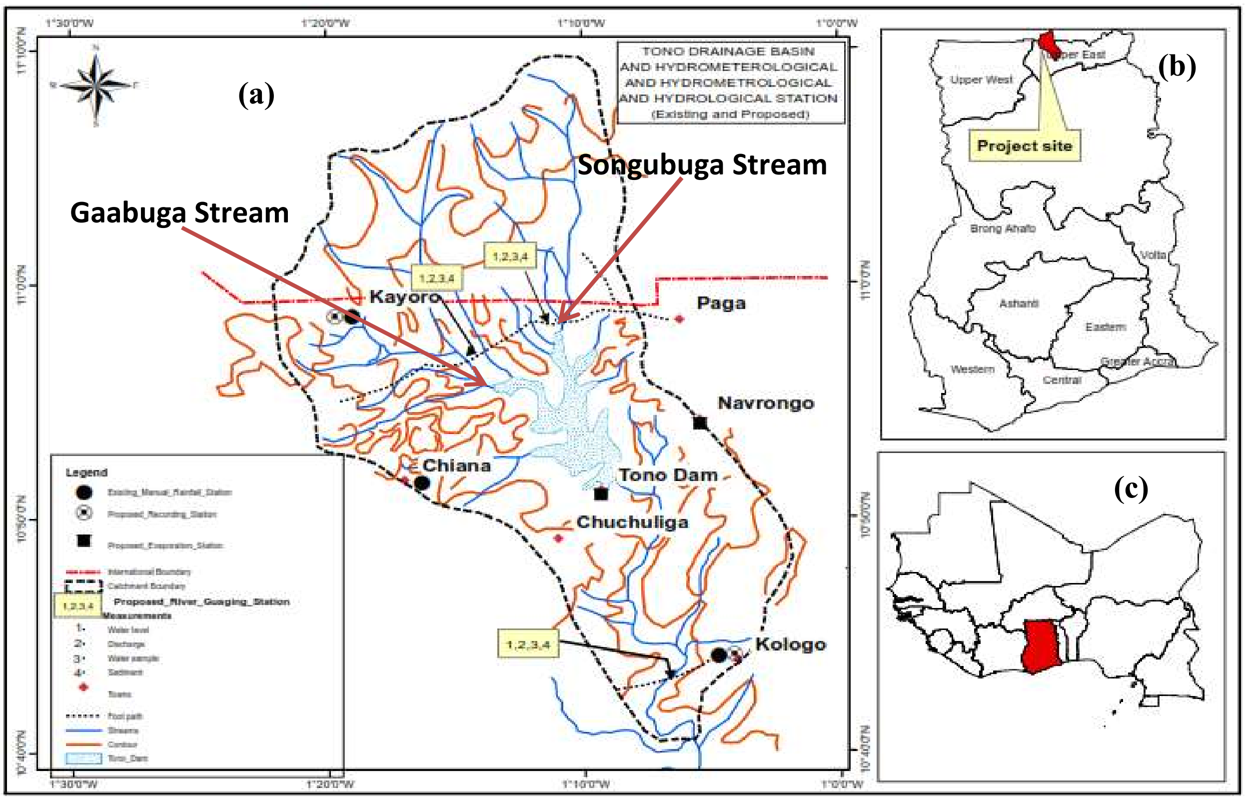

Figure 3.2 (a) Study area showing Tono basin stream network (b) Location of Project site on the map of Ghana and (c) location of Ghana on West African map.

3.2 Overview of Irrigation Sector in Ghana

Inadequate rainfall distribution and its erratic nature, makes it difficult to practice all-year-round cropping. The introduction of supplementary irrigation reduces the risks of crop failure. The practices of irrigation in the dry months (October-April) allow for all-year-round cropping and hence increase productivity.

Ghana has a potential of 500,000 ha of irrigable area (Gordon, 2006). However at present only 2% of this has been developed. The major forms of irrigation systems practiced are gravity flow (surface irrigation) and sprinkler irrigation system. Surface irrigation accounts for 80% of all types of irrigation. The major crop cultivated on most government financed irrigation schemes is rice. Unfortunately, under the prevailing macro-climatic conditions, the cultivation of rice has not proven to be competitive. Therefore, the cultivation of rice is being promoted in the flood plains. The cultivation of high-value exportable crops (e.g. vegetables, fruits, and cut flowers) has shown to have a much economic benefit on irrigation schemes compared to rice.

There are projections by the government to increase the current irrigable area (10,000) to 100,000ha by the year 2020. Therefore, the Government has laid down a number of strategies to enable it to achieve this target. This according to Gordon (2006) includes:

a) For existing irrigation schemes, funds are being sought for their rehabilitation to attract private sector management. The privatization of the management of existing government irrigation schemes will be done by leasing to nucleus out grower farmers, groups of small-scale farmers and cooperative societies, while ensuring a smooth take-over of the operation and maintenance of the facilities.

b) In respect of new irrigation projects, grants are being sought to update available feasibility reports. Planning and development of future irrigation projects will include canalization system for irrigation, the development of shallow aquifers wherever possible, water harvesting for dry season gardening, and the use of ponds, contour ridges or small narrow terraces for improved moisture restoration.

3.3 Description of Tono Dam

Dams are water resources that are designed to impound flowing streams or rivers for the purposes of water supply, hydropower, irrigated agriculture, flood control, recreation, navigation, and fishing. In recent times, dams are categorized based on their size or capacity to hold water. They are categorized as large or small dams and this description could also be related to the purpose of the dam. The International Commission on Large Dams (ICOLD) defines a large dam as one with a wall equal to or higher than 15 meters from base to crest. Clearly, however, 15 m high embankments in small narrow valleys create relatively small impoundments with possibly small environmental consequences (Gordon, 2006). The major dams are those with 150m high dam walls or with a water storage capacity equal to or greater than 25 km^3 (http://www.icold-cigb.org). By ICOLD definition, the Tono Dam is considered as a small dam. However the Tono dam is one of the largest agricultural dams in West Africa and serves as a place for year round farming. The Tono IS lies between latitude 10^0 52' 11.67" N and longitudes 1^0 08' 00.00" W with an altitude of 160 m. The Tono dam drains a catchment area of 650 km^2. The dam surface area is 18.6 km^2 and the dam is 4023.36 m long and 18.6 m of crest height. The dam has an estimated volume of 92.6 million cubic meters, however over the years; this has not been the case. Pelig-Ba (2011), reports of the volume of the dam as 17 million cubic meters.

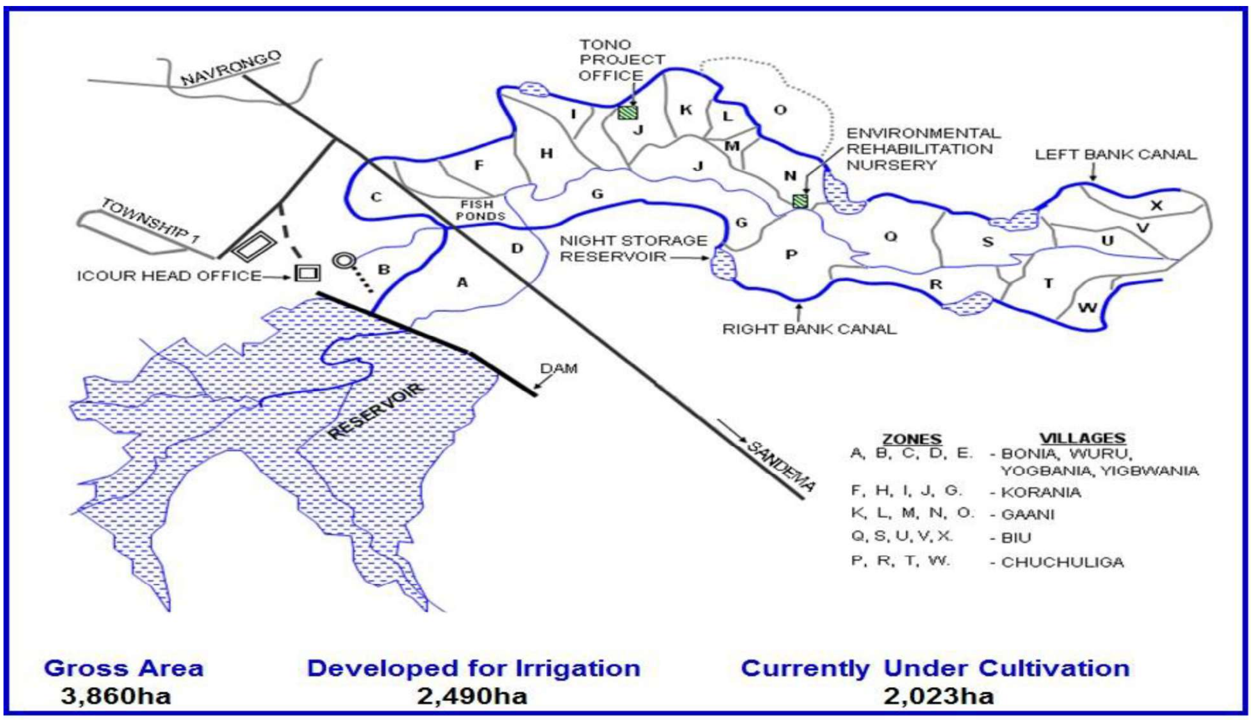

Figure 3.3 Conceptual outline of the Tono Irrigation Scheme

The secondary usage of this dam is domestic water supply and aquaculture. It is also documented by ICOUR that, there is a reduction in the irrigable area of the catchment (Figure 3.3) and this can be attributed to the availability of water in the dam. The main rivers draining into the catchment area are; Tono River (Gaabuga) and Chasi River (Songobuga).

3.4 Observed Stream flows into the Tono dam

Information on streamflow records and climatic data are very critical in water resources planning and management. The availability of streamflow data affords hydrologist and engineers the opportunity to design flood protection works for urban areas and agricultural land (Kumambala, 2010). This information is also used in the management of water resources supply, such that one can assess how much water can be extracted. Unfortunately, this kind of data is poorly collected, thus making it difficult for hydrological modeling. Missing stream flow records could be attributed to the malfunction of stream gauges, lack of technical staff to collect data regularly, insufficient training of staff in the techniques and methods used in collecting data from the field, among others. There were missing data and large gaps in the stream flow data for the Tono basin (data available from 1989-1991). The proposed Tono catchment discharge measuring stations are Gaabuga, 21 km from the ICOUR office and Songobuga 16 km from the office (Figure 3.3). Streamflow measurements of the proposed stream gauges for the basin have not been available until 2014; the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) installed a level gauge at the Gaabuga stream to extend the hydrological measurement network within the Tono basin. The measurements were taken at the onset (April/May) of the rainy season since there are no stream flows during the dry season. However, after a year of installation, the gauge was destroyed, thus, no data was collected in 2015 (see plate. 3.1).

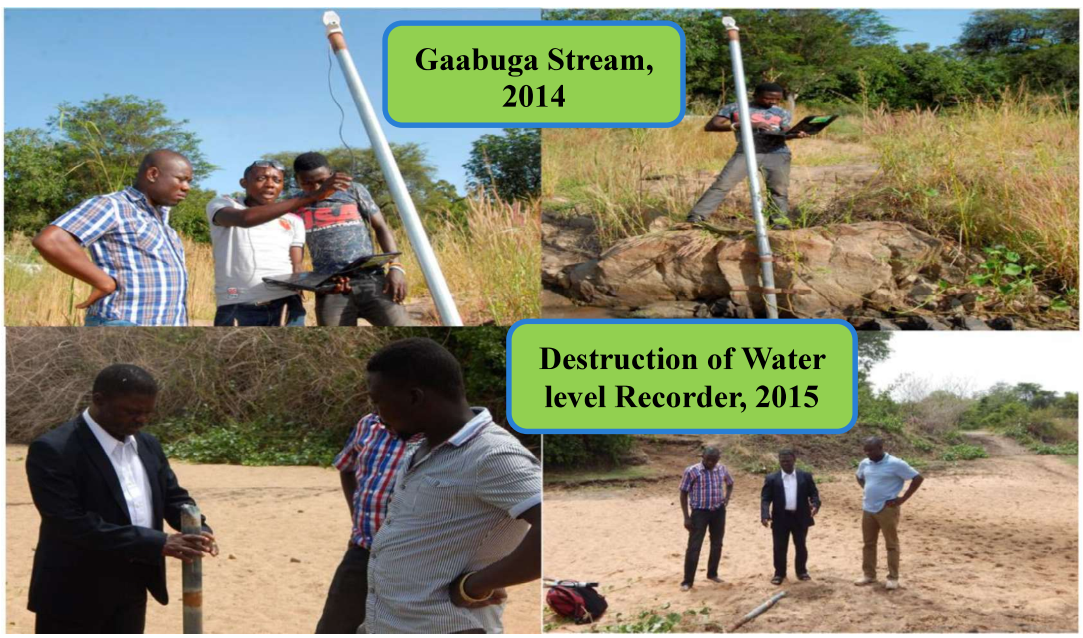

Plate 3.1 Visit to Gaabuga stream gauge

3.5 Observed dam levels and outflow of the Tono dam

The water levels of the Tono dam are the key information available to the water resource managers in assessing and managing the water resources. The water levels of the Tono dam depends on rainfall over the dam, inflows from rivers draining into the dam, evaporation losses from the dam surface, and outflow which is controlled at the weir. The regulation of the outflow depends on the level of the dam; hence, the outflow (Figure 3.4) shows similar trend characteristics of the dam level (Figure 3.5). It can be seen from Figure3.6 that the dam levels do not vary much (1 m increase in dam depth results in an increase in surface area of 20 hectares or 0.2 Km^2) with respect to the surface area and show a linear relationship with the surface area.

Monitoring of the dam levels is done by ICOUR using a water level recorder installed at the dam. The dam level readings started right after the construction of the dam, in 1985. Unfortunately, these records were not properly documented; hence, there are quite a lot of gaps (missing data).

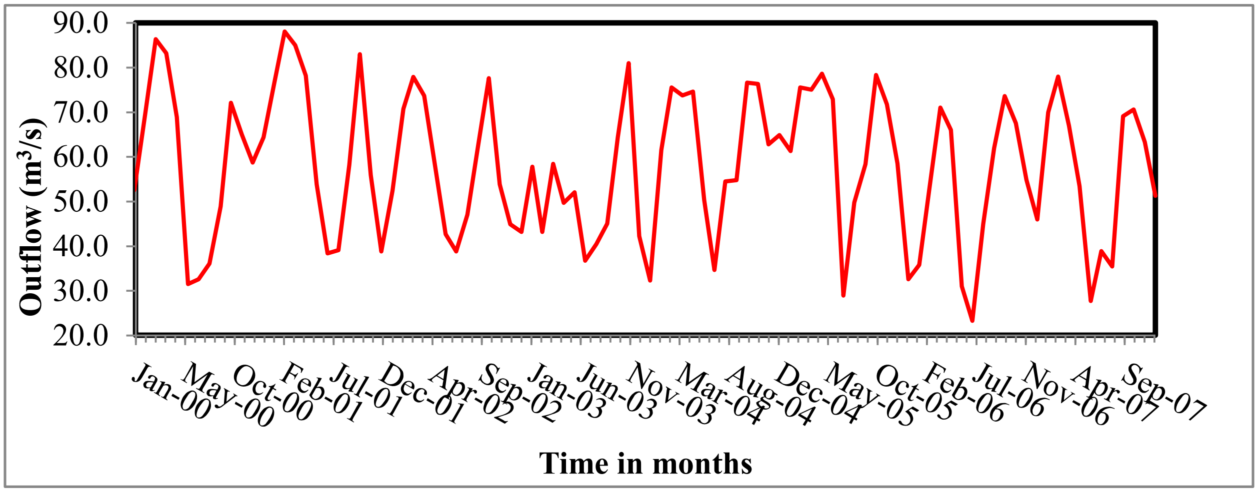

Figure 3.4 Outflow variations at the weir of the Tono dam

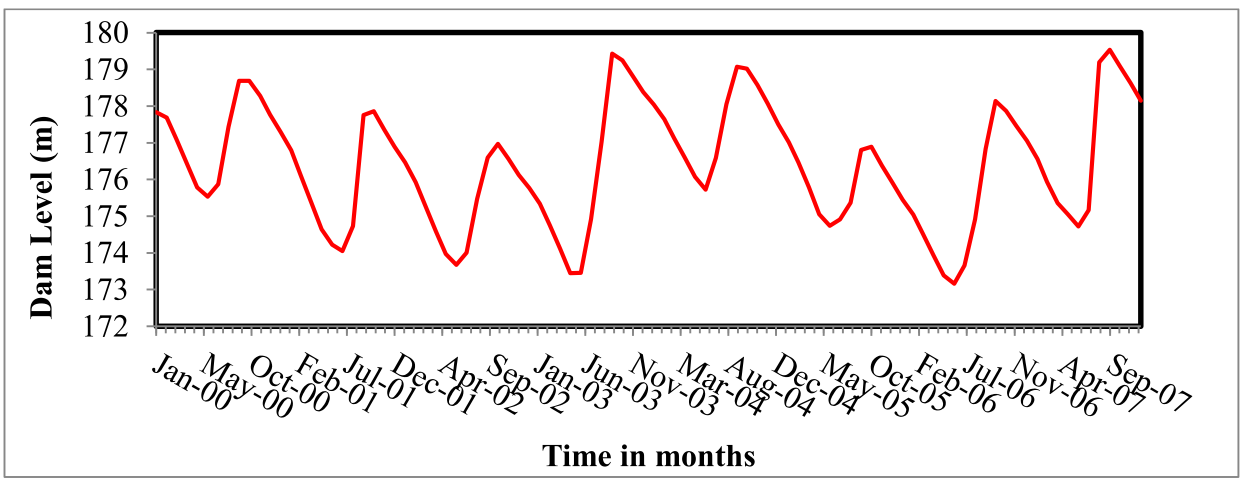

Figure 3.5 Observed Tono dam levels using a water level gauge

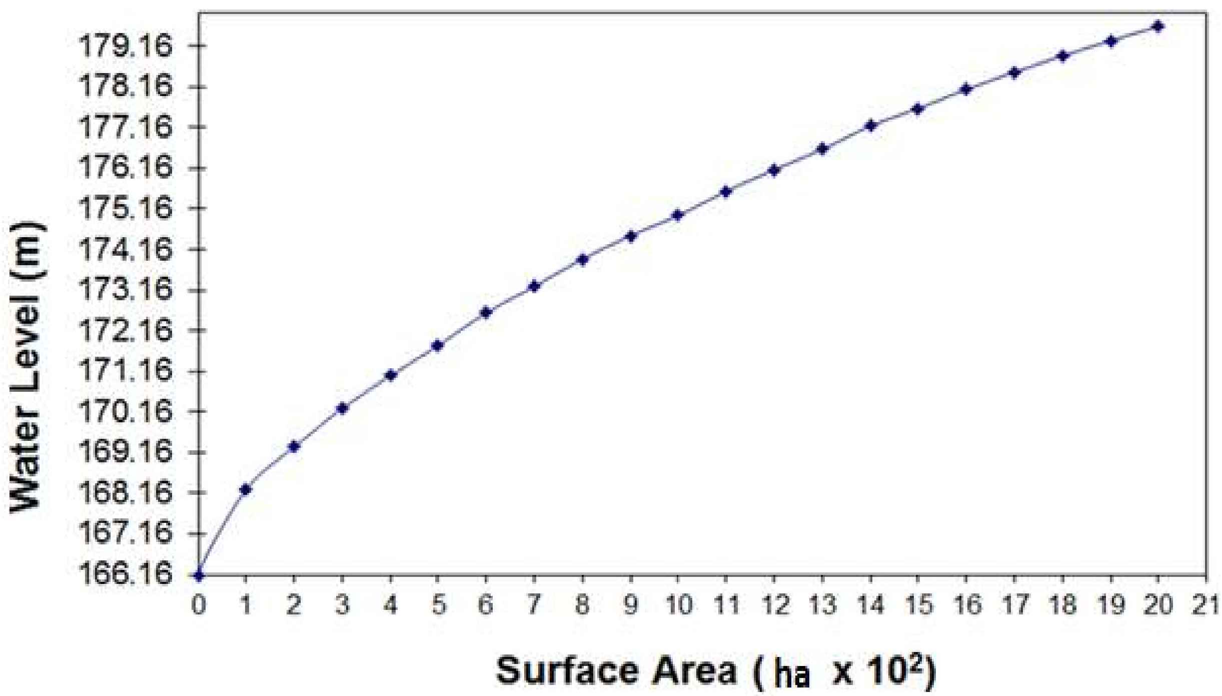

Figure 3.6 Relationship between the dam level volumes and the surface area of the Tono dam

The management of the Tono dam by ICOUR is mainly dependent on the dam level and the crop water requirement. The amount of water released is seasonal. During the dry season (January-May) when irrigation activities take place, more water is released with a threshold (T2) of $88.05m^3/s$ at a dam level of 176.1m (Figure 3.7). The peak dam level mostly occurs in September, with a dam level of about 179.5m. However, during this period, there is low water demand from the dam (T3). The critical threshold (T1) below which the dam will be shut is 173.6m, with the low outflow from the dam. This is usually after excessive extraction of water from the dam and the onset of rainfall is delayed, which occurs between June/July.

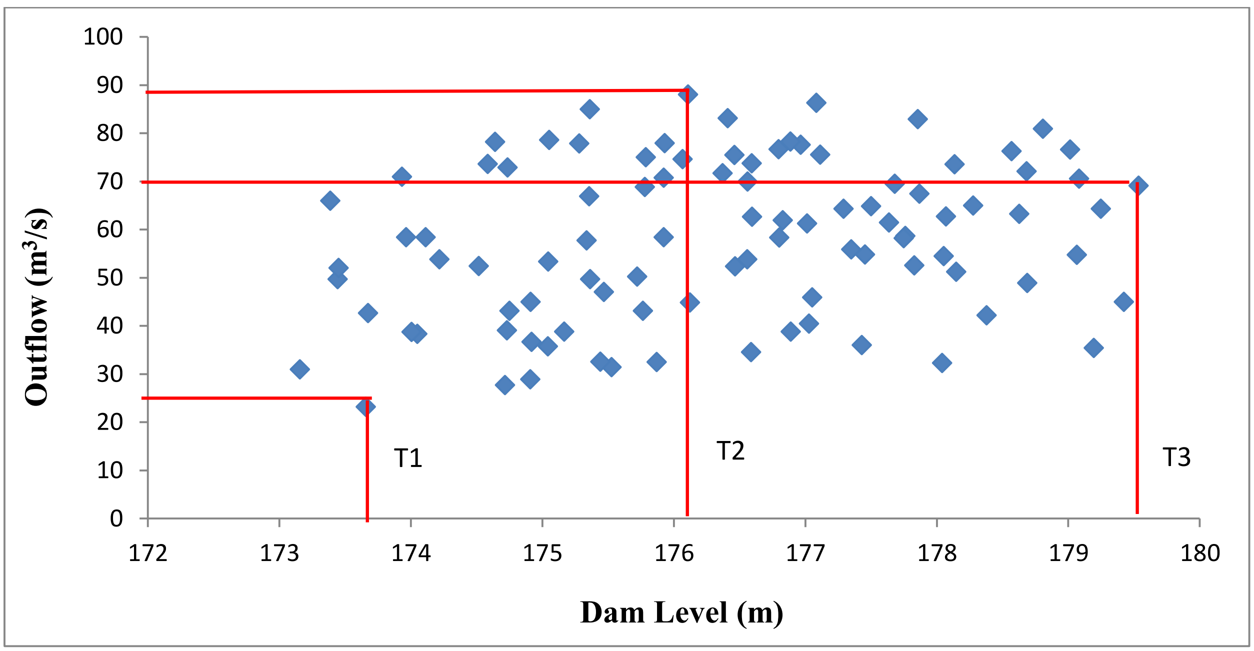

Figure 3.7 Relationship between outflow from the dam and the dam levels

3.6 Climate Data

3.6.1 Observed station data

Observed monthly evaporation data at the dam location (10.86 N, 1.14 W) for the period 2000 is available. This was provided by ICOUR. ICOUR also provided precipitation and temperature data for the period 2000 to 2008 at the location of the Tono dam. These data and other gridded data sets described below were used to assess the performance of the atmospheric and hydrological model.

3.6.2 Gridded station data

Different gridded data sets were used depending on their temporal and spatial characteristics. The Tropical Rainfall Measuring Mission (TRMM) data with a horizontal resolution of 0.25^0 x 0.25^0 was used to assess the performance of the model's precipitation. This is because TRMM provides precipitation at a daily time scale. For temperature comparisons, Climate Research Unit (CRU) data set for Africa version TS3.0 (Mitchell and Jones, 2005) were used. The data from the 5km (0.05^0 x 0.05^0) grid is aggregated to the CRU temperature at 50 km (0.5^0 x 0.5^0) horizontal grid resolution, using the Natural Neighbor interpolation (NNI) originally developed by Sibson (1981). This is a baseline method that has been used for many years as a standard part of the library of graphics functions provided by the National Center for Atmospheric Research (NCAR), (Haylock e*t al.*, 2008). This is to enable comparison with the Regional Climate Model (RCM) output at the same grid resolution to assess the performance of the model.

3.6.3 Model Data

The study used ECHAM6 general circulation model (GCM) based on its assessment on a global scale (Reichler and Kim, 2008) and also its availability. For the dynamical downscaling, a state of the art, non-hydrostatic regional climate model, the Weather Research and Forecasting (WRF) model was used. However, ECHAM6 model data has a large step in its horizontal resolution (80km) with the target resolution (5km). To adequately simulate regional circulation patterns in West Africa and in particular Northern part of Ghana, a nested approach was applied to the high-resolution domain located over Northern Ghana.

3.6.3.1 Boundary condition data

The ERA-Interim reanalysis and ECHAM6 model data were used as the boundary condition data for the regional model. ERA-Interim "is a global atmospheric reanalysis from 1979 to present". This was used for the atmospheric model configuration set-up and the calibration of the hydrological model. It is at T255 spectral resolution (~80km), (Berrisford *et al.* 2011). The ECHAM6 GCM was used for climate projection data. ECHAM6 is configured to run at several resolutions. It was developed for the purpose of coupled model inter-comparison (Stevens, *et al.* 2012). ECHAM6 is said to represent the present climate as well as or better than its predecessor ECHAM5, and also has a good representation of tropical variability, although a number of biases remain (Stevens, *et al.* 2012). ECHAM6 as a GCM focuses on the coupling between diabatic processes and large-scale circulations, both of which are ultimately driven by radiative forcing. For the future climate simulations, the Representative Concentration Pathways (RCPs) radiative forcing data for the RCP4.5 and RCP8.5 scenarios were used (see section 2.5.4), to assess the impact of climate change on the Tono basin water resources.

3.7 Coupled Atmospheric-Hydrological Modelling

3.7.1 Atmospheric model component set-up (WRF)

This study used the WRF model as a regional climate model (RCM). The WRF model was set-up with two nested domains at 25 km (outer domain) [WRF25] and 5 km (inner domain) [WRF5] horizontal resolution, using a one-way nesting approach. The outer domain with 160 x 130 grid points was designed to cover the West Africa Region (figure 3.8a). This covered a region large enough so as to reduce boundary effects in the inner domain. The inner domain with 111 x 111 grid points is designed to better resolve the mesoscale features in the Northern part of Ghana and the Southern part of Burkina Faso (figure 3.8b). The Tono Basin is located within this inner domain. The vertical resolution in both WRF grid domains was chosen for 35 vertical levels in the boundary layer with a model top at 20 hPa.

Studies carried out under the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) project came out with optimal physical parameterizations for the West African Region. The studies by Heinzeller *et al.* (2014) showed the optimal physical parameterization that gave a good precipitation and temperature distribution over the West Africa Region at a resolution of 12 km for the period 1980-2010. In this study their physical parameterization choices used were; Planetary boundary layer physics option [Asymmetrical convective model V.2 (ACM2), PBL 7], (Pleim, 2007), the Grell-Devenyi, Cumulus physics option (CU, 93), Grell and Devenyi (2002) and the microphysics scheme (WRF Single Moment 5, WSM5), Hong *et al.* (2004). However, the cumulus scheme for the nested domain was switched off, considering the spatial resolution of the nested domain was in the convective permitting scale (between 3 and 5km) and therefore would expect cumulus activities to be resolved explicitly at this scale. The simulation also used the Noah LSM, 4 soil layers and canopy moisture model (Chen and Dudhia, 2001). The radiation schemes were based on the shortwave and longwave radiation schemes of Dudhia, (1989) and RRTM scheme (Mlawer *et al.* 1997) respectively. The choice of configuration set-ups as indicated in many studies, especially over West Africa is quite subjective, based on the variable of interest, the focus of the region (study area), the verification methods and the chosen reference data sets (Klein *et al.* 2015; Sylla et al, 2013).

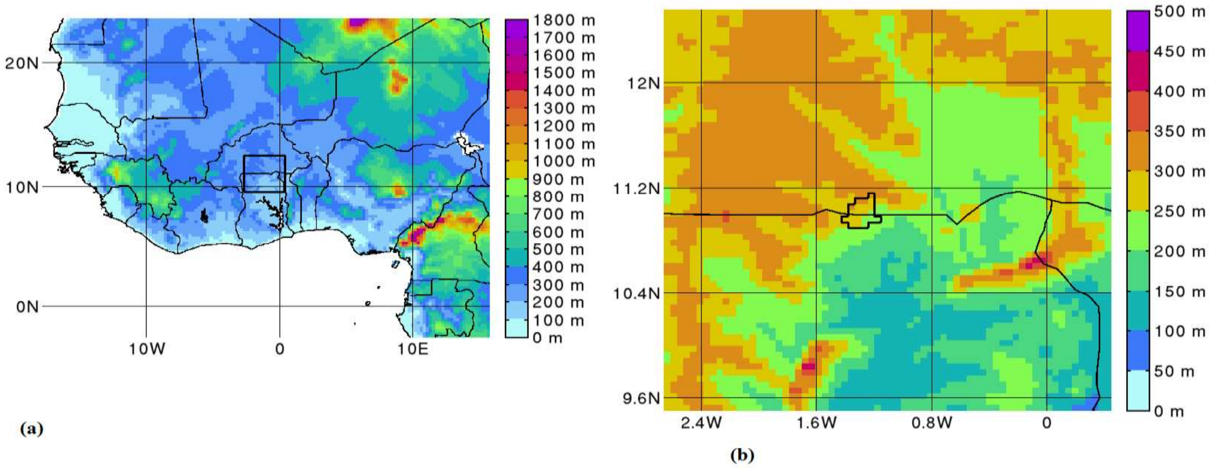

Figure 3.8 Plot of terrain in the (a) course domain (at 25 km horizontal resolution) and (b) finer domain (at 5 km horizontal resolution) with the basin location

3.7.2 Hydrological model set-up (WRF-Hydro)

The dynamics of a hydrologic system of water basins are extremely complex and it is not feasible at the moment to understand all the details of it (Xu, 2002). Therefore, hydrological models have been designed for varying objectives. However, there are two major underlying objectives for the development of these models.

One of the major objectives is to have a better understanding of the hydrologic phenomena operating in a catchment and the resultant effects of changes in the catchment due to these phenomena.

The second objective is the development of synthetic sequences of hydrologic data for project design and also for the purposes of forecasting. This also provides valuable information for studying the resultant impacts of changes in land use or climate.

The objective of this hydrologic system analysis is to study the basin operation and predict dam levels. The hydrological model is to approximate the characteristics of a hydrologic system, that is, its inputs and outputs are measurable hydrologic variables and its structure is defined by the concept of system transformation (figure 3.9). The hydrological model used to understand the hydrological dynamics of the Tono basin is the WRF-Hydro model.

3.7.2.1 WRF-Hydro pre-processing (Basin delineation)

The routing grid is defined by the WRF inner domain (WRF5) at 500 m resolution to compute overland routing. A Geographic Information System (GIS) tool is used for the basin delineation. This tool is also used to create the data layers for terrestrial *overland flow*, *subsurface flow* and the *channel routing* processes required by the WRF-Hydro model. Figure 3.10 illustrates the stream channel network and basins delineation.

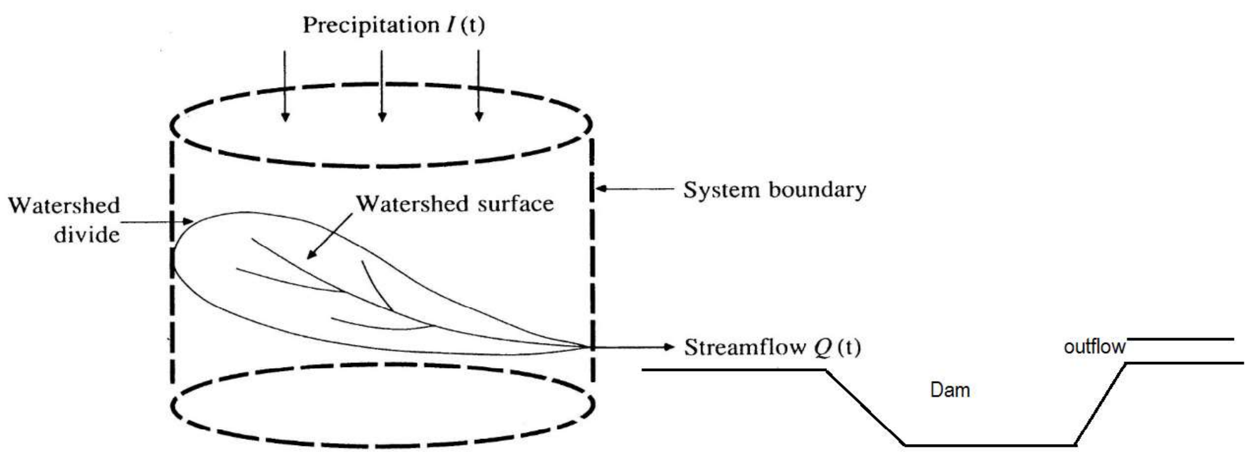

Figure 3.9 Hydrologic system of a basin (modified from Chow *et al.*, 1988)

In other to process geogrid files (a component in the WRF Preprocessing System [WPS]) as input static data for WRF-Hydro preprocessing, additional utility scripts have been created which is contained in the Python Toolbox. Processing the geogrid file requires the geogrid (geo_em.d0) file from WRF to be in a NetCDF format (.nc). The next input parameter though optional is the comma separated values (CSV; .csv) format file of the gauge locations for Songubuga and Gaabuga stations, in latitude/longitude coordinates (WGS84). Another input parameter required in this process is a high-resolution elevation grid (digital elevation model-DEM), which drives the output layers. The terrain processing is only successful when the input DEM has been hydrologically processed to ensure continuous flow paths.

The DEM datasets used for this is the 3 arc-second GRID USGS HydroSHEDS (http://hydrosheds.cr.usgs.gov/datadownload.php?reqdata=3dirg). A regridding factor of 10 was chosen. This parameter allows the user to set the output cell size for the derived datasets based on a relationship with the cell size in the input geogrid file. Therefore, the output high-resolution datasets from the WRF-Hydro preprocessing must be able to nest perfectly with the coarse geogrid resolution. The coarse geogrid is divided by the regridding factor to obtain the horizontal resolution of the WRF-Hydro. The sub-grid is obtained by dividing the inner domain by a regridding factor of 10. The minimal number of pixels to define a stream segment for this simulation was chosen as 4. The smaller this number is, the higher the drainage density of the output CHANNELGRID file will be. The choice of this number also depends on the resolution of the grid.

Once the above parameters have been defined, processing the geogrid file from ArcGIS tool is initiated and the output files are generated in NetCDF format. These files are concatenated into a file which becomes the static data for the WRF-Hydro simulations.

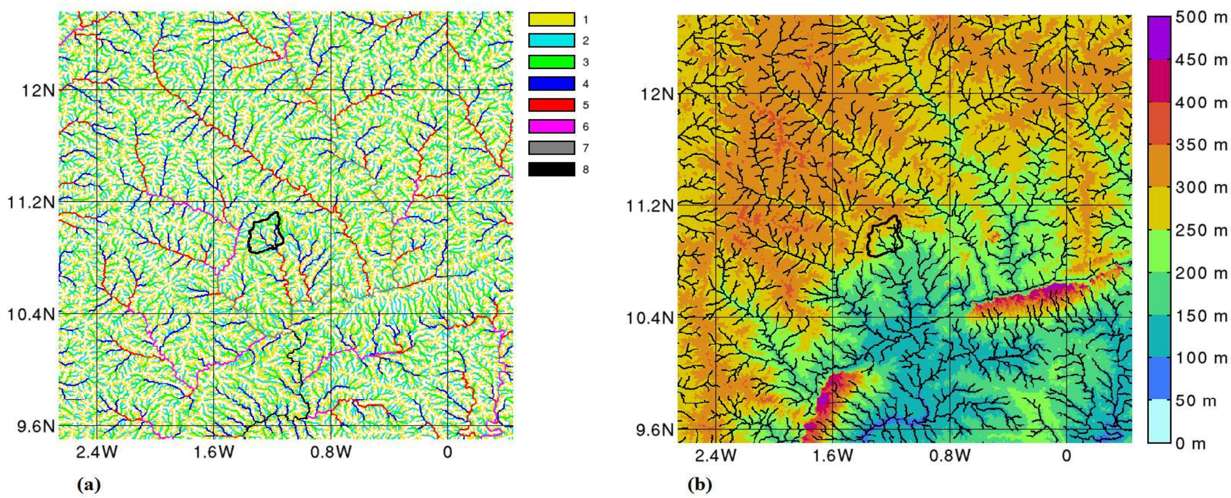

Figure 3.10 Tono basin (a) streamflow order and (b) terrain height at 500 m resolution of routing grid

3.7.3 WRF-Hydro model calibration

In other that the model will simulate the right stream discharge (at Songubuga & Gaabuga), the stations coordinates were placed in the preprocessing of the basin data for the hydrological model. The dam location was placed in the static data (geo_em.d02) of the inner domain of the WRF model and assigned a land-use category 17 (waterbody). The reason is to use the coupling approach to simulate the plausible evaporation of the Tono dam for the water balance. The calibration of the model was done and evaluated based on the only available stream discharge (Gaabuga) for 2014. The calibrated model was used to retrieve (generate) historical streamflow.

For gauged rivers, calibration knowledge of another watershed could be used as a basis for the calibration process. The initial calibration attempt was based on studies on the calibration and sensitivity analysis of the infiltration partitioning parameter (kdtref) for the Sisili basin (Arnault *et al.*, 2015). Two major steps were considered in the calibration process. The first step was to look at the parameters controlling total water volume that is the runoff infiltration partitioning parameter, kdtref. The second step was to look at the parameters controlling the shape of the hydrograph, Manning's roughness (MannN). This approach ensures that the model is capable of simulating the streamflow at each of these gauges, and then the amount of water is correctly distributed in time (Yucel *et al.*, 2015). In tuning the model parameters the optimum streamflow estimates during calibration were assessed using statistical measures (e.g RMSE, Bias, Pearson's correlation coefficient and Nash-Sutcliffe efficiency index).

The bias statistic shows sensitivity toward hydrograph volumes, R^2 shows sensitivity toward temporal variation of discharge, whereas Nash-Sutcliffe and RMSE statistics describes both characteristics (Gupta *et al.*, 2009; Yucel *et al.*, 2015).

The choice of different kdtref values, especially for the nested domain coupled to the WRF-hydro, influences the amount of water that infiltrates or makes it to the channel network as streamflow. Tested values of kdtref during calibration for (WRF25, WRF5) were: (3, 2), (18, 4), (18, 1.5), (18, 1.4). In the case of Manning's roughness, changes in the values based on the channel characteristics, (e.g. natural, bare soil, and agricultural field) influence the tuning of flood wave generation and propagation. The channel geometric characteristics were set to their default values since there is no available channel cross-section data for the basin with respect to the stream order. Hence, the only parameter tuned in this section is the channel roughness (Manning's N). Table 3.1, shows the default channel Manning's roughness values. Tuning these values was based on literature (Chow *et al.*, 1988). The individual Manning's values were changed based on the interval value between the default values. Having chosen the Manning parameter for the first stream order based on textbook values (the reference to channel characteristics), the subsequent values for the remaining stream order were based on the interval value from the default values. Different sets of Manning parameters were tested and the optimum parameter set was chosen based on a scaling factor ranging between 1.2 and 1.5 with increments of 0.1.

Table 3.1: Channel parameter values of base width (Bw), initial water depth (HLINK), channel slope (Ch SSlp), and Manning coefficient (MannN) based on each stream order (St Order).

St Order	'Bw	HLINK	ChSSlp	Mann N'
1,	5.,	0.02,	2.0,	1.5
2,	10.,	0.02,	1.0,	1.4
3,	20.,	0.02,	0.5,	1.3
4,	30.,	0.03,	0.18,	1.2
5,	40.,	0.03,	0.05,	0.55
6,	60.,	0.03,	0.05,	0.3
7,	60.,	0.03,	0.05,	0.25
8,	60.,	0.10,	0.05,	0.1
9,	60.,	0.30,	0.05,	0.03

3.7.3.1 Assessment of model calibration

The sensitivity of the hydrological model to different kdtref and MannN, on streamflow estimation, is presented in table 3.2. The choice of these parameters was based on knowledge of basin hydrological characteristics and existing studies of a basin (Sissili) close to the Tono basin. A number of different kdtref were tested using the manual calibration approach. The performance of each of the calibration option was subjected to four error statistics, root mean square error (RMSE), percentage bias (PBIAS), Nash-Sutcliffe efficiency (NSE), and Pearson correlation coefficient (r). The computation of each of these statistical approaches is described below;

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}({q_t}^{sim} - {q_t}^{obs})^2} \qquad (3.1)$$

$$PBIAS = \sum_{t=1}^{N}\left({q_t}^{obs} - {q_t}^{sim}\right) / \sum_{t=1}^{N} {q_t}^{obs} \ X \ 100 \qquad (3.2)$$

$$NSE = 1 - \sum_{t=1}^{N}\left({q_t}^{sim} - {q_t}^{obs}\right)^2 / \sum_{t=1}^{N}\left({q_t}^{obs} - q^{mean}\right)^2 \qquad (3.3)$$

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad where\ x\ is\ obs\ and\ y\ is\ sim \qquad (3.4)$$

These statistical equations provide some perspectives regarding the performance of the model. The first equation RMSE, computes the standard deviation of the model prediction error; a smaller value implies a better model performance. The second equation PBIAS, measures the average tendency of the simulated flows to be larger or smaller than the observed flows. The benchmark value is 0.0; positive values indicate a model bias toward overestimation, whereas negative values indicate a bias toward underestimation (Gupta *et al.*, 1999). The statistical equation NSE provides normalized indicators of model performance. The Nash-Sutcliffe efficiency (NSE) measures the relative magnitude of the residual variance ("noise") to the variance of the flows ("information"). The optimal value for NSE is 1.0 and therefore for a "minimally acceptable" performance of the model, values should be larger than 0.0. Where the value is equal 0.0, indicates that the mean observed flow is a better predictor than the model. The Pearson's correlation is a measure of the relation between two data sets. It indicates the linear relationship between these data sets, in this case, the relationship between simulated streamflow and observed streamflow. The result is between 1 and -1; the closer the value of r gets to zero, the greater the variation of the data points are around the line of best fit.

3.8 Components of the water balance model

Considering the length of data used in calibrating the streamflow was not long enough to justify the performance of the WRF-Hydro, the output variables of the model were subjected to further water balance analysis at the Tono basin. The water balance assessment will lead to producing the dam levels of the Tono dam of which there is a considerable amount of observation data to verify the performance of the model. The water balance of the Tono dam is assessed monthly. It is important to state that this approach is not without errors, however at the monthly or annual scale the errors are considered to be negligible (Kebede *et al.*, 2006). The source of these errors can be attributed to the lack of direct measurement of accurate evaporation rate or for instance in this case net groundwater flux is assumed to be negligible and also the lack of data from gauged stations. An additional source of error is the transferability of precipitation bias.

Table 3.2: Sensitivity Analysis of Model Streamflow Calibration

	OBS	WRF5, K=(3, 2)	WRF5, K= (18, 4)	WRF5, K= (18, 1.5)	WRF5, K= (18, 1.4)
Annual Sum	9.77m^3/s	19.5m^3/s	5.63m^3/s	9.66m^3/s	22.2m^3/s
RMSE		3.99m^3/s	1.68m^3/s	0.04m^3/s	5.09m^3/s
PBIAS		100%	-42.3%	-1.12%	128%
NSE		-0.44	0.74	0.78	-1.35
Pearson Correlation (r)		0.52	0.42	0.89	0.65

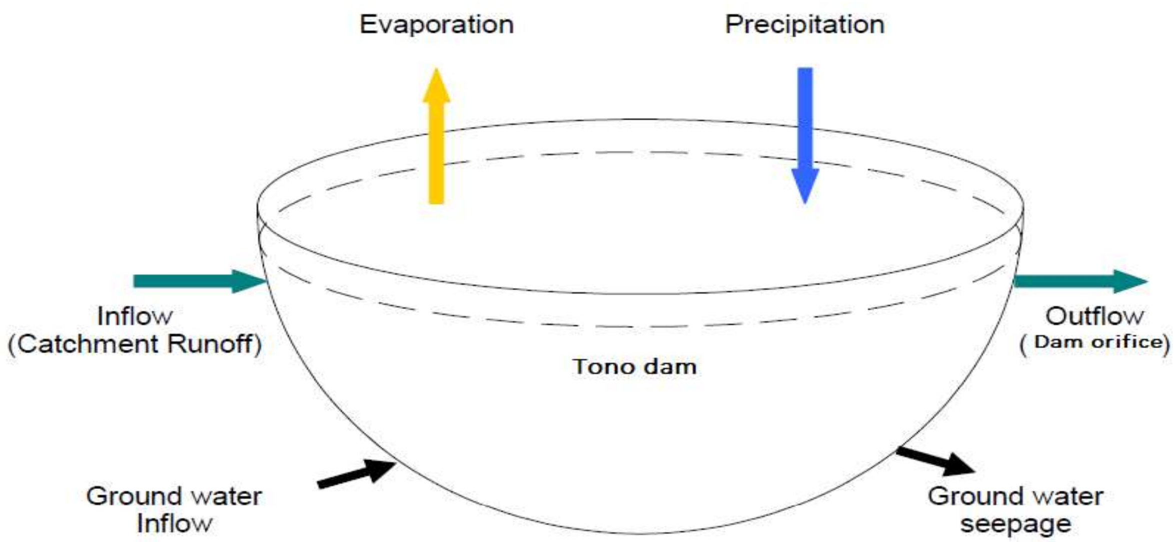

Figure 3.11 Tono dam water balance components

3.8.1 Evaporation

Evaporation from lakes (or dams) constitute the largest percentage of the water balance, therefore, its accurate determination is critical for an acceptable estimation of the water budget (Kebede *et al.*, 2006). The FAO Penman-Monteith evaporation estimation method has been proven to be suitable under any climatic conditions. This method takes into account the fact that evaporation is a diffusive process and that energy can be translated in terms of mass. The output variables from the WRF model could not be directly applied to the Penman equation; hence, the Penman approach was not used. A simplified evaporation method was used to estimate the plausible evaporation at the dam.

$$E = \frac{ACLHFLX}{LVH2O} \quad (3.5)$$

Where E = Evaporation at the Tono dam, ACLHFLX = accumulated latent heat flux, LVH_2O = $2.501 * 10^6$; latent heat of water evaporation (J kg-1)

3.9 Dam level simulation based on WRF-Hydro

At the moment there aren't any documented studies on the water balance of the Tono dam, however, most water resources attributes (e.g. water level) are governed by water balance which is a combination of runoff from rivers (streams) flowing into the dam, measured outflow from the dam, evaporation from the dam surface and rainfall on the dam (see Figure 3.11). Groundwater inflow and outflow in many cases are ignored due to lack of piezometric data for the water resource in question to be able to quantify groundwater flow. Water balance studies carried out by Neuland (1984) and Calder *et al.*, (1995) have recognised that increase in rainfall will lead to abnormally high lake levels, accelerated by the change in runoff characteristics in the catchment due to reduced forest cover. Previous studies on the water balance model for some water resources were based on the net balance between inflow (Qin) from the catchment, rainfall (Pt) and evaporation (Et) over the lake and outflow (Outf) in estimating the change in dam water storage ΔS. This model was further improved by introducing a one month time lag between inflow and outflow from the dam in estimating net storage of the dam (eqn. 3.6), which was attributed to Calder *et al.*, (1995).

$$\Delta S_{(t)} = P_{(t)} + Qin_{(t)} - E_{(t)} - Outf_{(t-1)} \qquad (3.6)$$

According to Kebede *et al.* (2006) equation 3.6 is a simplification of the water balance of an open lake normally given by the following differential equation;

$$\frac{dL}{dt} = P_{(t)} - E_{(t)} + \left(\frac{Qin_{(t)} - Outf_{(t)} + Gnet_{(t)}}{A(h)}\right) + \varepsilon_{(t)} \qquad (3.7)$$

Where *L* is the dam level, *A* is the depth dependent surface area of the dam, *P* is the rate of precipitation over the dam, *E* is the rate of dam evaporation, *t* is time, *Qin* and *Outf* are surface water inflow and outflow respectively and *Gnet* is the net groundwater flux. Epsilon term represents the uncertainties in the water balance associated with errors in the data and other factors such as minor abstraction or inflow from ungauged catchments. Kebede *et al.* (2006) also suggested a further simplification of equation 3.7 based on the following assumptions; Ɛt at the right most term in the equation is negligible, and the net groundwater flux is also considered to be zero. The dam surface area is also assumed to be constant taking into account the dam level and area relationship (figure 3.2). With reference to Figure3.2, a 1 m increase or decrease in lake depth results in a change in the area of the dam by about 1%. Based on the above assumptions, a simplified equation of the following form was used to reproduce the observed dam levels using input data from the WRF-Hydro model.

$$\frac{dL}{dt} = P_{(t)} - E_{(t)} + \left(\frac{Qin_{(t)} - Outf_{(t)}}{A(h)}\right) \quad (3.8)$$

However the application of this equation is not simplistic because at any given time there are two unknowns; the dam level at the time (L_t) and the outflow that corresponds to this dam level ($Outf_{(t)}$). The outflow from this dam is controlled depending on dam levels and the demand of water by the farmers for the various crops grown in the irrigation catchment. To get the model simulate the dam levels, the measured outflows were used in the water balance model.

3.10 Climate and Climate change modeling

In other to understand whether fully coupled WRF/WRF-Hydro model gives added advantage in climate modeling vis à vis running a standalone WRF model, output (precipitation and temperature) from both configurations were subjected to statistical tests. The statistical tests carried out were graphically summarized in a Taylor diagram (Taylor, 2001). This provides how the pattern (s) of the outputs from the two modeling configurations matches the observations (at a grid point). The similarity between two patterns is quantified in terms of their correlation, their centered root-mean-square difference and the amplitude of their variations (represented by their standard deviations). These diagrams are especially useful in evaluating multiple aspects of complex models or in gauging the relative skill of many different models (e.g., IPCC, 2001).

In general, the Taylor diagram characterizes the statistical relationship between two fields, a "test" field (often representing a field simulated by a model) and a "reference" field (usually representing “truth”, based on observations). The means of the fields are subtracted out before computing their second-order statistics, so the diagram does not provide information about overall biases; it mainly characterizes the centered pattern error.

The reason that each point in the two-dimensional space of the Taylor diagram can represent three different statistics simultaneously (i.e., the centered RMS difference, the correlation, and the standard deviation) is that these statistics are related by the following formula:

$$E^{I2} = {\sigma_f}^2 + {\sigma_r}^2 - 2\sigma_f\sigma_r R \qquad (3.9)$$

where R is the correlation coefficient between the test and reference fields, E' is the centered RMS difference between the fields, and σ_f^2 and σ_r^2 are the variances of the test and reference fields, respectively. The formulas for calculating these second order statistics are given below:

$$R = \frac{\frac{1}{N}\sum_{n-1}^{N}(f_n - \bar{f})(r_n - \bar{r})}{\sigma_f\,\sigma_r} \qquad (3.10)$$

$$E'^2 = \frac{1}{N}\sum_{n-1}^{N}\left[(f_n - \bar{f}) - (r_n - \bar{r})\right]^2 \qquad (3.11)$$

$${\sigma_f}^2 = \frac{1}{N}\sum_{n-1}^{N}(f_n - \bar{f})^2 \qquad (3.12)$$

$${\sigma_r}^2 = \frac{1}{N}\sum_{n-1}^{N}(r_n - \bar{r})^2 \qquad (3.13)$$

where the overall mean of a field is indicated by an overbar. In the case of a time-independent field, the sum is computed over all grid cells.

The climate change assessment was based on the representative concentration pathways (RCPs) scenarios of the intermediate carbon gas emission (RCP4.5) and extreme case of Carbon gas emission (RCP8.5). The assessment of these scenarios was with respect to precipitation and temperature in terms of the signal and magnitude (percentage) of change for the time slice, 2000-2005 (baseline or historical period) and 2020-2025 (projections).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Present-day Climate Assessment; WRF-only and WRF/WRF-Hydro

4.1.1 Precipitation

Figures 4.1a and 4.1b show the annual cycle of the average daily rate of precipitation at the Tono dam with WRF-only and fully coupled WRF/WRF-Hydro simulations forced with ERA-Interim reanalysis (Figure 4.1a) and ECHAM6 (Figure 4.1b) data sets. Both models capture the annual cycle relatively well but the WRF-only forced with ERA-Interim data has an early peak (in July) compared to the August peak in the other model realizations.

Figure 4.2 demonstrates the relationship between WRF-only and WRF/WRF-Hydro with TRMM data at the Tono dam with respect to correlation, Root Mean Square (RMS) error and the standard deviation. In the case of model B (WRF-Hydro_ERA) its pattern of correlation with observation is about 0.91. The green contours indicate RMS error values and it can be seen that in the case of model B the centered RMS errors is about 2.4 mm/day. The standard deviation of the simulated pattern is proportional to a radial distribution from the origin. For model B the standard deviation of the simulated precipitation (4.7mm/day) is greater than observed standard deviation which is indicated by the dashed black arc with the observed value of 2.9 mm/day. The merits of the other model configurations can be inferred from the same Figure 4.2. Simulated patterns that agree well with observation will lie nearest the part marked “OBS” on the x-axis. These models will have relatively high correlation and low RMS errors. In the case of the model A (WRF_ERA), it has a correlation of 0.82, with RMS errors of 3.6 mm/day.

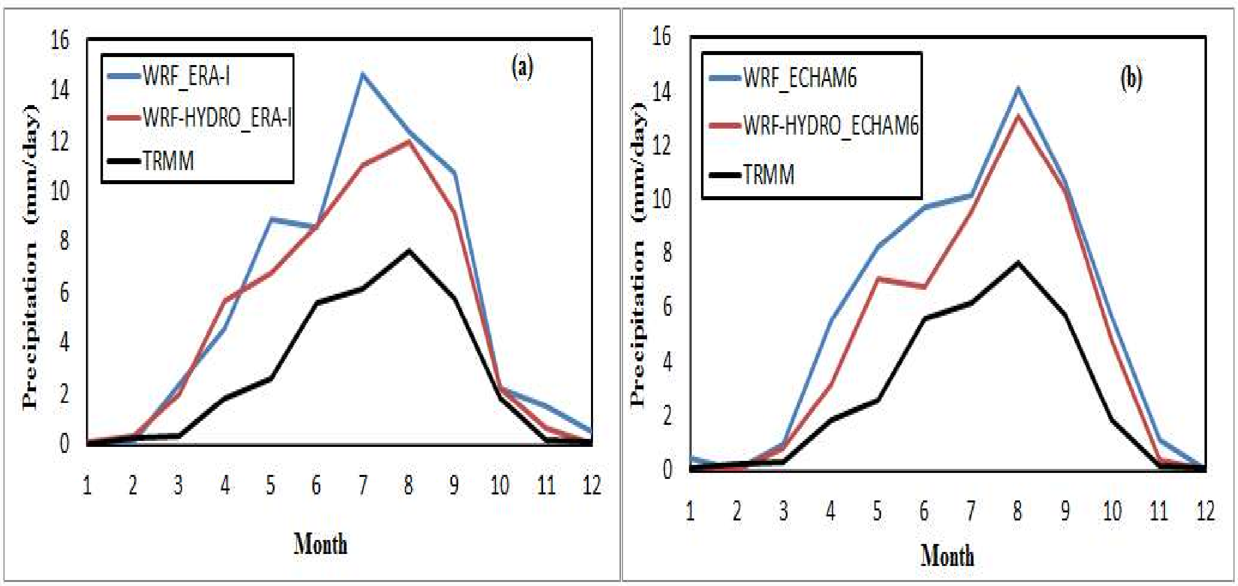

Figure 4.1 Precipitation plot at daily scale in months for the period 2000-2005 using (a) ERA-I and (b) ECHAM6 data sets

Its standard deviation of the simulated precipitation (5.8 mm/day) is greater than the observed standard deviation of 2.9 mm/day. From Figure 4.2 it can be seen that model C (WRF-Hydro_ECHAM6) and model D (WRF_ECHAM6) have the same correlation of about 0.75 and the same RMS errors of 3.8mm/day. The standard deviation of these two models (C and D) simulated precipitation (5.4 mm/day and 5.2 mm/day) are clearly greater than the observed standard deviation of 2.9 mm/day.

The variation in the performance of the coupled and uncoupled models with respect to precipitation estimates could be attributed to the choice of the optimum physics. The optimum physics used was based on studies of Heinzeller *et al.* (2014), which showed to perform quite well over West Africa region. However, their physical parameterization was configured for the uncoupled model (WRF) and also on a bigger domain and coarse resolution (12 Km) than the set-up for this study. Though the statistical results show an improvement in precipitation estimates for the fully coupled WRF/WRF-Hydro compared to WRF-only, it is possible that the optimum physics chosen may not be the optimum for this study. It has also been demonstrated that the choice of a forcing data also has an influence on the model performance. There are quite a number of studies over the region which has shown considerable good results in simulating precipitation using ERA-Interim reanalysis compared to observation (e.g. Heinzeller *et al.* 2014; Klein *et al.* 2015; Arnault *et al.* 2015). This is particularly the case for present-day climate analysis, however for climate change assessment ECHAM range of model data has been used over the region (e.g. Kunstmann and Jung, 2005, Heinzeller *et al.* 2014). In this particular study ERA-Interim, reanalysis data has shown to give good results with respect to climate and hydrological studies.

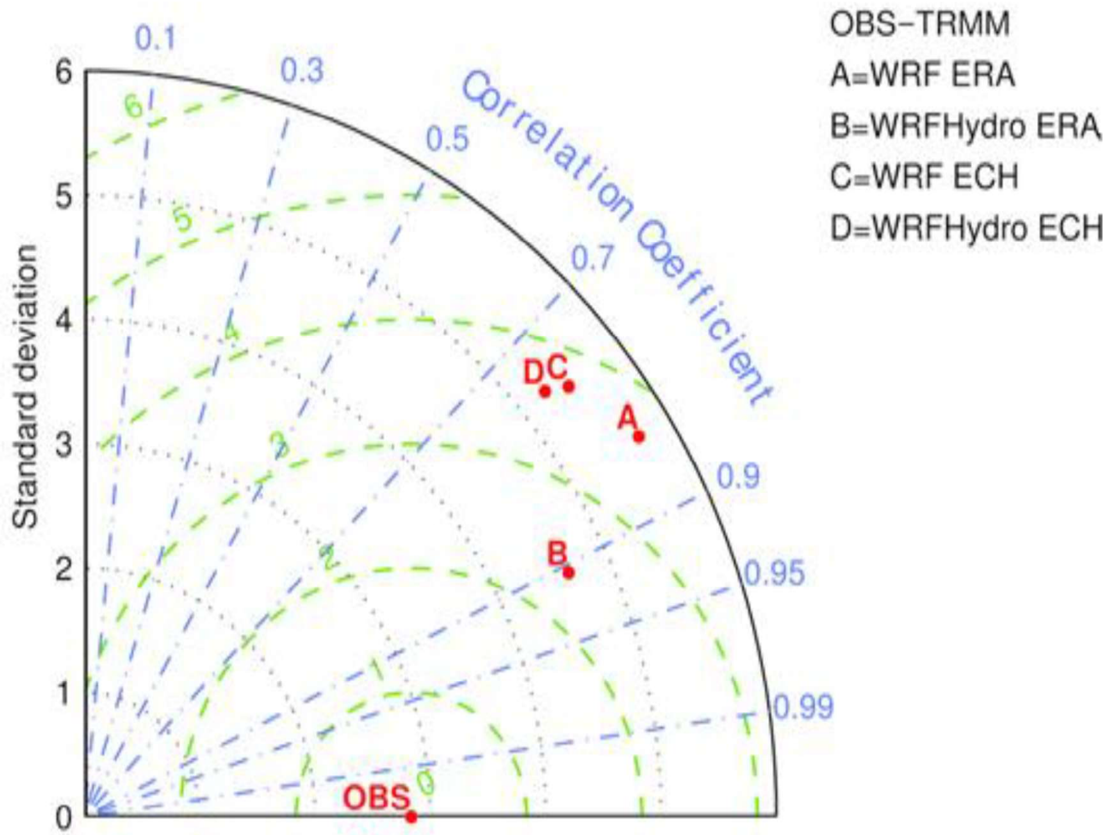

Figure 4.2 Relationship between WRF-only and WRF/WRF-Hydro precipitation with respect to TRMM

Precipitation bias maps as presented in Figure 4.3 and Figure 4.4 describes the locations of precipitation overestimating or underestimating within the basin. With respect to observed values, both WRF-only and WRF/WRF-Hydro show (positive) biases over the basin. The seasonal assessment of both models driven by ERA-Interim indicates that WRF-only model over estimated precipitation over the basin compared to WRF/WRF-Hydro (Figure 4.3). The same characteristic is reflected in both models when forced with ECHAM6 (Figure 4.4). It is also noted that both models forced with ECHAM6 overestimates precipitation compared with both models forced with ERA-I. The high biases and RMS errors demonstrated by these models over the basin could be attributed to the influence of irrigation activities on the soil moisture dynamics and its related effects could force significant changes in spatial distribution and magnitude of rainfall, depending on the latitudinal location of irrigation (Marcella and Eltahir, 2013). The remote response of rainfall distribution to irrigation, turn to exhibit a significant sensitivity to the latitudinal position of irrigation and the intra-seasonal variation of supplied irrigation water.

Fully coupled WRF/WRF-Hydro statistic demonstrate a better simulation of precipitation compared to WRF-only, although there is still uncertainty exhibited by both models in the accuracy of precipitation estimates over the Tono basin.

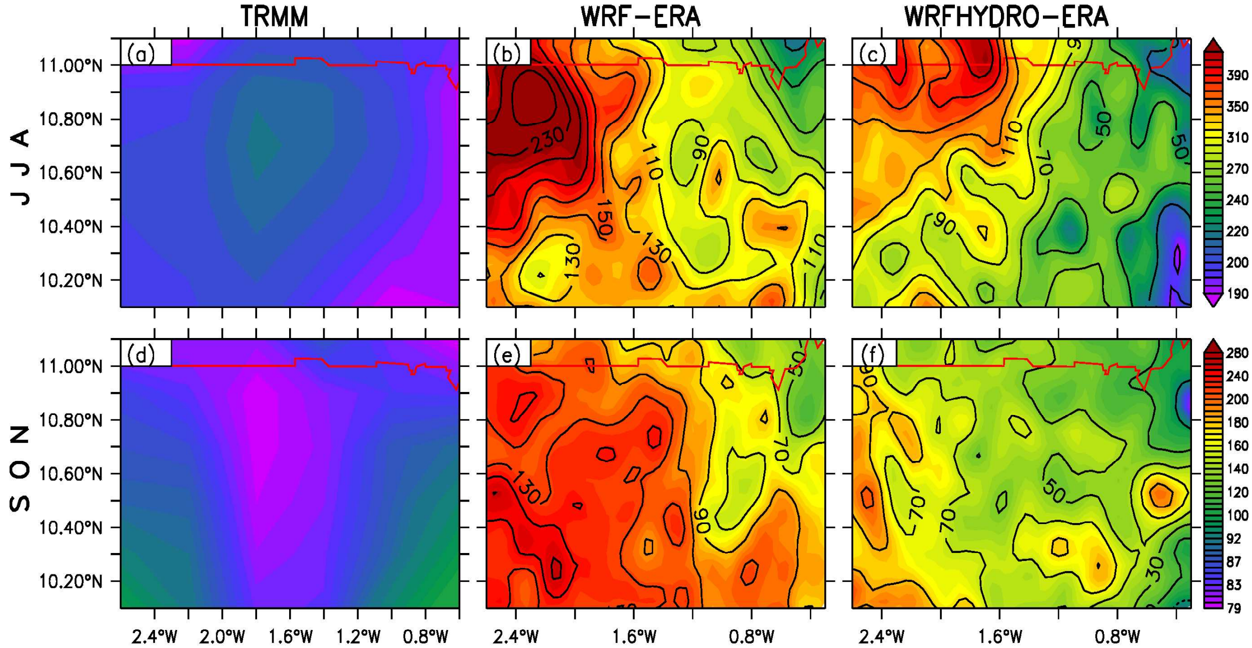

Figure 4.3 Seasonal (SON and JJA) precipitation bias maps (Obs minus model) over the Tono basin for the period 2000-2005 using ERA-I forcing data for WRF-only and WRF/WRF-Hydro simulations

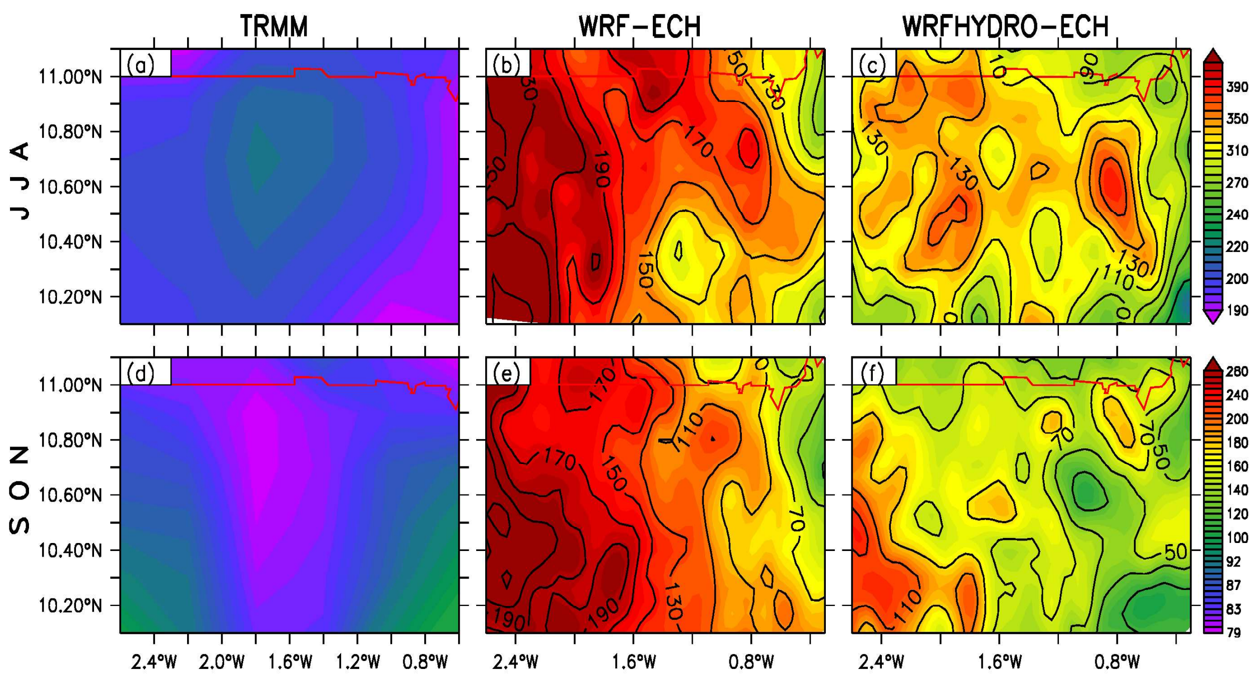

Figure 4.4 Seasonal (SON and JJA) precipitation bias maps (Obs minus model) over the Tono basin for the period 2000-2005 using ECHAM6 forcing data for WRF-only and WRF/WRF-Hydro

This could be attributed to the potential a fully coupled land-atmosphere modeling system offer for unified, mass and energy-conserving modeling of the full regional water cycle (Senatore *et al.*, 2015). Butts *et al.*, (2014) and Larsen *et al.*, (2014) demonstrated that a coupled model simulations performed more accurately than uncoupled simulations for longer than daily cumulative precipitation as has also been demonstrated in this studies. Jiang *et al.* (2009), coupled groundwater model with an atmospheric model demonstrating the importance in proper energy flux and soil moisture signal from land-surface for reproducing precipitation the over central USA. All these examples demonstrated the potential improvement coupling approach add to reproducing precipitation which has been demonstrated in this study.

4.1.2 Temperature

Figures 4.5 show the annual monthly mean temperature at the Tono dam with WRF-only and fully coupled WRF/WRF-Hydro simulations forced with ERA-Interim reanalysis and ECHAM6 data sets. Both models simulate temperature closer to observation (CRU). At the grid point of the dam, WRF/WRF-Hydro simulates temperature close to observation better than WRF-only (Figure 4.5). This is due to the coupling of land-atmosphere processes which improves on the representation of temperature variability. Zeng *et al.* (2003) demonstrated the considerable influence of land-surface temperature and moisture heterogeneities on simulations of sensible (H) and latent (LE) fluxes, which also represents evaporation estimates as well as indicate precipitation pattern. Both models forced with ECHAM6 did not adequately reproduce temperature (underestimated) during the dry season (Figure 4.5). The models forced with ECHAM6 could be indicating high soil moisture fluxes during this period which then affects the land-surface temperature representation.

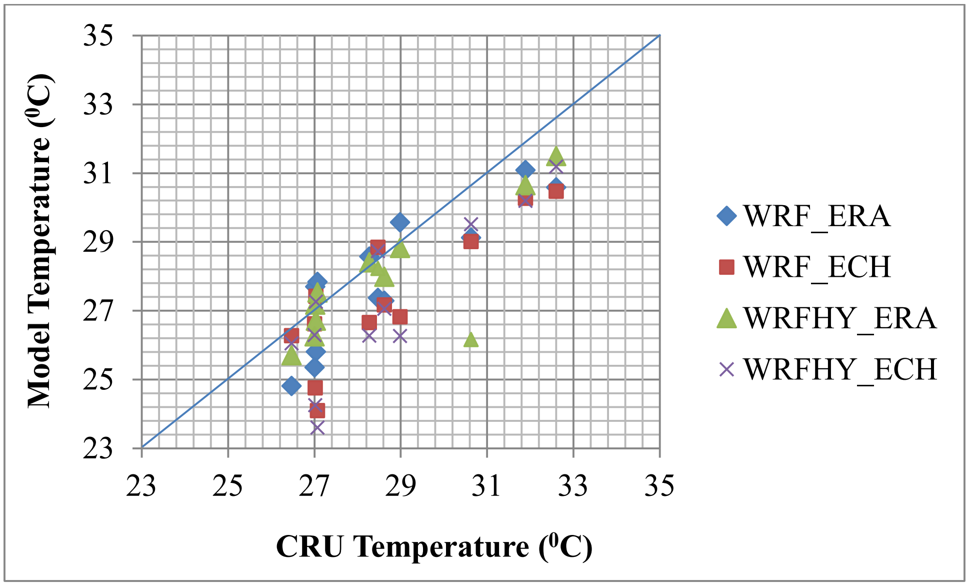

Figure 4.5 Mean monthly temperature plot over the period 2000-2005 using ERA-I and ECHAM6 data sets

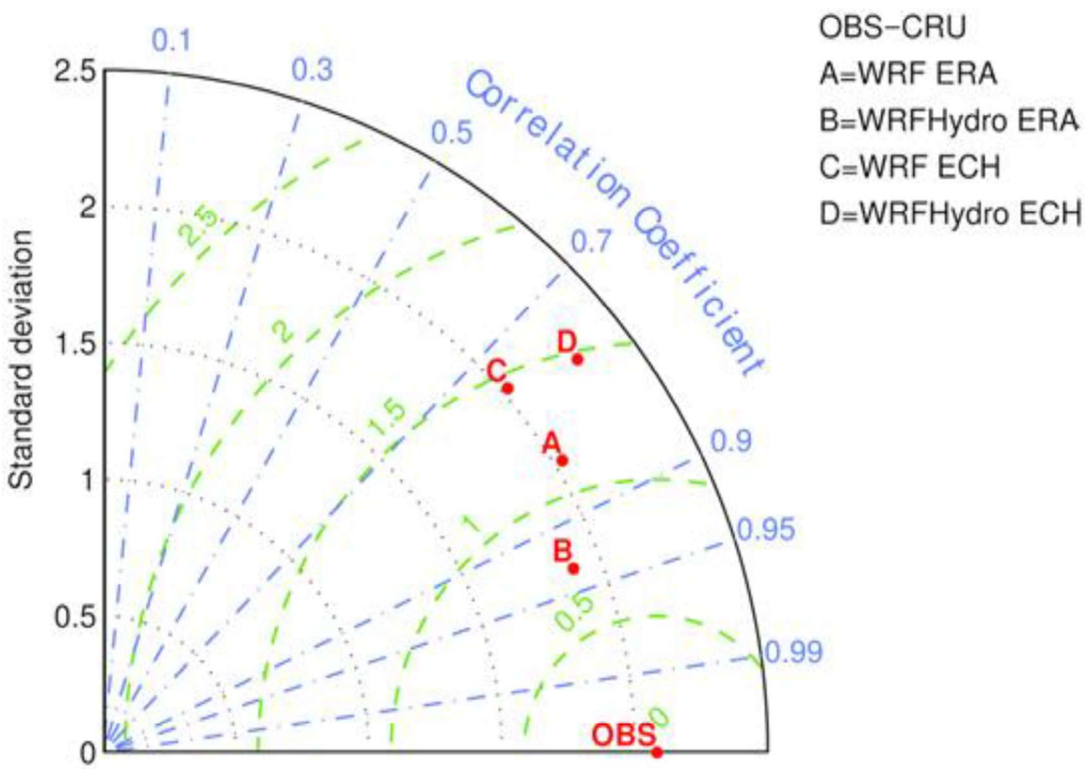

Figure 4.6 Relationship between WRF-only and WRF/WRF-Hydro temperature with respect to CRU

Figure 4.6 demonstrates the statistical relationship WRF-only and WRF/WRF-Hydro have with respect to CRU temperature at the grid point of the dam. The model B (WRF-Hydro_ERA) has a pattern of correlation of about 0.94 and its RMS error is about 0.6 ^{0}C. The standard deviation of the model B for simulated temperature (1.8 ^{0}C) is less compared to the standard deviation of the observed (2.2 ^{0}C). In the case of the model A (WRF_ERA), its pattern of correlation with observation is about 0.87, whereas its RMS error is about 1.2 ^{0}C. The standard deviation of model A of the simulated temperature (2.1 ^{0}C) is about the same with observation (i.e. 2.2 ^{0}C) which implies the pattern of variations is of the right amplitude (i.e. same magnitude as the observations). Model C (WRF_ECHAM6) and D (WRF-Hydro_ECHAM6) exhibit similar characteristics. They both have the same pattern of correlation of 0.78 and quite the same RMS error of 1.4 ^{0}C. However, the standard deviation of the simulated temperature (2.0 ^{0}C) in the model C is quite close to observation (2.2 ^{0}C). The standard deviation of the simulated temperature (i.e. 2.6 ^{0}C), in the model D, is higher than the observed (i.e. 2.2 ^{0}C). The results of model C and D in temperature simulation confirms similar results in precipitation assessment that ECHAM6 model data does not give good agreement with observation.

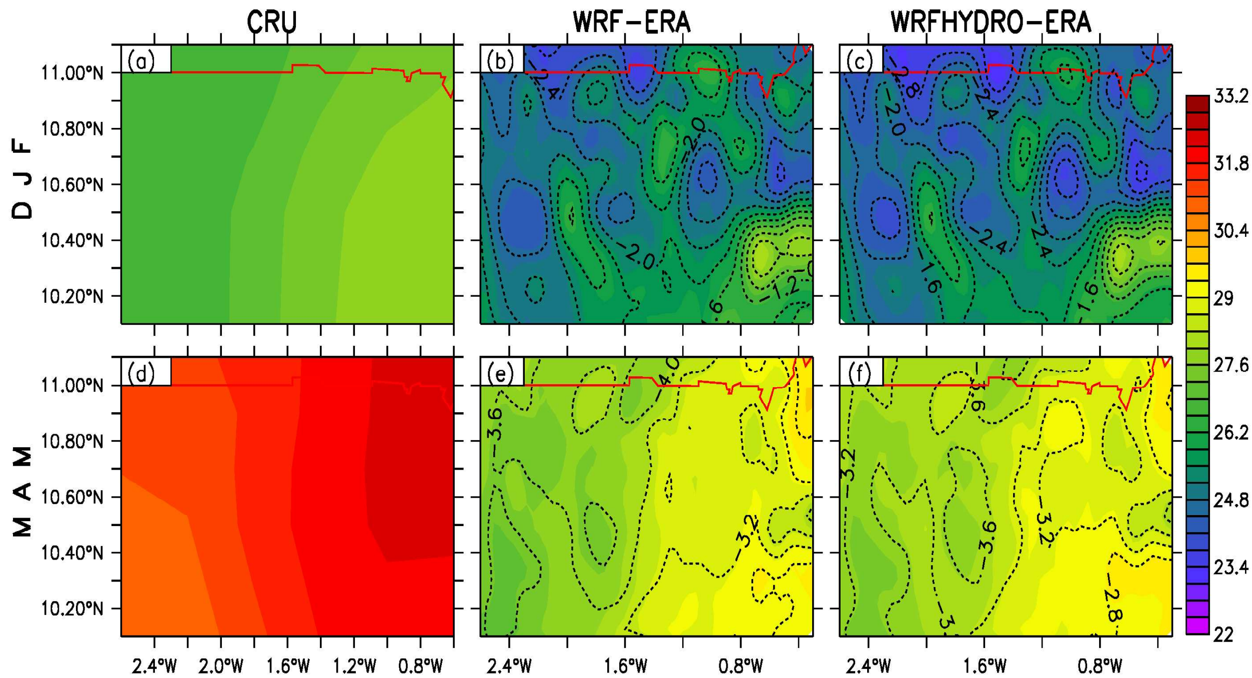

Figure 4.7 Spatial temperature bias maps (Obs minus model) over the Tono basin for the period 2000-2005 using ERA-I forcing data for WRF-only and WRF/WRF-Hydro simulations

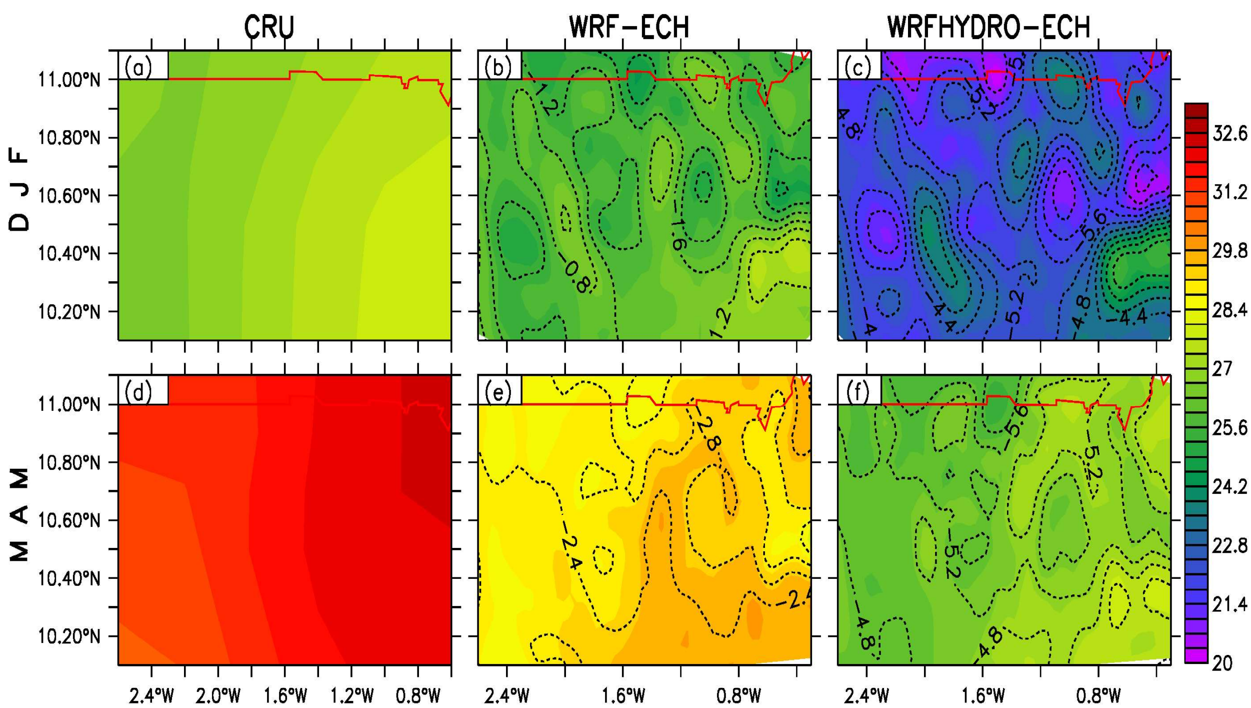

Figure 4.8 Spatial temperature bias maps (Obs minus model) over the Tono basin for the period 2000-2005 using ECHAM6 forcing data for WRF-only and WRF/WRF-Hydro simulations

The spatial seasonal temperature bias maps as presented in figure 4.7 and 4.8 confirm the result presented in the Taylor diagram (Figure 4.6) with both models indicating negative bias (underestimating). For the season DJF, WRF/WRF-Hydro forced with ERA-I had higher negative bias compared with WRF-only forced with ERA-I while for MAM season, WRF/WRF-Hydro had lower negative bias than WRF-only (Figure 4.7). In the case of both models forced by ECHAM6, WRF/WRF-Hydro did not perform well with respect to DJF and MAM seasons, with higher negative bias than WRF-only at the basin. Generally, WRF/WRF-Hydro has demonstrated simulating temperature better especially at the period when the temperature is usually noted to be high over the basin. The results support earlier studies by Zabel and Mauser, (2013) which indicated that fully coupled atmosphere-hydrology model simulation improved near-surface temperature. ECHAM6 model data as was the case with precipitation estimates did not produce good results with temperature estimation. Apart from the choice of the forcing data and the coupling approach influencing the performance of the model with respect to precipitation and temperature estimates, the other possible factor is the optimum physics options obtained by Heinzeller *et al.*, 2014 for WRF-only over the West Africa region. This physics option which was applied for this study may not be suitable when using WRF/WRF-Hydro configuration; secondly, the optimum physics option may not be the optimum in the Tono basin (microscale effect).

4.2 WRF-Hydro for Water Resources Assessment

4.2.1 Precipitation

Any assessment between water amounts of various hydrological variables only makes sense if precipitation inputs are equal or, at least, comparable. This situation is complicated by the fact that soil moisture can significantly influence precipitation (Findell *et al.*, 2011; Senatore *et al.* 2015). For this reason, the model assessment starts with precipitation. Precipitation estimates from the WRF model at the inner domain (WRF5) and the outer domain (WRF25) can be seen to be different. The difference in precipitation estimates could be due to the size and the horizontal resolution of the different domains. The expectation is that finer domain would give a better estimation than the coarse domain; however, this was not the case (as seen in Figure 4.9a and 4.9b). It is possible that due to the size of the finer (inner) domain, the boundary conditions were not well resolved. Precipitation estimates from the outer domain are quite close to the observed precipitation at the Tono basin (figure 4.9b), which also confirms the effect of the size of the domain. The effect of irrigation on soil moisture could also force significant changes in spatial distribution and magnitude of rainfall, depending on the latitudinal location of the irrigation scheme (Marcella and Eltahir, 2014). The other reason could be attributed to coupling the hydrological model with the inner domain of the atmospheric model, which has shown to have a feedback effect in precipitation estimates (Figure 4.9a). Using different infiltration partition parameter (kdtref) values tend to influence the soil moisture characteristics, which can significantly influence the precipitation amounts, hence different corresponding precipitation estimates. The calibrated model though exhibits the precipitation trends with respect to observed precipitation; however, the model tends to inherit the bias in the driving data (ERA-Interim) in estimating precipitation amounts.

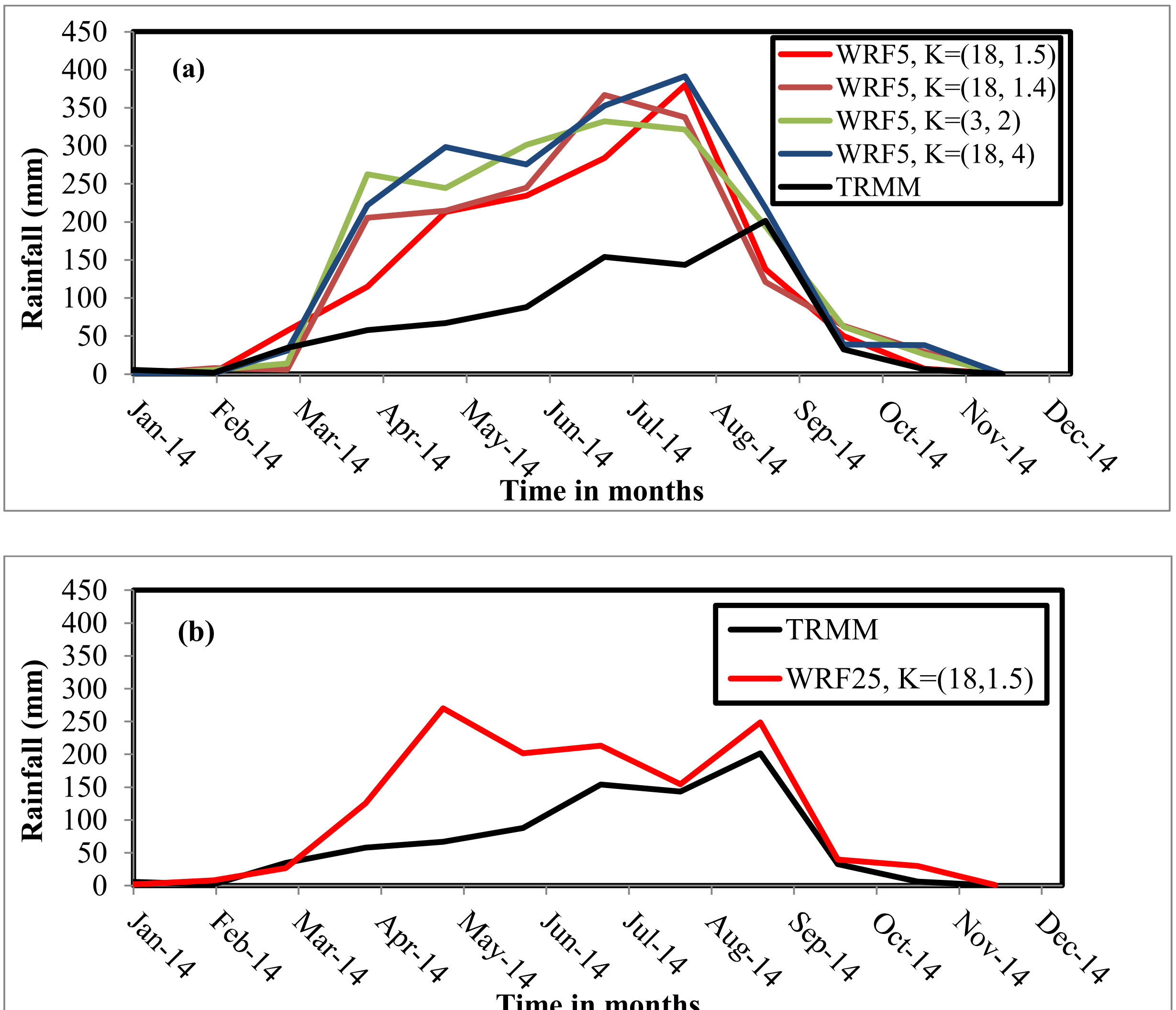

Figure 4.9 (a) Feedback effect of coupling hydrological model with atmospheric model on precipitation estimate and (b) model precipitation plot at 25 km horizontal resolution

4.2.2 Streamflow

The performance of the streamflow calibration based on different kdtref is summarized in Table 3.1. The annual sum of streamflow as presented in table 3.1, shows that K= (18, 1.5) gave closer estimate compared to observed flow. This is also evident from the hydrograph (Figure 4.10a). From table 3.1, both K = (18, 1.5) and K = (18, 4) gave good model performance with respect to RMS error statistics, whereas K = (3, 2) and K = (18, 1.4) gave the worst model performance. This could be attributed to the infiltration partition parameter (kdtref), the lower this parameter the higher the runoff. In relation to the PBIAS statistics performance, K = (18, 4) showed a definite tendency to underestimate, however, K = (18, 1.5) though from the PBIAS statistics underestimates the streamflow, the extent of bias is so small to conclude that it will be same for every year. Both K = (3, 2) and K = (18, 1.4) indicate a higher tendency to overestimate streamflow. Table 3.1 shows that the streamflow calibration of K = (18, 1.5) tend to be efficient with NSE statistic value of 0.78 for the reference period of calibration (2014). The other calibration options did not give good performance in relation to NSE, with K = (18, 1.4) and K = (3, 2) giving negative values. The same performance was shown with respect to Pearson's correlation. The calibration option K= (18, 1.5) showed a strong relationship with the observed streamflow with a correlation of 0.89, and therefore could produce the features of the observed streamflow. The foregoing results as presented in table 3.1 and figure 4.10a indicate the K = (18, 1.5) gives the best performance in estimating streamflow for the Tono basin.

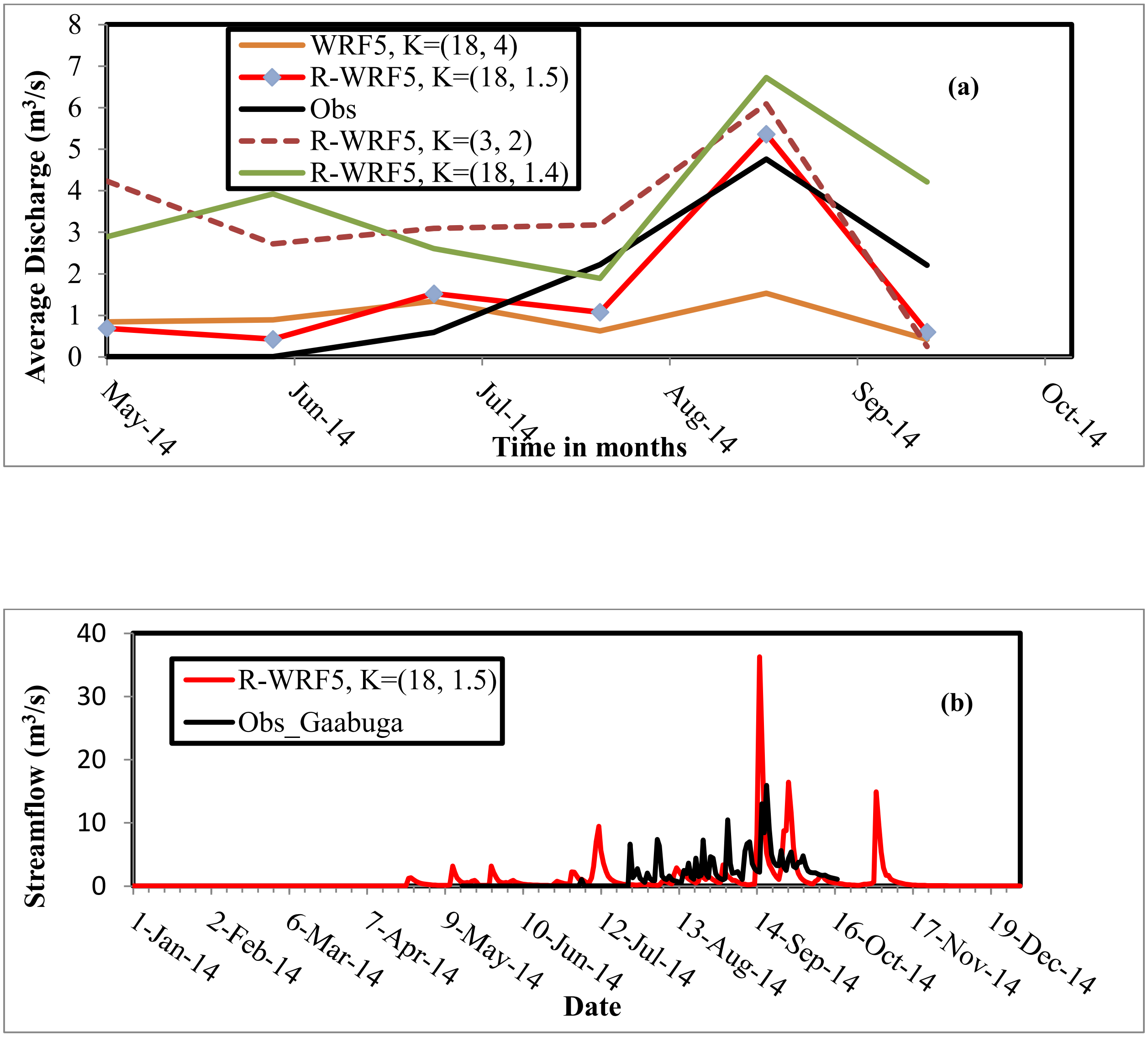

Figure 4.10 (a) Streamflow calibration based on different kdtref test for WRF at 5 km horizontal resolution, (b) calibrated daily streamflow with observed streamflow

It can also be seen that the kdtref has an influence on the streamflow estimates with respect to its choice of the coarse domain and the fine domain. When the default value is chosen for the coarse domain, the calibration of the streamflow is based on the choice of the kdtref for the fine domain. However, changing both the kdtref [K= (3, 2)] for the coarse and fine domain has shown to have a significant influence on the streamflow estimates, though in this case the result is not good as compared to maintaining a default kdtref for the coarse domain. It makes this approach of calibration quite laborious and time-consuming because the right kdtref to be set as the default for the coarse domain has to be determined before calibrating with respect to the fine domain which is coupled to the hydrological model. Interestingly K = (18, 1.4) which was the optimal kdtref for the streamflow estimates at the Sissili basin (Arnualt *et al.*, 2015) and therefore was used as the reference which actually did not meet the statistical performance criteria at the Tono basin. This indicates that different basins have their unique hydrological characteristics, especially in this particular region. The calibrated streamflow exhibits the same trend with the observed streamflow; however, the calibrated streamflow has a sharp recession (Figure 4.10a), likely due to a weak parameterization of the interflow processes. This drawback might also be connected to the simplified base flow model. The main flood pulses are dominated by fast surface runoff responses; infiltrated water must first pass slowly through the soil column before contributing to streamflow, well after the event and only as small changes in baseflow. Daily streamflow assessment shows the model appears to perform reasonably well in the simulation of Gaabuga streamflow (Figure 4.10b), particularly given a strong seasonality of the hydrologic regime. Figure 4.11a and figure 4.11b shows the streamflow estimates extended for the period 2000 to 2007 and its relationship with precipitation (at the Gaabuga sub-basin). Figure 4.11a and figure 4.11b shows the peak runoff (discharge) occurs one month after the peak rainfall, indicating a one-month lag period between the hyetograph and the hydrograph. The onset of rainfall at both gauges does not generate immediate runoff due to the infiltration and channel characteristics.

4.2.3 Tono dam water balance assessment

The approach used in estimating evaporation compared to observed evaporation data at the Tono dam showed a good correlation of 0.64 (Figure 4.12). The model evaporation (WRF5_ET_Tono) overestimates (positive bias) evaporation compared to the observed evaporation and this could be attributed to the bias in the model precipitation. The long-term assessment of evaporation at the dam presented in Figure 4.13 shows considerable variability. Interestingly the period 2005 to 2007 had lower evaporation estimates.

Evaporation constitutes the largest proportion of the water budget (Kumambala, 2010). The rate of evaporation relates to the temperature trend (Figure 4.14) over the dam and the humidity of the air above the dam. More water is evaporated during the dry season (January to April) when the temperature is high and the air is less humid, whereas loss of water due to evaporation is less during the raining season (May to September) when the temperature is low and the air is more humid. This characteristic influence the amount of water stored in the dam, hence the variation in dam levels.

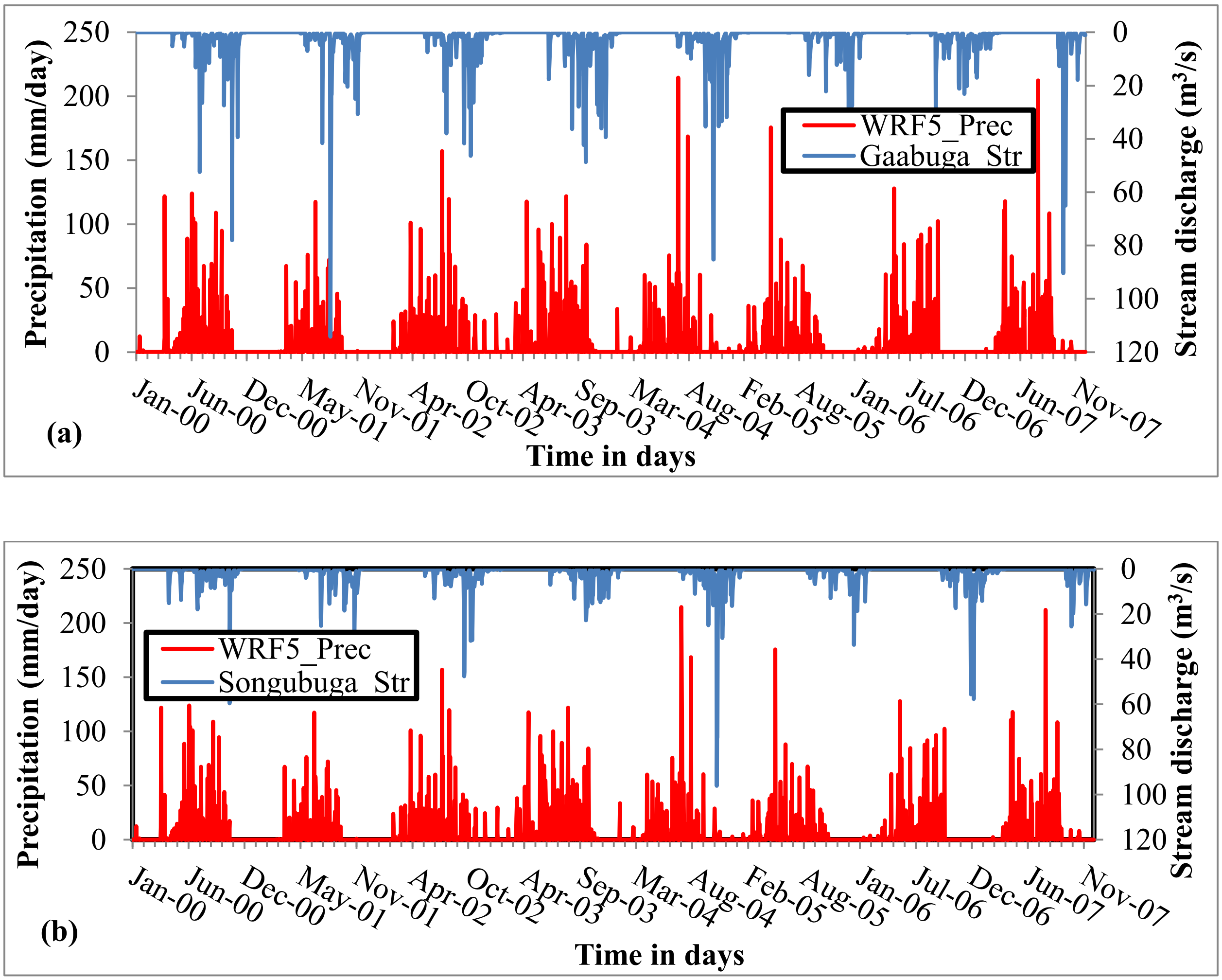

Figure 4.11 Calibrated model hydrograph in relation to hyetograph at (a) Gaabuga and (b) Songubuga sub-basin

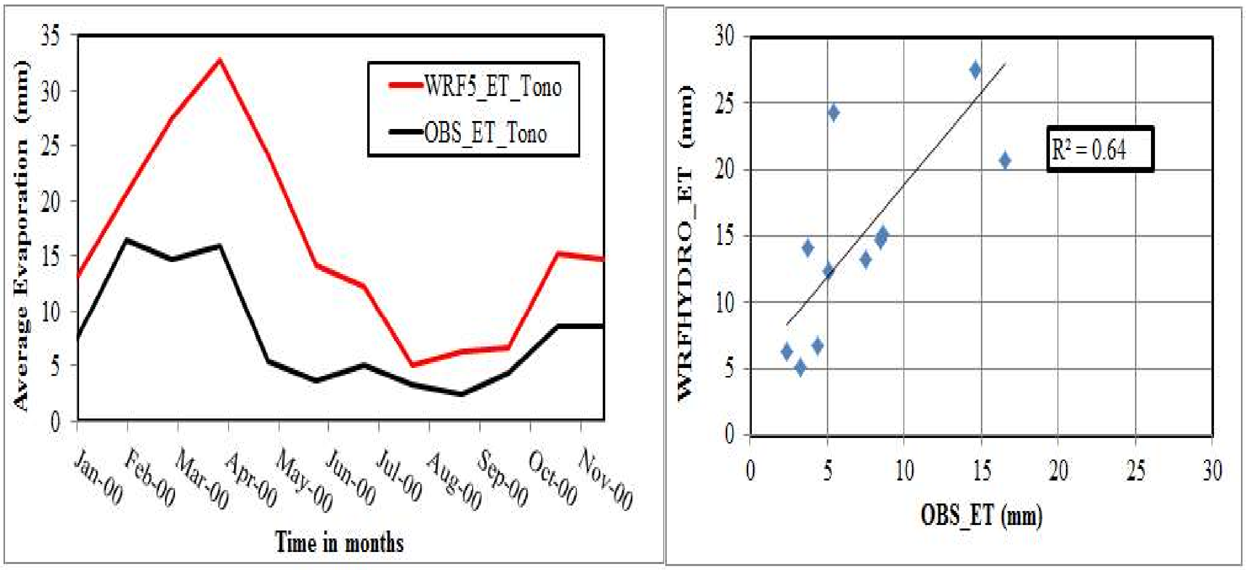

Figure 4.12 WRF5 evaporation compared with observed evaporation at the Tono dam

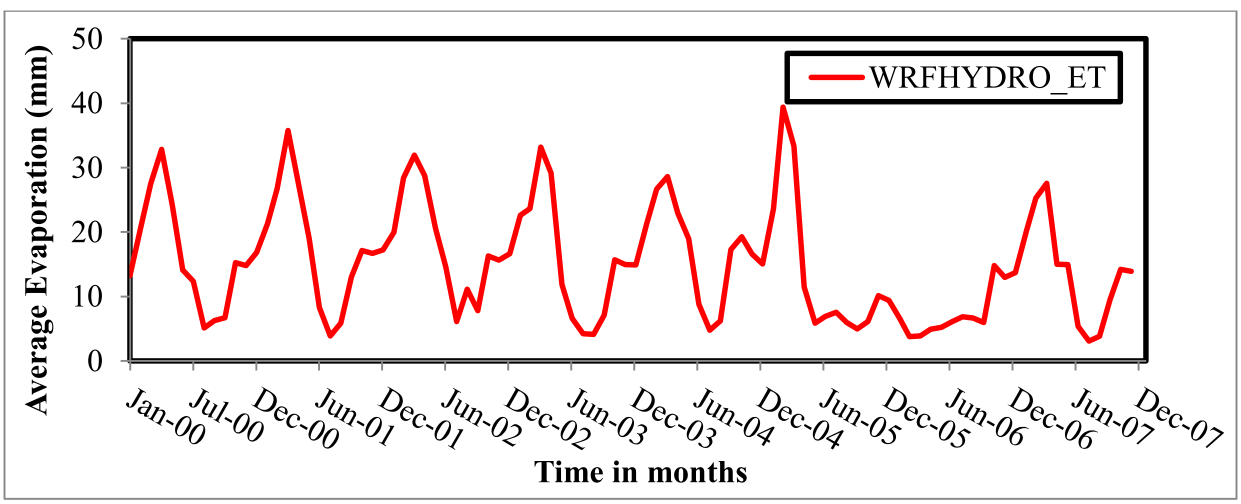

Figure 4.13 Long-term assessment of simulated evaporation at the Tono dam

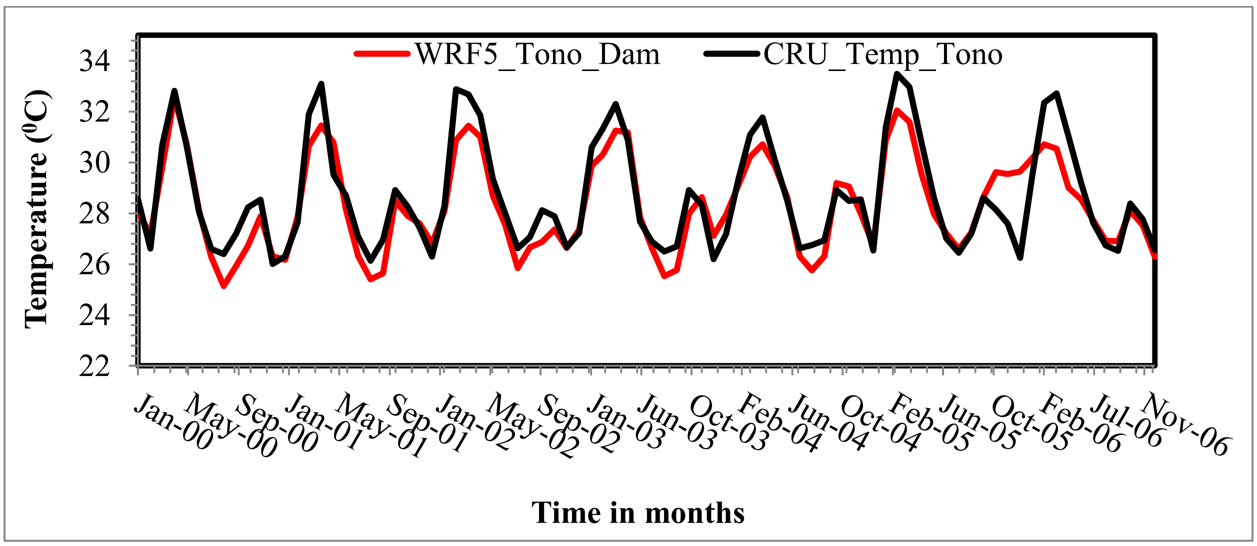

Figure 4.14 WRF5 air temperature compared with CRU temperature at the Tono dam

4.2.4 Tono dam water budget characteristics

A water budget reflects the relationship between input and output parameters of a hydrological system. The water budget illustrated in Figure 4.15 shows the relationship of the parameters controlling the Tono dam water budget. Precipitation and evaporation relationship is one of a supply of water and the natural demand for water. It also gives an indication of periods (July-September) with a lot of precipitation and when there is not enough (October-May). These two parameters control the variation of the dam level. The dam is purposely for dry season (October-May) irrigation activities. The supply of water from the dam for irrigation depends on the water level of the dam. Figure 4.15 shows that more water is released (outflow) during the dry season and more water available during the raining season (May-October) when evaporation is low and there is low release (outflow) of water for irrigation activities. What is uncertain is the peak evaporation in April. This is likely to be caused by low relative humidity with increase air temperature at this period. This phenomenon of the water budget of the Tono dam provides the basis for water management decisions, policies, and adaptation. It provides more understanding of the dam level variations and how this could be taken into account for reservoir sizing to support the supply and demand relationship of the water resource.

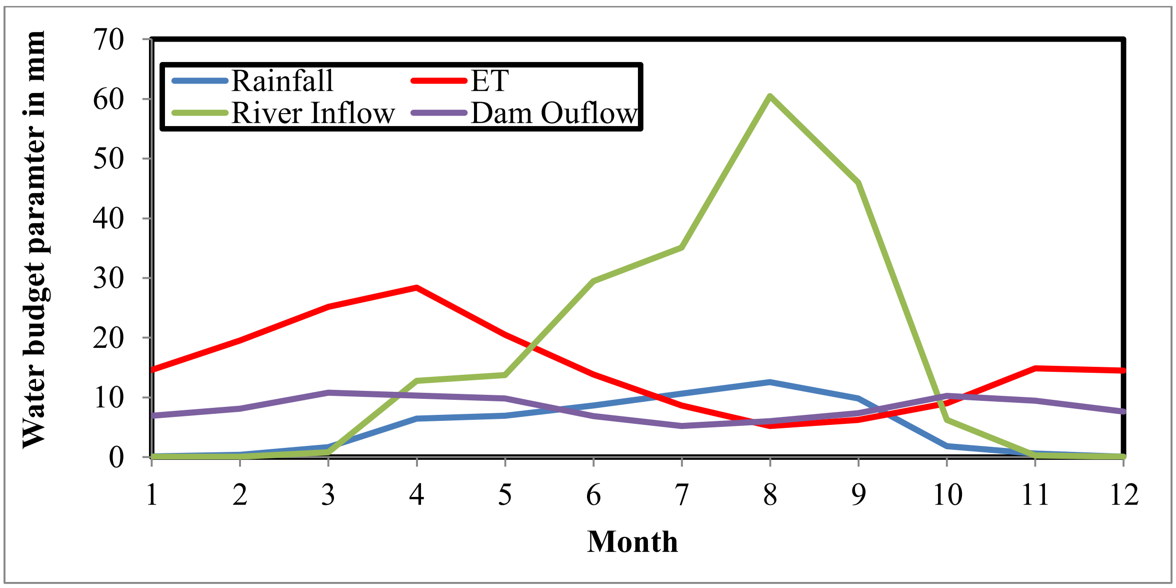

Figure 4.15 Tono dam water budget characteristics

4.2.5 Dam level simulation

Based on the calibration of the hydrological model in relation to its kdtref and Manning's coefficient as described, the simulation was carried out for 1999 to 2007 (using the year 1999 as the spin-up) to extend the streamflow. The performance of the model in reproducing streamflow for the historical period (2000 to 2007) was assessed based on the dam level estimation. Both streams have an annual runoff-precipitation ratio of 12% -13%. This ratio is influenced by the choice of the calibration parameter (kdtref). The outflow from the dam is controlled (or regulated) by the managers of the Tono dam. The rate and amount of water released (R_{out}) is dependent on the dam level (H_t). The observed outflow data was used in the computation of the dam level of the Tono dam. This is based on the assumption that the outflow for that period remains the same. The correlation of the simulated dam level at the daily scale compared to the observed dam level is 0.82. This indicates the strength of the WRF-Hydro model in simulating hydrological (e.g. streamflow) and meteorological (rainfall, temperature) variables at the Tono basin. On a monthly scale assessment of the model, it shows general agreement with the observed dam levels and a correlation coefficient (R^2) of 0.81, (Figure 4.16).

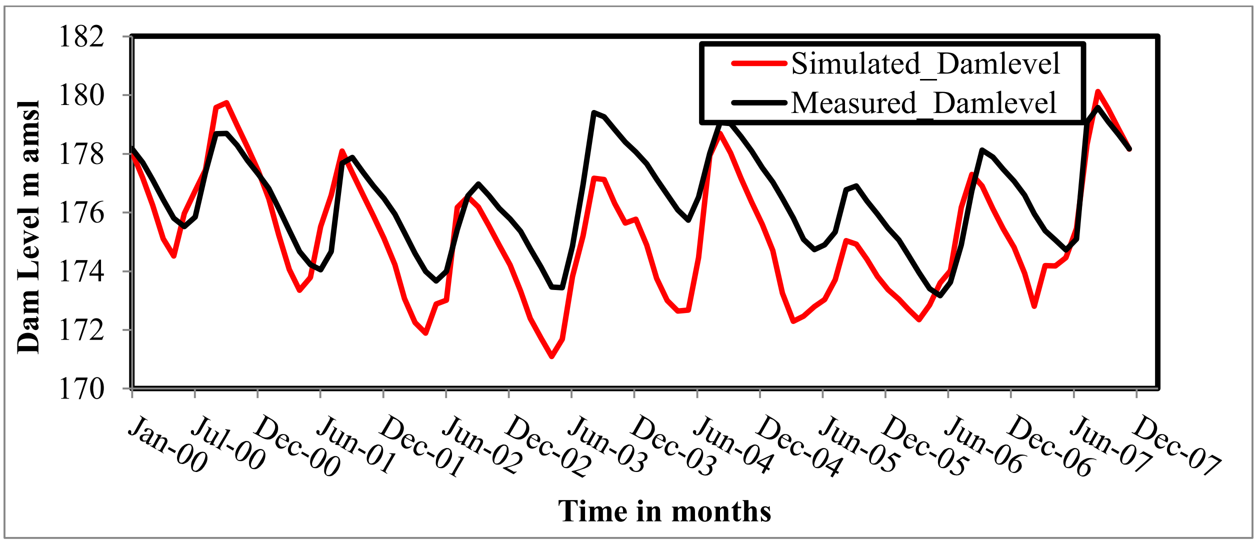

Figure 4.16 Comparison between observed dam level and model dam level between 2000 and 2007 using the relation: $H_t = H_{t-1} + P(t) + Inf(t) - E(t) - R_{out}(t)$ assuming the initial level (H_o = 178.4m amsl)

4.3 Modeling Climate Change Impact on Water Resources

To assess the sustainability of the water resources of the Tono basin and the water levels of the Tono dam, it is necessary to model how these resources will behave in the future. Most studies have documented that the future water availability will be affected not only by population increase but also by climate change. Such changes are likely to have far-reaching consequences on every aspect of human well-being, agriculture and energy production, flood control and ecology of freshwater environments. Modeling the impact of climate change on water resources will require long-term data including the past and estimated future data set (Kumambala, 2010). Inadequate long-term data in this region is a major challenge. The coupled model approach was not also successful in running with future global climate model data so as to generate flows. This section presents the assessment of climate change and its consequent impact on runoff regime, hence on the water resources of the Tono basin. The section explores the changes in precipitation and temperature based on the Representative Concentration Pathways (RCPs) and how these changes will influence future streamflow into the dam and consequently the variations in the water level of the dam.

4.3.1 Climate change based on Representative Concentration Pathways (RCPs)

Studies on climate change impact depend on projections of future human activities. IPCC over the years continues to improve emission scenarios to be used in driving GCM to develop climate change scenarios. Its recent development is the Representative Concentration Pathways (RCPs), published in its Synthesis Report, 2014. IPCC describes emission scenarios as an alternative image of the future socio-economic, demographic and technological change. Anthropogenic GHG emissions are driven mainly by the factors mentioned. The RCPs, which is used for making projections, based on these factors, describe four different 21^{st} Century pathways of

GHG emissions and atmospheric concentrations, air pollutant emissions and land use (IPCC, 2014). The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5) as indicated in Figure 4.17. This study focused on the intermediate scenarios (RCP4.5) and the extreme scenario (RCP8.5) to understand how each of these scenarios will influence future climate and streamflow over the Tono basin.

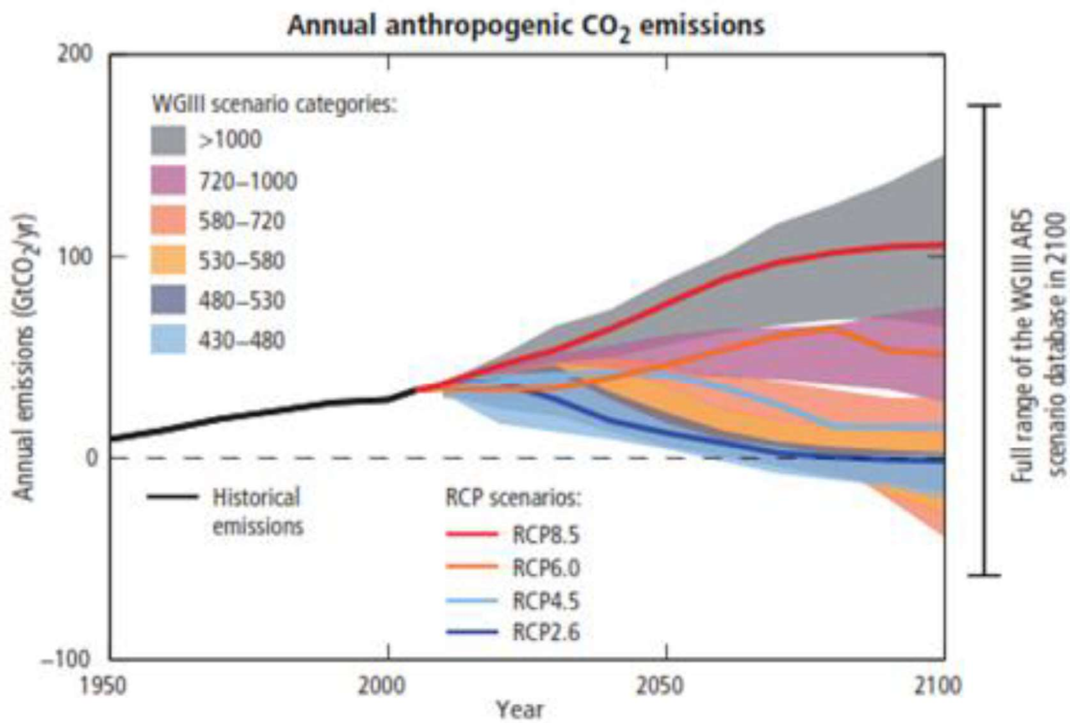

Figure 4.15 Global GHG emissions (in $GtCO_2$-eq per year) based on RCP scenarios (IPCC, 2014)

4.3.2 Climate change; Precipitation

Figure 4.18a presents the variations in average daily precipitation rate at the Tono dam and figure 4.18b presents the percentage change in precipitation. RCP4.5 generally shows an increase in precipitation compared to RCP8.5 (Figure 4.18a). Using ECHAM6 model data as the baseline or controlled time slice (for the period 2000-2005), both RCPs indicate about 95% to 98% increase for February, whereas in March RCP8.5 indicated a decrease (-30%) in percentage and RCP4.5 indicate about 50% increases in precipitation. Between the onset of rainfall (April) to the peak rainfall (August), RCP4.5 indicates a percentage increase of rainfall ranging from 10% to 25% with the exception of May for which it indicated a decrease in precipitation (-30%). During this period RCP8.5 also indicated an increase in precipitation (5% to 15%), with the exception of June, which had a decrease (-15%) of precipitation. Both scenarios indicate a decrease of precipitation at the climax of the rainfall period (September-October). Between November and December, RCP4.5 indicates a precipitation percentage change of 90% to 100% respectively. With respect to the two emission scenarios, RCP4.5 indicated higher annual rainfall amounts with an annual relative percentage change of +7.4% and RCP8.5 indicating annual relative percentage change of -9.6%.

Rainfall is the major source of runoff generation and input to the Tono dam. Examining these two scenarios the implication is that, RCP4.5 would likely increase runoff generation over the basin for the period 2020-2025, whereas RCP8.5 would likely lead to a decrease in runoff generation over the basin for the same period. The dam level variations will depend on temperature and humidity characteristics (i.e. evaporation) projected by these scenarios.

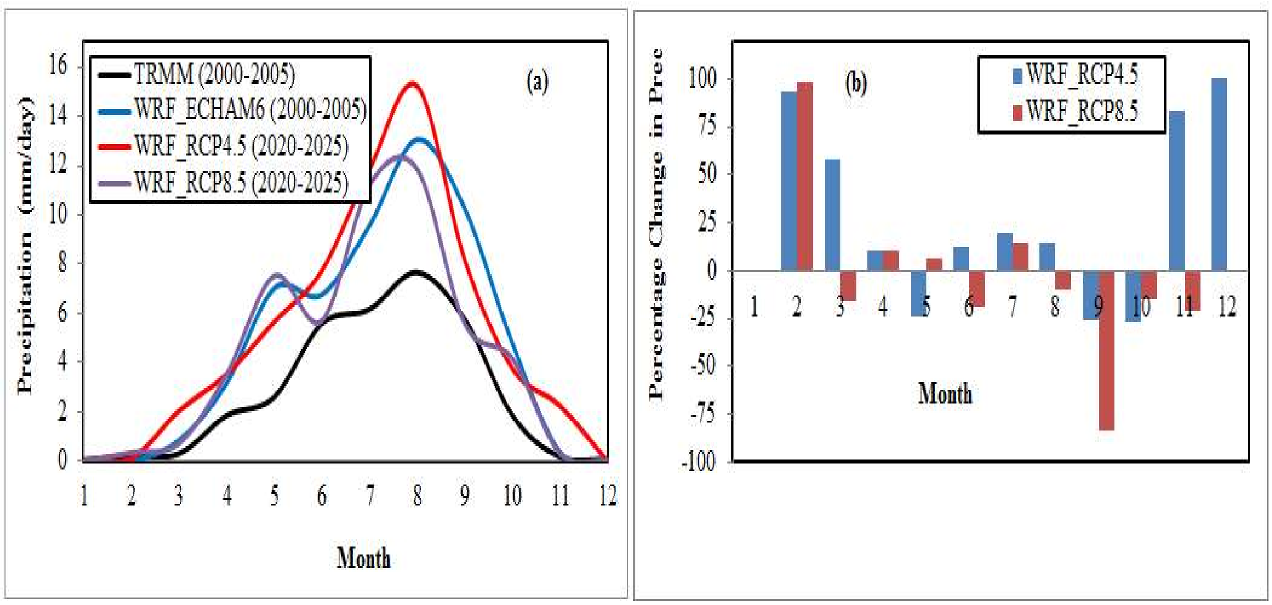

Figure 4.18 Precipitation change assessment of projected period (Ps) and controlled period (Pc) with a time slice of 2020-2025 and 2000-2005 respectively

The IPCC climate projections in 2007 indicate increases in precipitation amounts are very likely in the high latitudes and decreases are likely in the subtropical land regions by as much as 20% in the A1B scenario in 2100. However, the climate models fail to agree on the sign of the future evolution of precipitation over West Africa. About 50% of these models predict an increase in rainfall and about 50% agree on a decrease (Vigand *et al.*, 2011; Berg *et al.*, 2013), but project changes ranging from -20 to 20% in annual rainfall (Sultan *et al.*, 2013).

Figure 4.19 presents the seasonal variations of the precipitation change of the two RCPs with respect to the controlled period. The major rainfall seasons at the basin are June, July, August (JJA) and September, October, November (SON). Both scenarios capture the position of intense rainfall (towards the west). RCP4.5 at the Tono basin for JJA season indicates a precipitation change ranging from 20 to 50 mm, whereas RCP8.5 indicates a decrease in precipitation change of -10 to -40mm. However, both scenarios for SON season indicate a decreasing precipitation change; with RCP8.5 showing higher decreasing values (see also Figure 4.18b). RCP4.5 presents a case of intense rainfall and shorter duration. A shorter duration will not generate adequate flows into the dam to sustain irrigation activities. This is even worse when we consider the RCP8.5 scenario. However, it is important to note that both scenarios project the precipitation patterns of the controlled period. The sign or magnitude of change is quite different depending on the season (Figure 4.19).

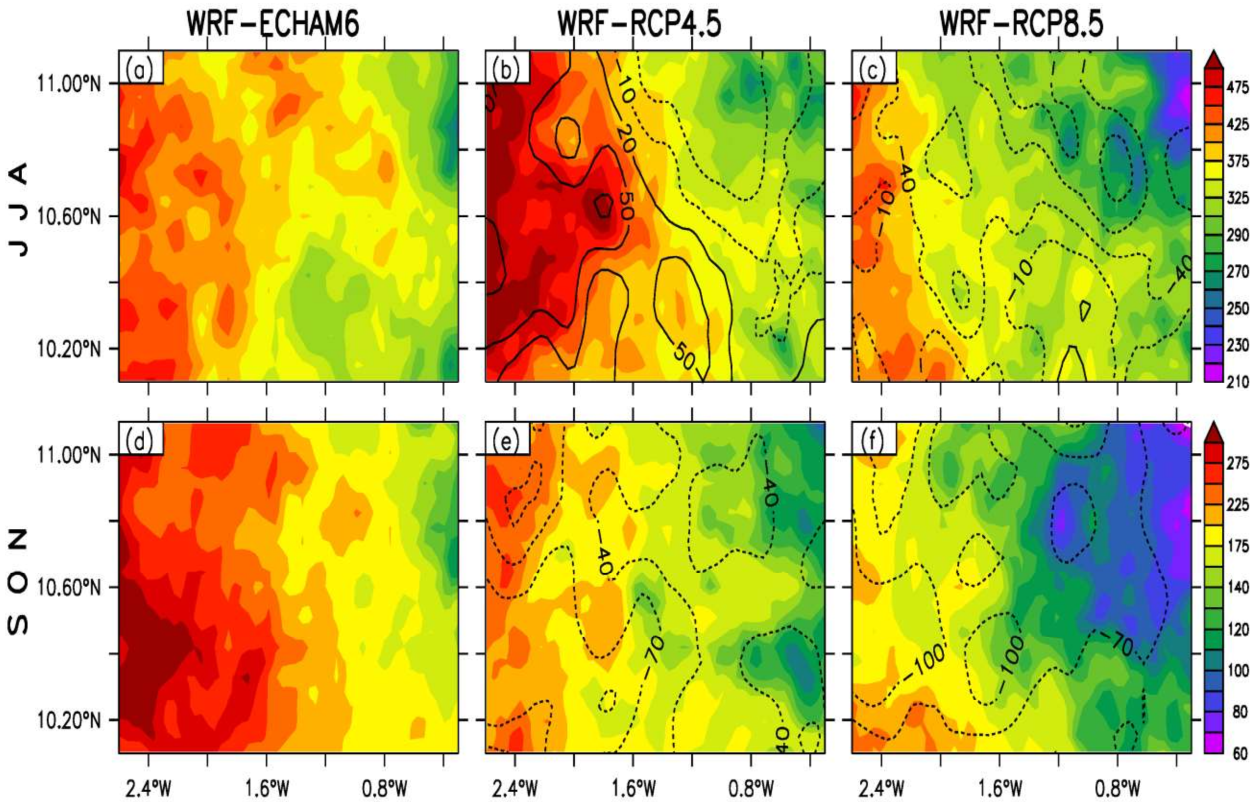

Figure 4.19 (a) to (c) JJA and (d) to (f) SON seasonal precipitation change (bias) maps. Precipitation for controlled period (ECHAM6, 2000-2005) and Precipitation for projected period (RCP4.5 and RCP8.5, 2020-2025) over the Tono Basin

4.3.3 Climate Change; Temperature

The variation in annual temperature of both RCPs with respect to the control period is minimal. However, both scenarios give temperatures lower than the observations from January to April and higher than the observations from May to October and then lower than the observations again from November to December (Figure 4.20a). Figure 4.20b present the percentage change in temperature for the RCPs with respect to the control period. The temperature change depicts the annual variation. RCP4.5 indicates colder condition than RCP8.5 for January to April with a percentage ranging from -0.5% to -8.2%. RCP8.5 scenario produces warmer conditions than RCP4.5 scenario for the period from May to October with temperature change ranging from 1% to 7%. The increase in temperature change at this period would influence evaporation, hence reducing the water level in the dam. The last two months of the year experience cold temperature conditions by both scenarios indicating a decreasing change in temperature (~ -7%). This characteristic is expected to result in lower evaporation, hence more water available in the dam.

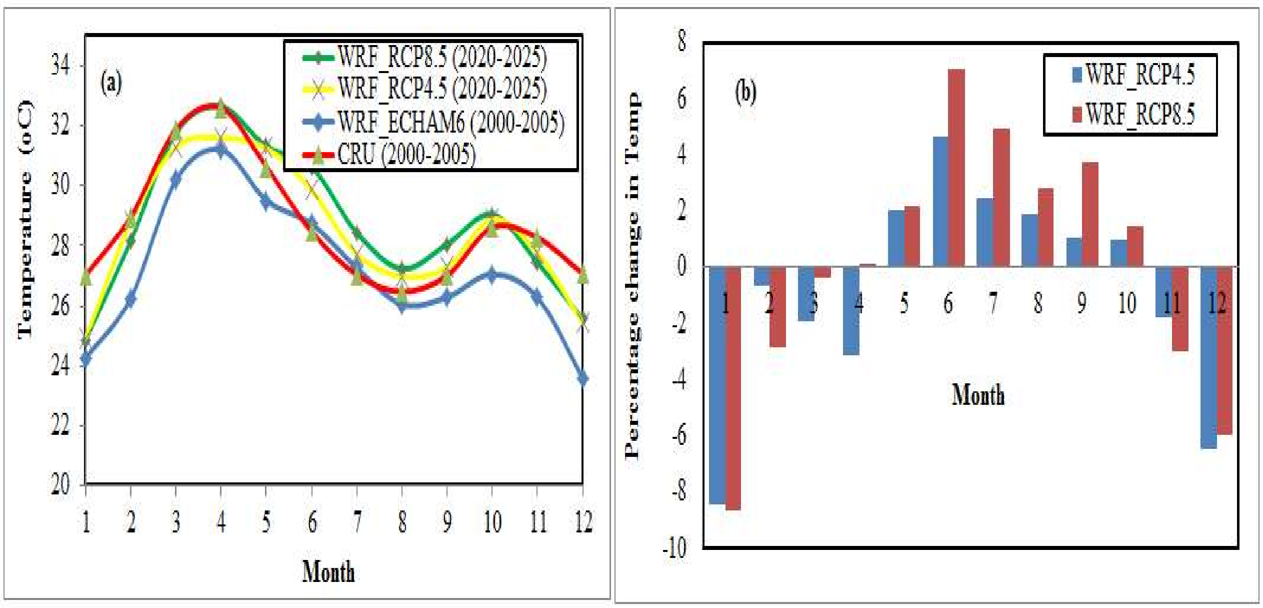

Figure 4.20 (a) Annual cycle of temperature for projected period (Ps) with respect to controlled period (Pc) (b) Percentage change in projected temperature over the Tono Basin

The change in mean monthly temperature for RCP4.5 relative to the controlled period is +1.2 ºC and for RCP8.5 is +1.5 ºC. These increases in temperature are high compared to the controlled period, thus indicating warmer conditions, which, will trigger evaporation, hence affect the hydrological cycle. The temperature projections are within the range of IPCC, 2007 report. The temperature change projections based on the SRES emission scenarios indicated a range from +0.6 ºC (constant year 2000 concentration) to +4.0 ºC (A1FI scenario) for the end of the 21st Century (2090 – 2099), (IPCC, 2007). Projections all agree on a warming in WA even though its magnitude ranges from +2 to + 6 ºC in 2100 across climate models (Christensen *et al.*, 2007).

The seasonal change in temperature as presented in figure 4.21 indicates RCP4.5 scenario having lower temperature change (between +0.4 to +1.6 ºC) compared to the RCP8.5 scenario (+0.8 to +2.2 ºC) over the Tono basin.

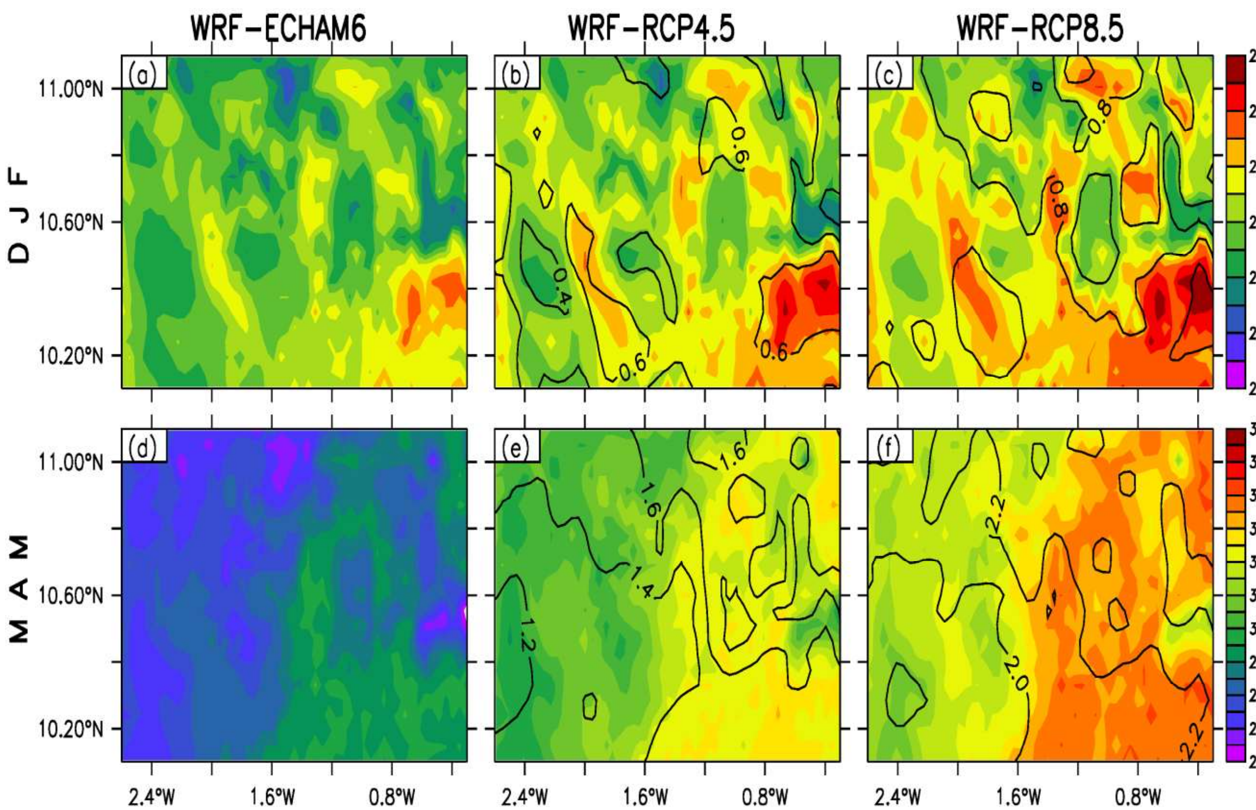

Figure 4.21 (a) to (c) DJF and (d) to (f) MAM seasonal temperature change (bias) maps. Temperature for controlled period (ECHAM6, 2000-2005) and Temperature for projected period (RCP4.5 and RCP8.5, 2020-2025)

In summary, RCP4.5 indicates an increase in percentage change in precipitation, especially during the rainy season. The change in precipitation is characteristic of high intensity and short duration. Earlier studies by Biasutti and Sobel, (2009), describe the changes in the rainy season over West Africa as one of a delayed onset and early cessation and thus shortening of the rainy season. The RCP4.5 Scenario also projects an increase in temperature change though lower than RCP8.5 during the rainy season. However, during the dry season (November to April), it projects a cold temperature regime. The implication of this scenario is that more heavy flows during the season, however, the water levels of the dam could be influenced by increased evaporation during this period. Evaporation at the basin is expected to be lower during the dry season; due to cold temperature projections thus the rate of decreasing dam levels will be low. This could support irrigation activities. RCP8.5 projects lower precipitation change and increasing temperature change. This scenario could lead to less runoff; high evaporation thus lowers dam levels and the possibility of the dam going dry if the trend continues.

4.4 Water Resources Management and Adaptation Strategies

Most studies have shown that discharge evolutions over the past decades in West Africa (WA) have been strongly affected by rainfall variations. After the wet 1950s and 1960s, a strong rainfall deficit has been happening since 1970 in the Sahelian and Sudan-Sahelian regions (Paturel *et al.*, 2003) with dramatic droughts like the 1973/1974 and 1983/1984 cases (Roudier, *et al.*, 2014). Recent studies by Lebel and Ali (2009), however, suggest a recovery of the rain in eastern parts of WA, whereas drought conditions continue to prevail in the western parts. These rainfall variations have led to strong fluctuations in river discharge with a generally negative trend from 1960 to 2010 (Descroix *et al.*, 2013), mostly in Sudanian parts. Though it is also the case in Gulf of Guinea areas, the decrease is quite moderate. The non-linear effect of this rainfall drop over much of WA underlined by Mahe *et al.* (2013) indicates a 20% decrease in rainfall resulting in a decrease of 60% in the runoff. The characteristics of WA climate and climate projections carried out by previous studies have been confirmed in this current study over the Tono basin. Both scenarios present a potential threat to the future of the hydrological cycle of the Tono basin. A decrease in rainfall and increasing temperature will have consequences on the availability of surface and sub-surface water, which intends affect, other sectors that depend on this water resource. The magnitude or percentage change in future stream flows remains uncertain over WA and in this particular study it was not immediately possible to quantify it. This uncertainty stems from the fact that, precipitation projections are quite uncertain and most of the scenarios do not agree on the direction of change. Some studies have suggested that for a predicted reduction in rainfall of 10 to 20%, a fall-off in flow of 20 to 40% might be expected (Amani, *et al.*, 2007) over WA, however this could vary from one basin to the other depending on the runoff precipitation ratio of that basin. The Tono basin has an estimated runoff precipitation (R/P) of 8%, based on this estimation, RCP4.5 with an annual rainfall projection of +7% will lead to a future increase in flows of about 56% and for RCP8.5 with rainfall projection of -9.6% will lead to about -76.8% reduction in flows. As mentioned earlier, these scenarios do not agree on the direction of precipitation change and hence future flow regimes. The impact of climate change on the basin can only be directly discussed by associating the characteristics of the West Africa region to the characteristics in which these scenarios were developed. If it is expected that future population of WA would increase significantly, with increased industrial activities, increased technology, increased commercial agriculture; which will lead to increased greenhouse gas emissions (GHG) without control, then the region would be associated with the

RCP8.5 scenario. The implications of this scenario over the basin include but not limited to; a change in annual average river flows reflecting the drop in rainfall and a depletion of surface water resources (dam) of about 76%, that is more pronounced than precipitation. Other implications are, a drastic fall in water volumes transiting through the major rivers, an increase in runoff coefficient for the small basins and a failure to fill the dam reservoir during the rainy season. The changes being predicted by the RCP scenarios suggest the following impact on the water resources of the Tono basin; an intensification of the hydrological cycle, an increase in the scale or frequency of flooding, more and more severe droughts and deterioration in water quality.

4.4.1 Possible adaptation measures for the Tono basin water resources

The chronic shortage of rainfall in West Africa (WA) has led to a considerable reduction of water flows in the rivers throughout the river basins (ENDA, 2007). The Tono dam after construction had an estimated volume of 92.6 million cubic meters, however over the years; this has not been the case. Pelig-Ba (2011), reports of the volume of the dam as 17 million cubic meters. This reduction in water volume has been attributed to the rainfall variability and the effect of climate change. Plate 4.1a and Plate 4.1b demonstrates the effect of rainfall variability on the Tono dam levels. In 2014 the dam levels were at dead storage (174 m amsl) due to low inflows as a result of low rainfall and in 2015, the region recorded high rainfall leading to more river flows into the dam with the dam levels increasing to 179 m amsl (Plate 4.1b). In other to address the impact of climate variability and climate change on the water resources of the Tono basin, the following measures could be considered and adopted; legal and institutional support/cooperation to empower institutions that manage and regulate these water resources, physical structures (e.g. reconstruction and lining of canals), protection and restoration of the ecosystem, strengthen human resource, information and awareness creation.

Plate 4.1 (a) Tono dam level using staff gauge, measurements in October, 2014 and (b) in October, 2015

However, these adaptation measures will come to not if efforts are not made to strengthen the local capacity to respond to intense pressures linked to climate change in terms of water management. There is the need to define the capacity-building actions required to ensure that the adaptation measures are carried through. Considering water resources availability is increasingly coming under threat due to increasing climate variability and climate change, which substantially has affected environmental conditions and generated the concepts of availability, accessibility, and renewable in the management of water resources. These concepts should be developed into sustainable management policy that might well be appropriate for managing adaptation to climate change and other pressures on water resources management such as;

a) Demographic growth and change,
b) Development and modernization of agriculture,
c) Development of mining industries,
d) Development of services provided by aquatic ecosystem

There are two fundamental approaches that could be used to incorporate the pressures into the concepts of availability, accessibility and renewal for future water resources management in the Tono basin. The two approaches are:

Adapting Needs to Resources; this begins with an assumed knowledge of resources in terms of quantity, quality, and geographical spread, with needs planned to reflect available supply. However, there are gaps in knowledge on the supply-side.

Adapting Water Resources to Needs; in this case, the assumption is one of sufficient control of water resources to meet planned needs, which are growing exponentially.

Based on these two approaches, a combined view on how to tailor water resource management with respect to climate change to ensure the future sustainability of these resources. The main argument is that one has to properly take into account the matching of available water resources to needs while, at the same time, matching the management of proposed water resources to future pressures, including those of climate change. This suggests that capacity building has to be designed in a way that will increase the knowledge of the resource and improve the way it is used.

4.4.1.1 Physical Infrastructure

The Tono dam, mainly used for irrigation activities, requires that the infrastructure of the irrigation scheme be realigned to adapt to the pressures of climate change. In other to reduce the impact of evaporation on the dam, planting of trees along the peripheral of the dam is required. Possible desiltation of the dam is also required to allow the dam to hold much streamflow. The canals carrying water from the dam to the irrigation fields should be lined with concrete or polythene to prevent infiltration. This is to ensure that much water is not wasted to infiltration as the water travels to the irrigation fields. Trees should also be planted along these canals to reduce evaporation. It is important streamflow gauges are installed at the proposed gauges to ensure streamflow measurements. Weather stations should also be installed at the dam location and at the irrigation fields to collect data. These data will provide timely information and analysis on the water resources to support decision making and management of the resource.

4.4.1.2 Irrigation system

The irrigation system practiced is surface (flood) irrigation. This system of irrigation demands a lot of water and most cases the water released for irrigation goes waste. In other to adapt to the change in climate and climate variability, irrigation schemes that, require less water and low loss of water to evaporation is required (e.g. drip irrigation, sprinkler irrigation). However, most of these systems of irrigation are quite expensive to implement. To implement these irrigation systems will also require adjusting to the types of crops cultivated. Mostly, crops with high economic value and less demand for water are used. This will offset the cost of the irrigation scheme, improve incomes of farmers and also sustain the irrigation dam.

4.4.1.3 Human resources and awareness creation

Adaptation requires developing the human resource capacity. This requires training of staff to understand climate change impact on the water resource, data collection, and analysis, new irrigation technologies, water resources technology and management, and crop management. Farmers' training is also important to adapt to the new irrigation technologies and also the new cropping system. There is the need to create awareness of the impact of climate change on the water resources and its consequent impact on food production. This will position the minds of people to appreciate the adaptation measures.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Contributions to Knowledge

The study contributed to knowledge by providing baseline information useful in the management of water resources with regard to polices and decision making of the Tono Basin. The WRF-Hydro model for water resources assessment has provided useful tools which could applied in the management of other water resources in the West Africa region. The results of the study supported other findings on the climate change pattern over the region, which would serve as critical information for policy makers regarding strategies for adaptation and sustainability of water resources under climate change.

5.2 Conclusion

The study assessed the strength of WRF-Hydro in simulating streamflow of gauged rivers in the Tono basin. The ability of the hydrological model to adequately simulate stream flows of these rivers would serve as a tool for estimating historical and future stream flows of these rivers to support the water resource management of the dam. The performance of the fully coupled WRF/WRF-Hydro modeling system was also assessed in comparison with standalone WRF model. This was to ascertain whether fully coupled approach improved climate simulations. The analysed variables of the fully coupled modeling system and the standalone model were precipitation, surface temperature, and stream flow. Values obtained were compared with observation data and the results were reasonable (e.g. temperature with a correlation of 0.94 and RMSE of 0.6 ^{0}C; precipitation with correlation of 0.91 and RMSE of 2.4mm/day; Streamflow with NSE of 0.78). Despite significant variations in precipitation simulations with respect to precipitation amounts, WRF/WRF-Hydro and WRF-only were comparable in terms of timing and distribution of precipitation in the basin. Precipitation variation is more difficult to predict since it's generation in the domain (West Africa region) is dominated by the convective system and the movement of ITCZ, rather than land surface soil moisture content alone. Nonetheless, both over the Tono basin and at the gauge station, WRF/WRF-Hydro modeling system was slightly better in simulating climate variables than WRF-only, especially with respect to model bias and correlation. The results of the comparison of fully coupled WRF/WRF-Hydro and WRF-only forced with ECHAM6 global model data, indicated a poor outcome for WRF/WRF-Hydro. This could be due fact that the optimum physics options obtained by Heinzeller *et al.*, 2014 for WRF-only over the West Africa region, which was applied for this study may not be suitable when using WRF/WRF-Hydro configuration; secondly, the optimum physics option may not be the optimum in the Tono basin (microscale effect). WRF/WRF-Hydro model forced with ERA-Interim reanalysis data performed reasonably well in the simulation of Gaabuga streamflow, particularly given the strong seasonality of the hydrologic regime. Considering that the calibration was done manually, with inadequate streamflow records for model verification, the assessment was further carried out based on the water balance of the Tono dam. Since the hydrological model is coupled with the atmospheric model, the components of the water balance from the hydrological model were also assessed to further understand the strength of the model. With respect to rainfall, the WRF-Hydro model was positively biased (overestimating by 47.2%) to the observed rainfall and this is speculated to be due to feedback effect of the coupling process and also the inherent bias in the model data. The effect of this bias was transferred in the evaporation estimates. The dam level simulation based on the components of the water balance from the hydrological model showed good agreement (R^2 = 0.81) with the observed dam level.

This, therefore, supports WRF-Hydro's ability to simulate streamflow of gauged rivers. The flows from the streams mostly depict the rainfall trends. The daily streamflow estimates from WRF-Hydro showed strong agreement with the observed streamflow indicating the strength of the model in flood forecasting. The dam levels generated over longer period also demonstrate the strength of the hydrological model in supporting water resource management. The results achieved are mainly relevant to long-range simulations, where it has been demonstrated that its implication, especially for the evaluation of water resources availability, can be much important. The availability of the water resource under future climate change has been assessed based on two Representative Concentration Pathways (RCPs) scenarios. Both scenarios (RCP4.5 and RCP8.5) do not agree on the sign of precipitation change, whereas they predict a warmer temperature condition. Although RCP4.5 indicates an increase in runoff contribution, increasing warmer temperature conditions will affect the volume of flow into the dam. RCP8.5 gives a worse scenario in runoff contribution and with this trend continuing, will lead to drought and the dam going dry. The future management of the water resources of the Tono basin will require adaptation measures to ensure the sustainability of the water resource and the irrigation activities.

5.3 Recommendations

1. The effect of correcting the bias in precipitation estimates on the streamflow estimates should be investigated.
2. The effect of irrigation activities on the microclimate of the basin should be examined.
3. The potential of running fully coupled WRF/WRF-Hydro based on RCPs to generate future stream flows to allow estimating the variation in the dam levels should be explored.

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