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By

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IMPACTS OF CLIMATE AND LAND USE CHANGES ON VEA CATCHMENT AND IRRIGATION SCHEME IN UPPER EAST REGION OF GHANA

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DEDICATION

I dedicate this work to my little daughter, Vania Ubiin Limantol, my wife, Evelyn, my father, Limantol Nchomba; my late mother, Yamob Limantol and my late sister, Tayilpu Limantol, for the support, encouragement and unconditional love I enjoyed from you. You are and will forever remain deeply rooted in my heart.

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ABSTRACT

Vea catchment hosts one of the two major irrigation schemes in the Upper East Region of Ghana, inhabited by many rural farming communities and offers opportunity for all-year-round agricultural production for these communities. The catchment will continue to experience irrigation expansion and upsurge in domestic water demands due to population growth and urbanisation. Any adverse effects of climate change (CC) will be an add-on pressure on the catchment water resources and will be detrimental to the entire population in the area. This study assessed the influence of CC on future water resources availability in the catchment for irrigation and also examined land use/cover changes in the area. Water mass balance method was used to estimate historical streamflow for the catchment with the bathymetry data and the storage-area-height relationship (function) at the irrigation reservoir site. The IHACRES rainfall-runoff model was successfully calibrated and validated for future flow prediction using outputs from all the Regional Climate Models (RCMs) of Coordinated Regional Downscaling Experiment (CORDEX) that provided data for the Africa domain based on the highest emission scenario (RCP8.5). Based on socioeconomic scenarios drawn from survey data gathered through household and institutional interviews, focus group discussions and review of national policies on CC, the water allocation and planning model, WEAP, was successfully configured and used to assess future water availability situation in the catchment in two future periods, 2021-2050 and 2071-2100. Climatic data for the period 1972-2012 from four stations were additionally analysed. Landsat satellite imagery was also analysed to assess land use/cover changes in the catchment. The results indicate a rising trend in both historic and projected temperature and evapotranspiration over the past 41 years and in the next decades. No long-term trend and no variability changes in rainfall data were evident. With the lowest streamflow derived from RCMs simulated conditions and the current irrigation rate of 1.1%, the catchment will experience average annual water supply deficit (AWSD) of about 1.3 x 10^6 m^3 and 1.8 x 10^6 m^3 in the periods 2021-2050 and 2071-2100 respectively. If the potential irrigable area (1400 ha) of the catchment is developed under the current practices, both lowest and highest streamflow derived from RCMs simulated conditions indicate that in the period 2071-2100 the catchment will experience AWSD of about 3.3 x 10^6 m^3 and 0.7 x 10^6 m^3 respectively. Closed and open savanna woodland cover in the catchment decreased by about 55.7% and 44.2% respectively between 1990-2010 while grass/herbaceous cover and bare surface/built-up areas increased by about 168.5% and 203.0% respectively over the same period. The study indicates a projected considerable shortfall in water availability for irrigation in the coming decades due to CC coupled with population growth and associated water demand. Government and stakeholder organisations need to assist farmers by providing alternative irrigation facilities with improved irrigation efficiency in order to sustain livelihoods of farmers on the long run. This should go along with the introduction of new improved seeds and drought resistant crops to farmers. Land cover restoration programmes that include incentives for protection of forest reserves be introduced to curtail the high pace depletion of the vegetation cover in the area.

***Key words* :** Climate change, impact, land use/cover changes, water resources, irrigation, Vea catchment

SYNTHÈSE

Le bassin versant de Vea abrite les deux principaux périmètres d'irrigation de la région nord est du Ghana. Habité par de nombreuses communautés rurales, ce bassin offre la possibilité d'une production agricole toute l'année. Une expansion de l'irrigation et une hausse des besoins en eau domestique en raison de la croissance démographique et de l'urbanisation y sont envisageables. Le moindre effet néfaste du changement climatique (CC) constituera une pression supplémentaire sur les ressources en eau du bassin et sera dommageable pour les populations. Cette étude a évalué l'impact du CC sur la disponibilité future en eau d'irrigation du bassin et a également examiné la dynamique de l'occupation des terres et de la couverture végétale de la région. La méthode du bilan massique de l'eau a été utilisée pour estimer le débit historique du bassin à partir des données de bathymétrie et la relation surface de stockage-profondeur au niveau du réservoir d'irrigation. Le modèle pluie-débit IHACRES a été calibré et validé avec succès pour la prévision des débits futurs en utilisant les données du scenario climatique le plus pessimiste (RCP8.5) des Modèles Climatiques Régionaux (RCM) de l'Etude Coordonnée de Recherche sur le Climat à Echelle Régionale (CORDEX). S'inspirant des données d'enquête (menées auprès des ménages et des institutions) et de l'examen des politiques nationales sur les CC, des scenarios ont été définis et appliqués avec succès au modèle d'allocation et de planification de l'eau (WEAP) pour évaluer la disponibilité future en eau du bassin pour les périodes 2021-2050 et 2071-2100. Les données climatiques de la période 1972-2012 de quatre stations ont été analysées. Des images satellitaires Landsat ont été également analysées pour évaluer les changements dans l'occupation des terres et de la couverture végétale du bassin. Les résultats indiquent que la température (voir la Figue 1 & la Figue 2) et l'évapotranspiration (voir la Figue 3 & la Figue 4) ont connu une tendance à la hausse au cours des 41 dernières années ; laquelle tendance qui va se maintenir durant les prochaines décennies.

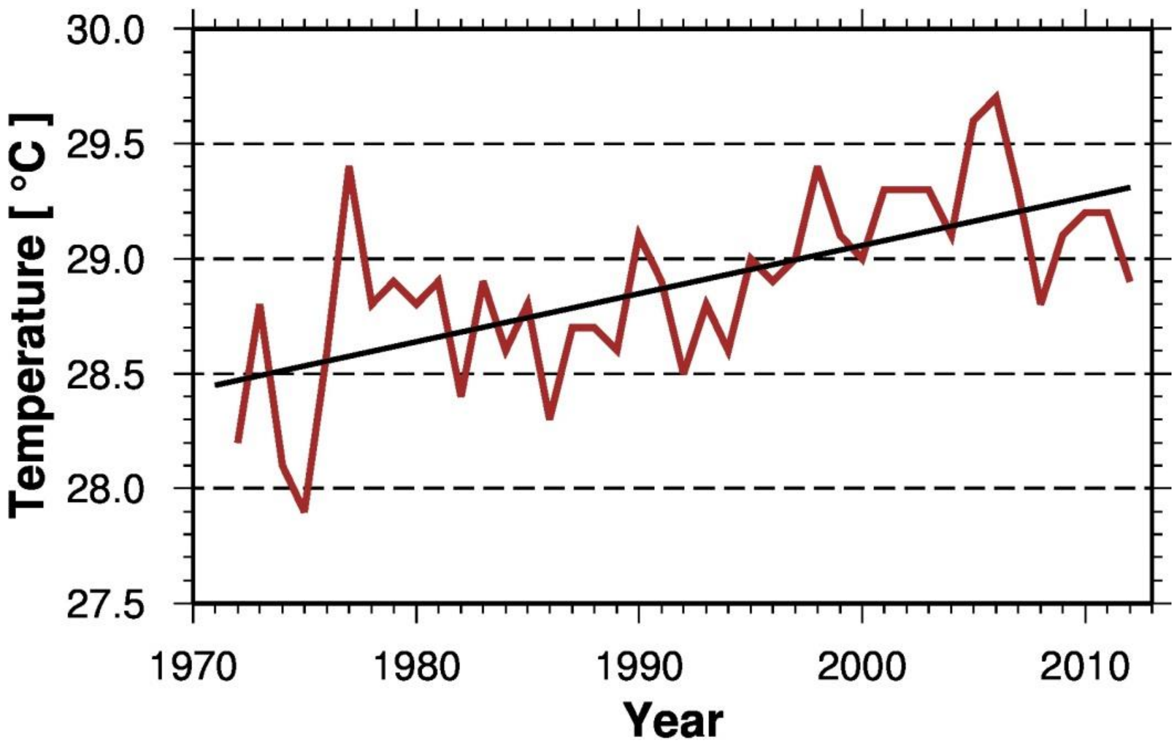
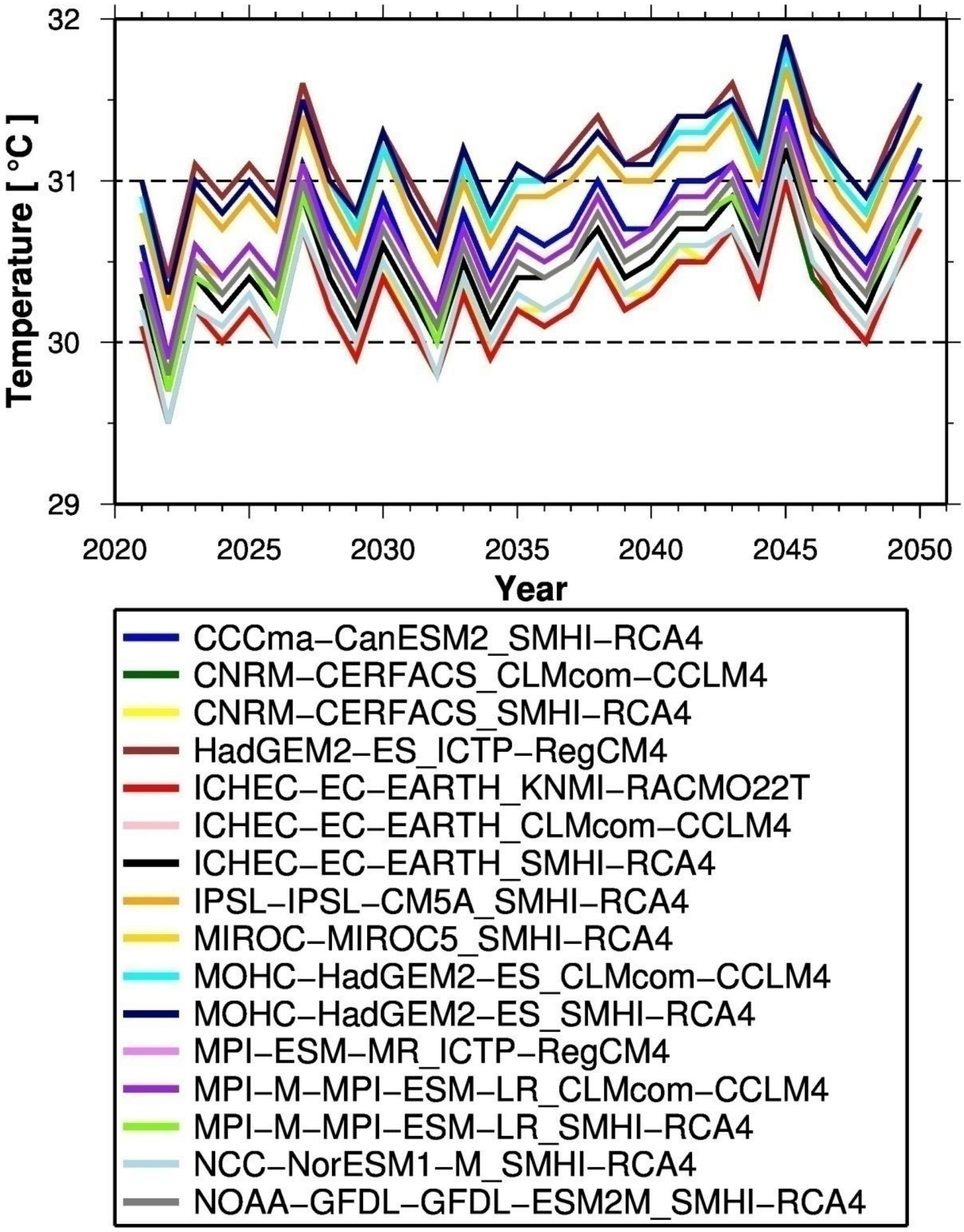
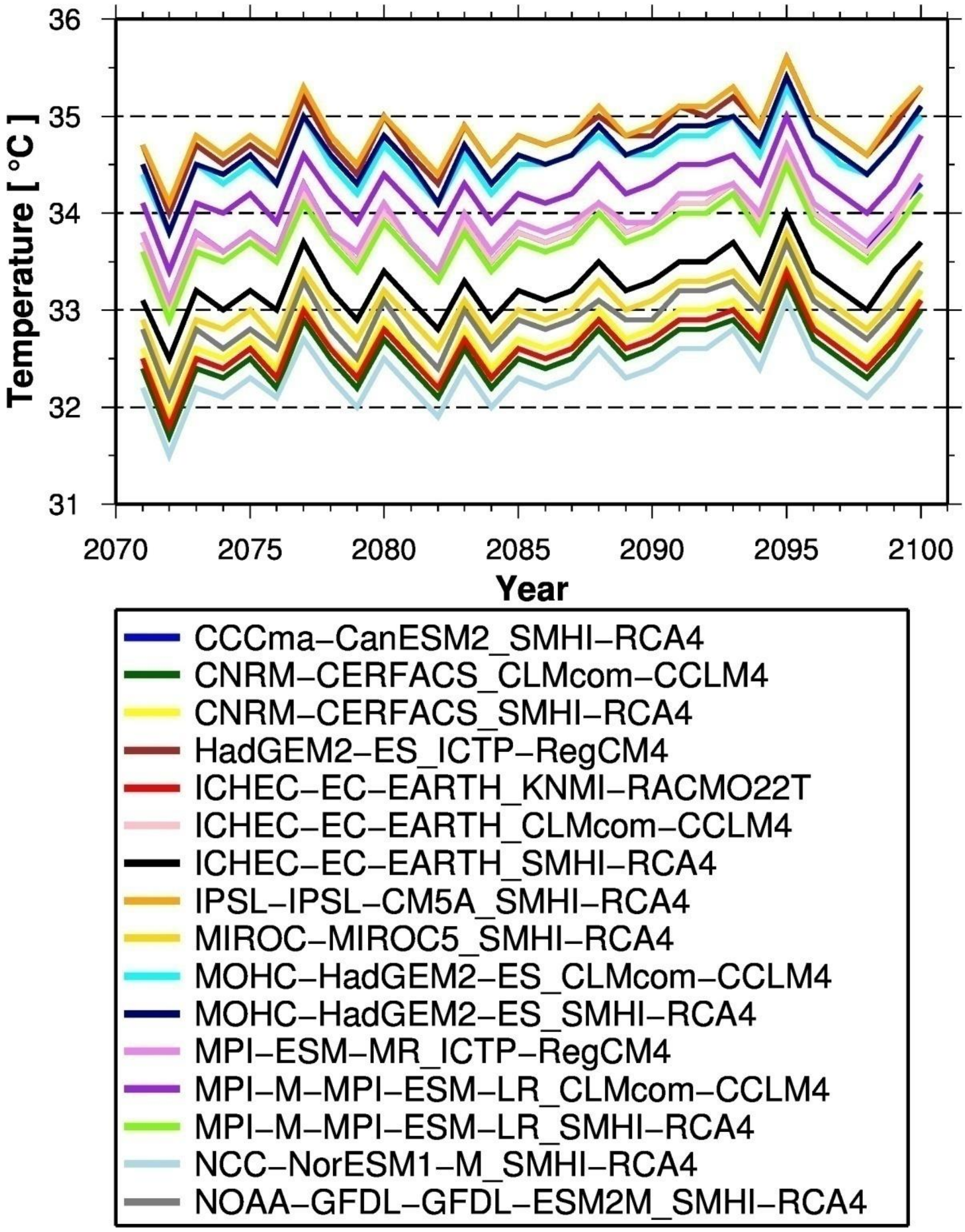


Figure 1: *Tendance de la température moyenne annuelle du bassin versant (source de Données : Agence Météorologique du Ghana)*



32
31
30
29
Temperature [°C]
2020
2025
2030
2035
2040
2045
2050
Year
CCCma−CanESM2_SMHI−RCA4
CNRM−CERFACS_CLMcom−CCLM4
CNRM−CERFACS_SMHI−RCA4
HadGEM2−ES_ICTP−RegCM4
ICHEC−EC−EARTH_KNMI−RACMO22T
ICHEC−EC−EARTH_CLMcom−CCLM4
ICHEC−EC−EARTH_SMHI−RCA4
IPSL−IPSL−CM5A_SMHI−RCA4
MIROC−MIROC5_SMHI−RCA4
MOHC−HadGEM2−ES_CLMcom−CCLM4
MOHC−HadGEM2−ES_SMHI−RCA4
MPI−ESM−MR_ICTP−RegCM4
MPI−M−MPI−ESM−LR_CLMcom−CCLM4
MPI−M−MPI−ESM−LR_SMHI−RCA4
NCC−NorESM1−M_SMHI−RCA4
NOAA−GFDL−GFDL−ESM2M_SMHI−RCA4

(a)



(b)

Figure 2: *Température du bassin de la Vea simulée par les modèles régionaux climatiques (RCMs) sous le scenario RCP8.5 après correction du biais. Le (a) représente la série de température de chacun des 16 RCMs pour les conditions climatiques 2021-20150 tandis que le (b) représente les données de température pour chacun des 16 RCMs pour la période 2071-2100.*

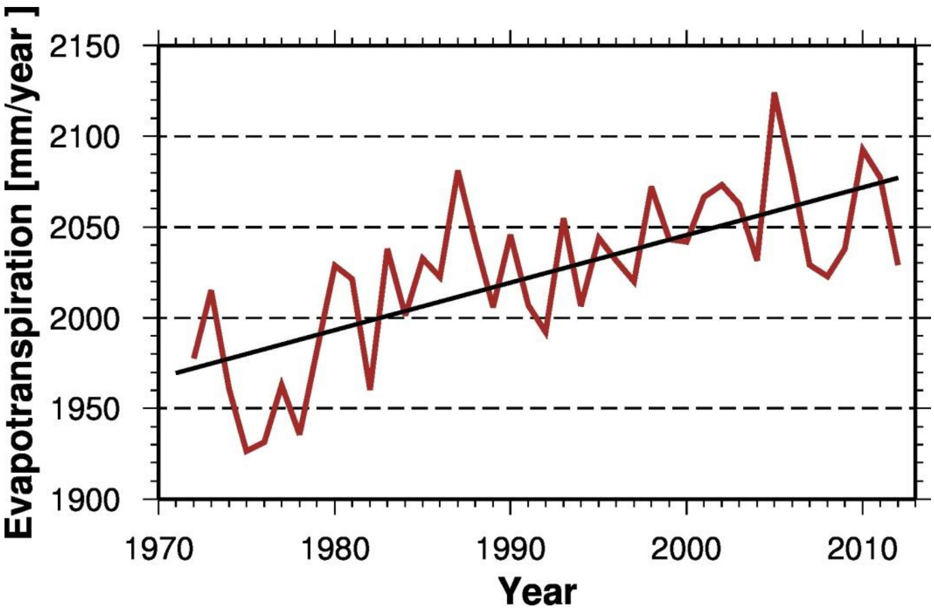
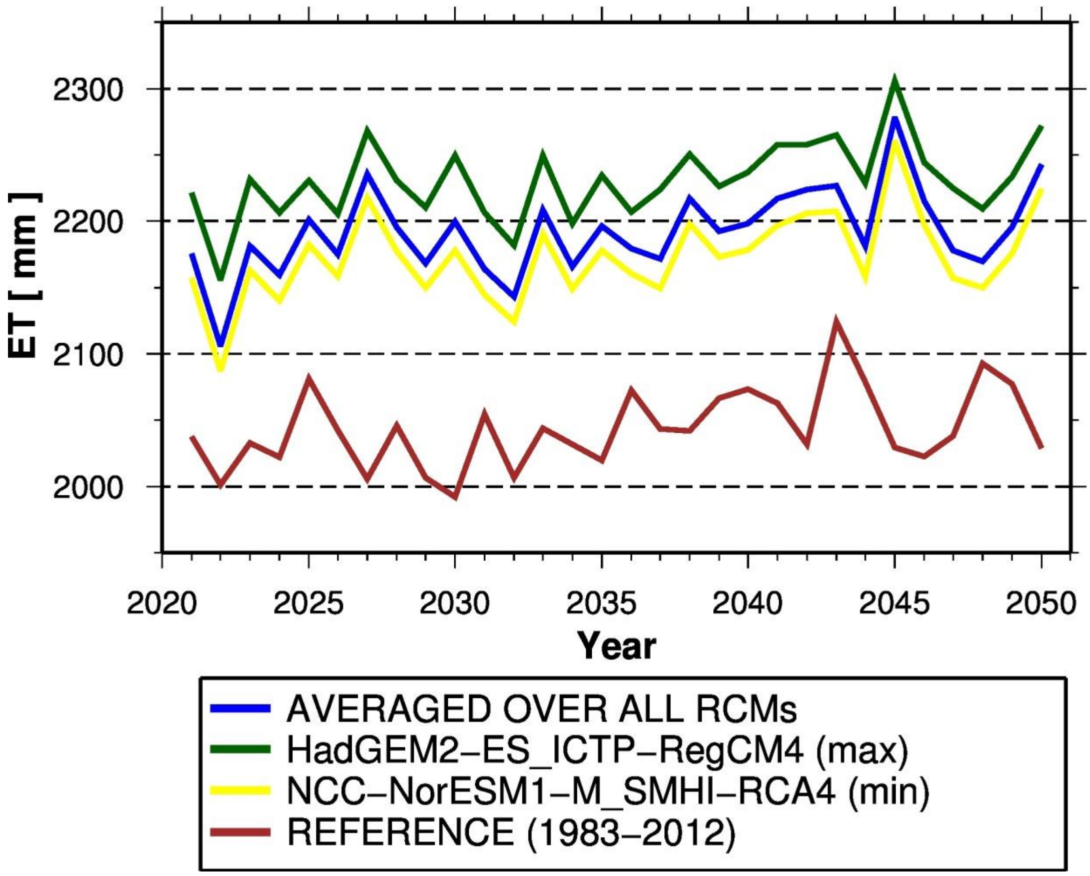


Figure 3: *Tendance de l'évapotranspiration annuelle dans le bassin*



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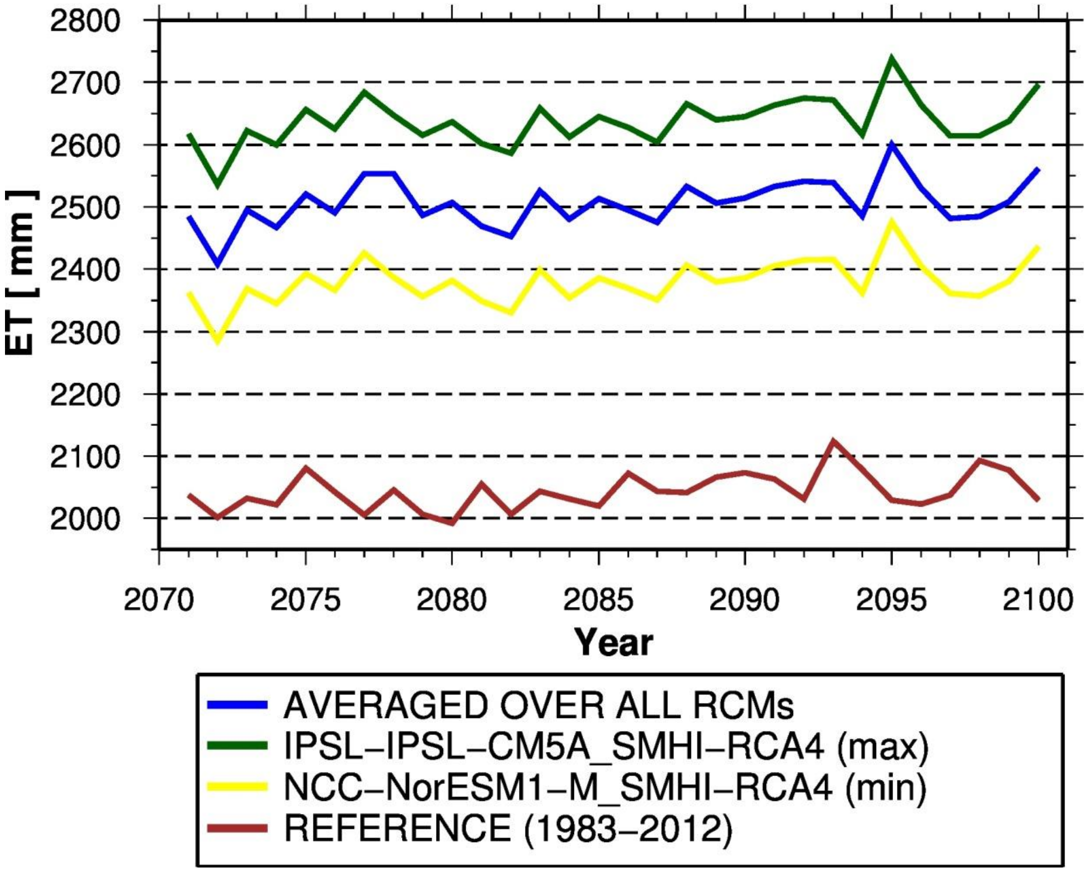
(a)



(b)

Figure 4: *Evapotranspiration annuelle des deux séries de température extrême future simulée (le plus haut et le plus bas) et de la température moyenne des 16 RCMs pour les conditions climatiques futures en comparaison avec l'évapotranspiration annuelle de température de la période de référence (1983-2012). (a) représente évapotranspiration annuelle de chacune des quatre séries de température pour l'avenir proche (2021-2050), pendant que (b) représente l'évapotranspiration annuelle de chacune des quatre séries de température pour 2071-2100.*

Les tendances futures et la variabilité des précipitations ne sont pas évidentes. Suivant le scénario pessimiste (baisse de la pluviométrie) et si le taux d'irrigation actuel de 1,1% se maintenait, le bassin connaitra respectivement un déficit moyen annuel en eau d'environ $1.3x10^6$ m^3 et $1.8x10^6$ m^3 pour les périodes 2021-2050 et 2071-2100. Si la superficie potentielle irrigable (1400 ha) du bassin est exploitée suivant les pratiques actuelles, les scénarios pessimiste (baisse de la pluviométrie) et optimiste (hausse de la pluviométrie) indiquent qu'au cours de la période 2071-2100, le bassin connaitra respectivement un déficit en eau de $3.3x10^6$ m^3 et $0.7x10^6$ m^3. La surface des savanes arborées et des savanes claires a été réduite respectivement d'environ 55,7% et 44,2% entre 1990 et 2010, tandis que les superficies herbeuses et les sols nus et bâtis ont augmenté d'environ 168,5% et 203,0% au cours de la même période. L'étude met en relief un déficit drastique en eau d'irrigation dans les décennies à venir en raison de CC couplé à la croissance démographique qui a pour

corolaire une hausse de la demande en eau domestique. Afin de préserver les moyens de subsistance des agriculteurs sur le long terme, le gouvernement et les parties prenantes devront soutenir les agriculteurs en mettant en place des installations d'irrigation beaucoup plus efficientes. Cela devrait aller de pair avec l'introduction de nouvelles variétés améliorées et des cultures résistantes au stress hydrique. Des programmes incitatifs de restauration de la couverture végétale et protection des réserves forestières devront être mis en place afin de limiter le déboisement dans la région.

Mots clés: Changement climatique, impact, Changements dans l'utilisation des terres et la couverture terrestre, ressources en eau, irrigation, Bassin versant de Vea

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AAGDS	Accelerated Agricultural Growth and Development Strategy
AEAs	Agricultural Extension Agents
AEWs	African Easterly Waves
AMGRAF	Adaptive management of groundwater in Africa
AP	Adaptation Partnership
AWSD	Annual water supply deficit
BAU	Business as usual
CC DARE	Climate Change Adaptation & Development Initiative
CC	Climate change
CERSGIS	Centre for Remote Sensing and Geographical Information System
CMD	Catchment Moisture Deficit
CORDEX	Coordinated Regional Downscaling Experiment
CRES	Centre for Resource and Environmental Studies
CRI	Crop Research Institute
CSIR	Council for Scientific and Industrial Research
CWI	Catchment Wetness Index
CWR	Crop water requirement
CWSA	Community Water and Sanitation Agency
DAs	District Assemblies
ENRAC	Environmental and Natural Resources Advisory Council
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
ESM	Science House of water
ET_a	Actual Evapotranspiration
ET	Evapotranspiration
ETM	Landsat Enhanced Thematic Mapper
FASDEP	Food and Agriculture Sector Development Policy
GDP	Gross domestic product
GHG	Greenhouse Gas
GIDA	Ghana Irrigation Development Authority
GMet	Ghana Meteorological Agency
GNCCP	Ghana National Climate Change Policy

GPS	Global Positioning System
GSGDA	Ghana shared Growth and Development Agenda
GSS	Ghana Statistical Service
GTZ	German Technical Co-operation
GWCL	Ghana Water Company Limited
HHQ	Household questionnaire
HSD	Hydrological Service Department
IAHS	International Association of Hydrological Sciences
ICOUR	Irrigation Company of Upper Region
IFAD	International Fund for Agriculture Development
IFPRI	International Food Policy Research Institute
IH	Institute of Hydrology
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
IWMI	International Water Management Institute
MDAs	Ministries, Departments and Agencies
MDGs	Millennium Development Goals
MLG & RD	Ministry of Local Government and Rural Development
MOFA	Ministry of Food and Agriculture
MWRWH	Ministry of Water Resources, Works and Housing
NADMO	National Disaster Management Organization
NC	National communication on climate change
NCCAS	National Climate Change Adaptation Strategy
NE	North-easterly
NEPAD	New Partnership for Africa's Development
NGOs	Non-governmental Organizations
NIPSARP	National Irrigation Policy, Strategies and Regulatory Programs
PET	Potential evapotranspiration
POs	Producer organizations
PSIA	Poverty and Social Impact Analysis
PUB	Prediction of Ungauged Basins
PURC	Public Utilities Regulatory Commission
RCMs	Regional Climate Model

SMA	Soil moisture accounting
SPSS	Statistical Package for the Social Scientists
SSA	Sub-Saharan Africa
SSTs	Sea Surface Temperatures
TEJs	Tropical Easterly Jets
UER	Upper East Region
UNDP	United Nations Development Programme
UNEP	United Nations environment programme
UNFCCC	United Nations Framework Convention on Climate Change
W/A	West Africa
WAM	West African Monsoon
WD	Water Directorate
WEAP	Water Evaluation and Planning
WMB	Water Mass Balance
WRC	Water Resources Commission
WWDR4	Fourth World Water Day Report

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Context and problem statement

Around the world, water demand will increase over the next decades, mainly because of population growth and increased standard of living, vast expansions in irrigated agriculture and irrigation water demand as a consequence of climate change (CC) (Bates *et al.* 2008). Unfortunately, the existing water management practices in many water resource locations are not efficient in coping with even the current adverse effects of climate fluctuations (Bates *et al.* 2008). Unmanaged water resources could be most vulnerable to CC (Kundzewicz *et al.* 2007).

The CC is a key factor affecting freshwater quantity and quality (Tu, 2009) and will change allocation of regional water resources (Mauser and Bach, 2009). According to Kundzewicz *et al.* (2007), the experience of a net negative impact of CC on water resources is expected almost all around the world. Water resources in many semi-arid and arid areas around the world will decline due to CC and the interventions being made to the adverse effects will suffer setbacks as regions already in water-stressed situation will further experience significantly decline in groundwater recharge in view of rapid population growth and the associated water demand (Kundzewicz *et al.* 2007). Though, some other regions would experience a rise in annual runoff, the associated positive impacts will be hampered by the adverse effects of high variability of rainfall and seasonal runoff on water supply in those areas (Bates *et al.* 2008). Consequently, the adverse effects of CC on water resources around the globe outweigh any positive impacts and further exacerbate the impacts of other primary factors, like population growth and land-use/cover change (Bates *et al.* 2008).

Water planners and managers consider the issue of CC as important because it could change the fundamental water management conditions (Barnett *et al.* 2008; IPCC, 2007a; cited in: Groves *et al.* 2008) and thereby call for more innovative ways of water management and capital investments (California Urban Water Agencies, 2007; Salem *et al.* 2011). At the local level, the effects of CC remain uncertain and difficult to predict and this could further pose challenges to water resources planning (Conway *et al.* 2009; cited in: Mounir *et al.* 2011).

Definitive knowledge about the impact of CC on various components of the water cycle is so vital for sustainable management of water resources amidst the rising societal water demand (Abbaspour *et al.* 2009). Appropriate modelling tools are therefore required for practical understanding of the impacts of CC on river catchments and identification of effective adaptation measures (Mauser and Bach, 2009), especially at the catchment level. In view of the adverse implications of CC, immense interest is now being shown for development of tools and methods for predicting the impact of CC on streamflow (Gardner, 2009) and water resources in general. Many studies in most part of the globe have therefore investigated the effects of CC on hydrology and findings indicated that CC was, to a great extent, responsible for streamflow variability and expected to also affect water quality (Tu, 2009)

Besides the effects of CC, land use changes have been observed to have significant effects on water resources. According to Zhi *et al.* (2009), land use change and climate variability are the two major factors that have direct impacts on catchment hydrology, and distinctive description of their effects is vital for sustainable land use planning and water resources management. Several studies around the globe have examined the effects of land use changes on hydrology and results showed significant impact on water resources with regards to both quantity and quality (Tu, 2009).

The indications that future runoff will likely decrease necessitates that appropriate strategic responsive planning and state-of-the-art water resources management strategies and policies be employed **(**Chiew *et al.* 2009). Studies on water resources have therefore become necessary to develop appropriate assessment tools for water resources management in view of threats by global CC and land use changes. Water resources in Africa are not yet covered in this regard and vulnerable to CC and land use changes.

The drought conditions in the Sahara and Sahel sub-regions of Africa will worsen as rainfall is likely to reduce due to CC (Ofori-Sarpong, 2001). Oyebande and Odunuga (2010) observed that the series of droughts that occurred in West Africa (W/A) during the past three decades have adversely impacted the water resources in the region, particularly Volta, Niger and Senegal basins and consequently the fragile economies of the riparian countries including Ghana. The challenges and uncertainties posed by the impacts of projected CC on water resources in W/A are further compounded by several other factors that include regional demographic factors, non-existent or inadequate water policies, inefficient management strategies and lack of reliable and adequate data (ibid). These challenges are of great concern to most sub-Saharan Africa (SSA) countries in view of the key socio-economic role played by water resources in these countries. Osei-Asare (2004) observed that water scarcity is a great challenge and acute concern to most SSA countries.

International Water Management Institute [IWMI] (2000) projected that Ghana is one of many SSA countries to experience economic rather than physical water scarcity by 2025. However, by virtue of geographical settings, the Northern Regions of Ghana which include Upper East Region (UER) often face acute physical water scarcity far above the figure suggested as national average per capita water resources (Mdemu, 2008). It is against this backdrop that, this study seeks to examine the impacts of CC on the water resources of Vea catchment and the irrigation scheme in the UER. This will include assessment of changes in the primary land cover categories of the area.

1.2 Literature review

1.2.1 Overview of climate change projections and impacts on water resources and agriculture

1.2.1.1 Global and regional perspective

A little over a decade ago, the question asked was whether climate change (CC) was real. Many a people in the scientific world doubted the reality of CC. Today, the scientific world, governments, organisations and institutions have all embraced the reality of CC following unfolding clear signs of its global impacts. From global to sub-regional levels, clear evidences of its effects on temperatures and weather patterns have been proven with the projected warming of climatic system described as unequivocal (IPCC, 2007b; Nicholson, 2012). In Africa, these effects have been clearly detected in temperatures and rainfall patterns where it is scientifically established that the continent is particularly highly vulnerable to the various manifestations and impacts of CC on the hydrological cycle, water resources and agriculture (IPCC, 2001; Stanturf *et al.* 2011). Although, in highly uncertain ways, it is established that, CC will considerably influence food and water security in the coming decades, with worst effects expected in the developing countries of Africa (Ringler *et al*. 2011). This follows previous observations that water is becoming increasingly scarce in Africa, despite being the most important natural resource in the continent (AfricanBank, 2007).

Besides being the world’s poorest and least developed continent, the economic activities of most countries in Africa are heavily dependent on climate-sensitive agriculture (rain-fed) and water, with agriculture alone employing 90% of the rural population (UNECA, 2007; UNEP, 2010). Considerable linkages between water, agriculture, the environment and poverty as well as national economy in the continent is well established (UNEP, 2010). This tied linkage makes Africa vulnerable to climatic variations as that can highly influence the fate of the economy (IPCC, 2001).

About nine African countries are already challenged by "water scarcity", eight countries in "water stress" conditions and more than six countries are expected to fall in the same situations over the coming decades (AfricanBank, 2007). Currently, over 300 million people across the continent, mainly from sub-Saharan Africa have no access to safe water, while it is projected that by 2025, about 50% of Africans will live in conditions of water scarcity (AfricanBank, 2007).

The sub-Saharan Africa is especially most vulnerable to the adverse effects of CC because, aside the rain-fed agriculture being the principal source of rural livelihoods, the adaptive capacity of these rural smallholder farmers in the sub-region is exceedingly low (Ringler *et al*. 2011). "*Consequently, it is important to understand the impacts of global change on agriculture and natural resources in sub-Saharan Africa and to identify informed and effective adaptation measures and investment priorities to alleviate the harmful impacts of global change"* (Ringler *et al*. 2011). This is particularly important because, *"compared to other sectors, stimulating economic growth through agriculture is four times more effective in raising incomes of poor people; investing in agricultural water has even higher potential multipliers"* (UNEP, 2010).

Building strong adaptive capacity and resilience of rural smallholder farmers of the sub-Saharan Africa countries is very crucial in view of the emerging extreme climatic conditions such as high temperature-driven-evapotranspiration and frequent droughts in most areas of the sub-region. These manifestations of CC often lead to high evapotranspiration rates that excessively exceed annual rainfall and resulting in high soil moisture deficit as well as scarcity of water for both domestic and agriculture/irrigation purposes. For instance, high evapotranspiration rates owing to rising temperature in large part of the Volta basin that span across Burkina Faso and Ghana is the cause of diminished runoff contribution to river flow within the Basin (Fig. 1.1) (UNEP, 2010). Consequently, the vulnerability of farmers within the basin could worsen, particularly in the Sudan Savannah and Guinea Savannah zones. This follows projections that CC will worsen the already stressed water resources due to population growth, land use and other anthropogenic activities by increasing the frequency and severity of CC manifestations such as rises in temperature, rainfall variability and hydrological changes including diminishing river flows (WWAP, 2012). Unfortunately, taking comprehensive stock of water resources for efficient planning and management purposes and for optimal use to improve standards of living of the people remains a challenge all over Africa (AfricanBank, 2007). Research studies in this regards at catchment levels are therefore crucial for national developmental agenda of each African country, particularly in the sub-Saharan Africa.

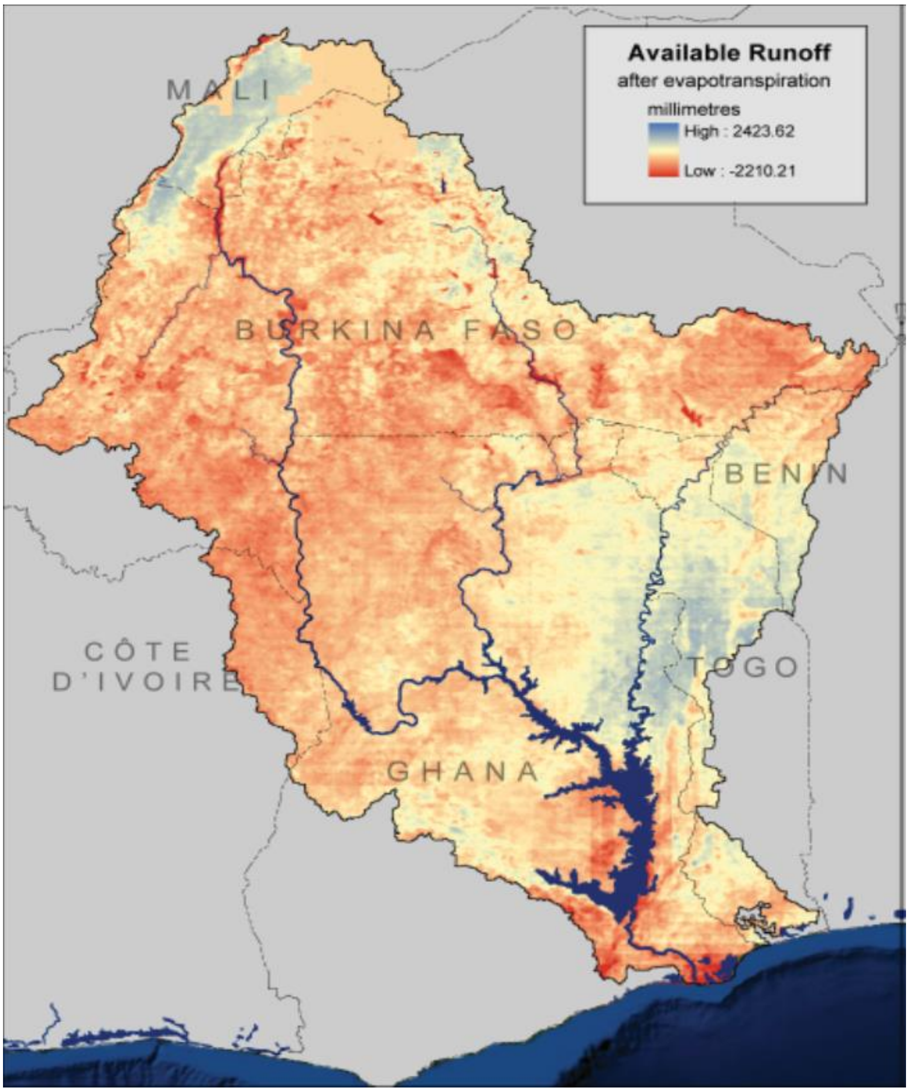


Figure 1.1: *Volta River Basin modelled available runoff (Source: UNEP, 2010)*

1.2.1.2 Ghana's climate and projected changes

1.2.1.2.1 General climate

Ghana is located in West Africa, bordering Gulf of Guinea to the south, Togo to the east, Cote d'Ivoire to the west and Burkina Faso to the north. It is between latitudes 4.5°N and 11.5°N; and longitudes 3.5°W and 1.3°E (Asante and Amuakwa-Mensah, 2014). The country is divided into six agro-ecological/climatic zones (see Fig.1.2 below) and three hydro-climatic zones. The agro-ecological zones are namely, Sudan Savannah, Guinea Savannah, Transitional, Deciduous Forest, Rainforest and Coastal Savannah, whiles the three hydro-climatic zones are the Volta basin system, the South-Western basin system and the Coastal basin system (EPA, 2001). For simple climatological purposes, Ghana is often divided along latitude 8°N as Northern zone above and Southern zone below that latitude (Owusu and Klutse, 2013). The climate of the Northern zone is marked by a mono-modal rainfall season that occurs between May/June and October/November, given opportunity for only one cropping season as rainfed agriculture is the main practice in the area (Owusu and Klutse, 2013). From late November till the onset of rains (April/May) marks the long dry season in northern Ghana characterised by the air masses from the north-east, the northeasterly (NE) trade winds, which as described by Stanturf *et al*. (2011), blows dry and dusty air from the Sahara desert (known as 'Harmattan').

The Southern zone is marked by two separate rainy seasons (bi-modal) occurring between March to July (major season) and September to November (minor season) (Stanturf *et al.* 2011; Owusu, *et al.* 2008; McSweeney *et al.* 2010a). A short dry period separates the two rainy seasons and serves as a period for land preparation for the next season cropping (Owusu and Waylen, 2012; Cited in: Owusu and Klutse, 2013).

The local climate of Ghana is mainly driven by the movements and interaction of the Inter-Tropical Convergence Zone (ITCZ) and the associated West African Monsoon (WAM) (Stanturf *et al.* 2011; Bielli *et al*. 2009; Weldeab *et al.* 2007). Detailed descriptions of the ITCZ and WAM are available in Weldeab *et al.* (2007). Other notable drivers of Ghana's climate as described by several studies e.g. Owusu and Klutse (2013), Weldeab *et al.* (2007), Opoku-Ankomah and Cordrey (1994), and Lamb and Peppier (1992) include the African Easterly Waves (AEWs), Tropical Easterly Jets (TEJs), the El Niño Southern Oscillation (ENSO) phenomena and variations of the Atlantic Sea Surface Temperatures (SSTs).

Significant variations in seasonal, annual and decadal mean rainfall occur in Ghana and partly attributable to "*variations in the movements and intensity of the ITCZ, and variations in timing and intensity of the West African Monsoon*" with the ENSO observed to be the cause of those variations (McSweeney *et al.* 2010a).

The northern Ghana experiences the highest seasonal variations in temperature with dry and wet seasons' temperatures between 27-30°C, and 25-27°C respectively, while those of the south range between 25-27°C and 22-25°C respectively (McSweeney *et al.* 2010a).

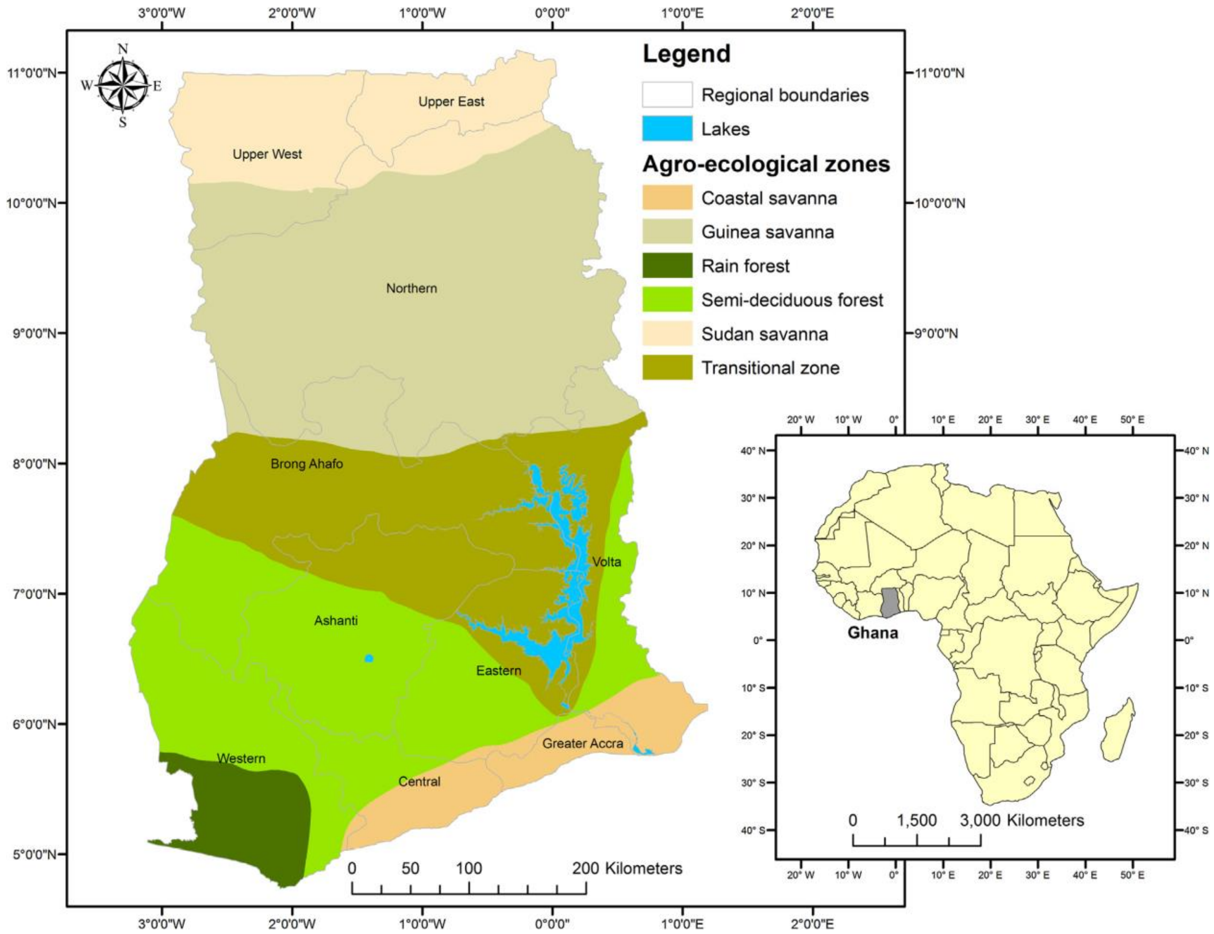


Figure 1.2: *Map showing six agro-ecological zones in Ghana.* *(Source: Rhebergen et al. 2016)*

1.2.1.2.2 Recent climate trends

The long-term trends of temperature and rainfall in Ghana have been significantly researched and relatively well documented. These covered both the national and regional levels of research studies. Climatic patterns at the various climatic zones and sub-river basins or catchments in Ghana have also been the focus of considerable research studies. Findings of these studies have all indicated signs of CC.

1.2.1.2.2.1 Temperature

Temperatures across Ghana have been generally high with evidences from meteorological data pointing to further increases over the coming years (EPA, 2011). An increased in mean annual temperatures over the six major ecological zones of Ghana within the period 1960-2000 have been observed with greater increases occurring over the Sudan and coastal savannah zones from 28.1^{O}C in 1960 to 29.0^{O}C in 2000 and from 27.0^{O}C in 1960 to 27.7^{O}C in 2000 respectively (EPA, 2011) (see also Fig.1.3 below). The mean annual temperature across the country ranges between 24^{O}C and 30^{O}C as a result of the location of low latitude and low altitude areas with extreme temperature conditions ranging between 18^{O}C and40^{O}C commonly experienced in the southern and northern sectors respectively (EPA, 2011). In a related study, it was observed that temperatures in northern Ghana had increased during the 20th century averaging 28°C and occasionally reaching extreme values of about 46°C in some parts of the area during dry seasons of November to April (Dietz *et al.* 2004: Cited in: Awen-Naam, 2011). It has been shown from available data that the mean annual temperature of entire Ghana has been on the increase at an average rate of 0.21°C per decade and rose by 1.0°C since 1960 (MESTI, 2013; McSweeney *et al.* 2010a; Stanturf *et al.* 2011) (see also Fig.1.4). The Environmental Protection Agency [EPA] (2001) similarly observed this rise in temperature by 1.0°C across the country over the same period. The increasing rate has been faster in the northern sector than southern Ghana (Minia 2008; McSweeney *et al.* 2010a).

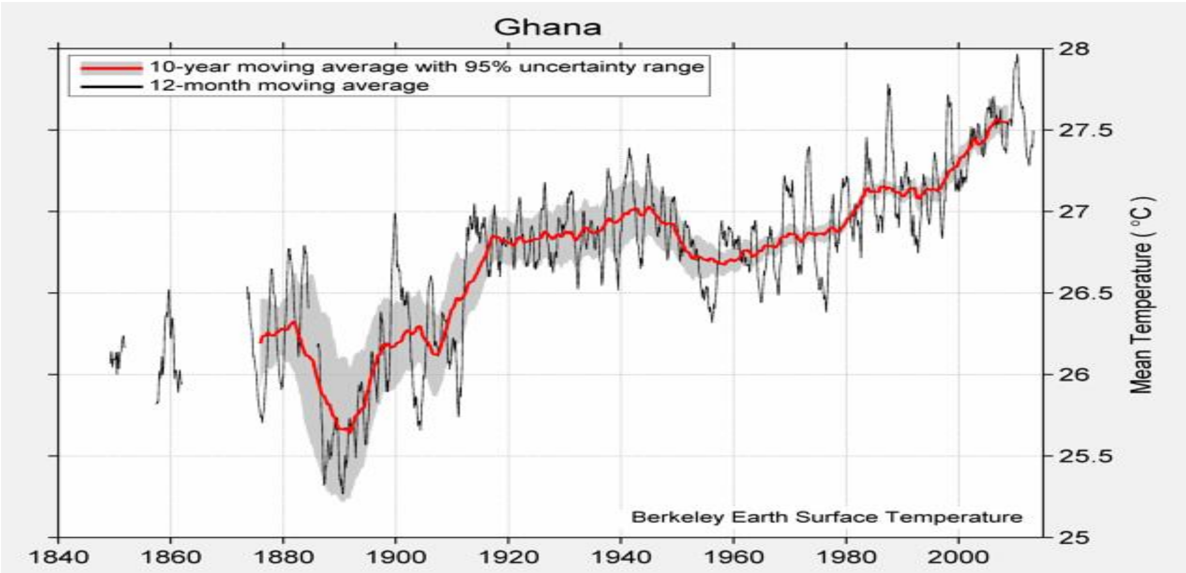


Figure 1.3: *Climate Change in Ghana (Source: Berkeley Earth, 2015)*

1.2.1.2.2.2 Rainfall

No clear long-term trends in annual rainfall of Ghana have been identified due to the highly variable nature of rainfall in the country except the general observed high rainfall in the 1960s, followed by low rainfalls in the late 1970s and early 1980s that resulted in a net decreasing trend between 1960-2006 at an average of 2.3 mm per month and 2.4% per decade (McSweeney *et al.* 2010a; Stanturf *et al.* 2011). Nonetheless, several other studies have observed a significant and generally decreased rainfall across the country. The EPA (2011) observed that there have been changes in both rainfall intensity and seasonal distribution across the country with decreased annual rainfall amount over the years. According to EPA

(2001), 20% reduction in rainfall over a 30-year period of 1961 to 1990 was experienced across Ghana.

Evidence of long-term considerable decrease in mean annual rainfall in parts of the country, particularly in northern Ghana has been well documented. For instance, Ofori-Sarpong (2001) clearly demonstrated a decrease in mean annual rainfall between two 30-year periods, when he used 60-year period (1931-1990) rainfall data for Navrongo to show a change in mean annual rainfall between 1931-1960 and 1961-1990 with mean annual rainfalls of 1087.6 mm and 986.1 mm respectively. By that observation, Ofori-Sarpong (2001) indicated that the first 30-year period, 1931-1960, was wetter than the second 30-year period, 1961-1990. This is attributable to the dry periods of 1970s and 1980s as noted above. Considerable decreases in rainfall in the Sudan and Guinea savanna zones of 1.5% at Tamale, 2.3% at Yendi, 7.2% at Navrongo, and 11.3% at Wa were also observed in a comparison analysis of annual rainfall data between 1950-1970 and 1971-1990 (Gyau-Boakye and Tumbulto, 2000). Moreover, declining trend of rainfall across meteorological stations in Ghana has been observed in a comparison analysis of the mean annual rainfall difference between two 20-year periods, 1951-1970 and 1981-2000 (Owusu and Waylen, 2009).

1.2.1.2.3 Climate projections for Ghana

1.2.1.2.3.1 Temperature projections

The various models and future climate scenarios have been used extensively in predicting future impacts of CC on Ghana. Although, predicted impacts on the country varied considerably among the models, there is consensus on evidence of CC and the increase in temperature across the country among all the models, with higher increasing rate in the northern sector of the country (De Pinto *et al.* 2012). Out of a consensus by 15 different models, the mean annual temperature of Ghana is projected to increase by 1.0 to 3.0°C by 2060, and by 1.5 - 5.2°C by 2090 with more rapid increases expected in the northern sector of the country (McSweeney *et al.* 2010a; De Pinto *et al.* 2012). Related study by EPA (2001), also projected that mean daily temperatures will rise by 2.5°C to 3.2°C by the year 2100 with average maximum expected to rise by 3ºC in the northern savanna region and by 2.5ºC in other parts of the country (see also Fig.1.4 below). This projected increase is observed by Awen-Naam (2011) to be higher than the global projected average of 2°C over the same period. The Ministry of Environment Science, Technology and Innovation of Ghana

[MESTI] (2013) also projected an average temperature increase of 0.6°C, 2.0°C and 3.9°C by the year 2020, 2050 and 2080 respectively.

According to the World Bank Report (World Bank, 2010), there will be an increasing trend in temperature across all regions of Ghana over the period 2010–50, with rapid increases in the northern sector up to 2.2–2.4°C, that will lead to high average temperatures of about 41°C. Projections have been made by other studies which observed continued increases in temperature across the country for 2050 and 2080 (e.g. Stanturf *et al.* 2011; Minia 2008). These projected results of increases in temperature are consistent with global projections by IPCC (2007b) in which warming of the climate system has been described as unequivocal, following clear evidence that abounds of increasing global average air and ocean temperatures.

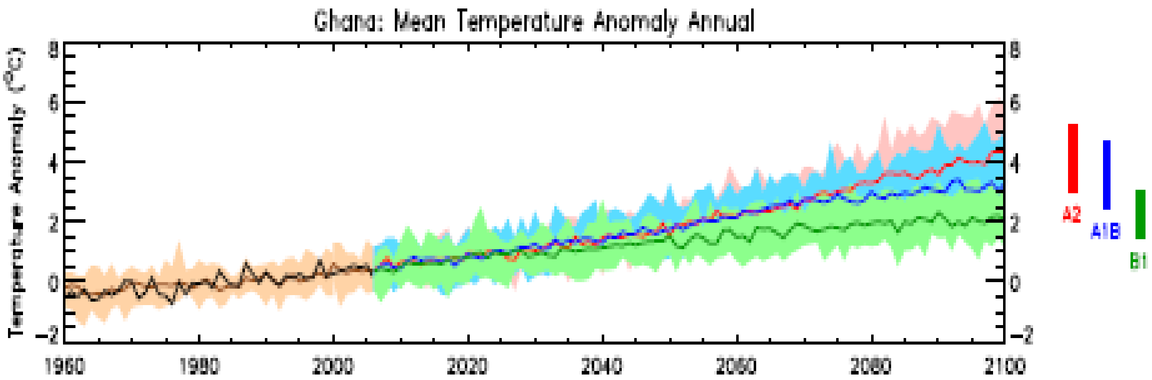


Figure 1.4: *Observed and future temperature trends for Ghana (Source: McSweeney et al, 2012)*

1.2.1.2.3.2 Rainfall projections

In contrast to projected changes in temperature, model results for changes in rainfall are commonly characterised by much uncertainty as half of the models predict a decrease while the rest project an increase (McSweeney *et al.* 2010b; Cited in: De Pinto *et al.* 2012). Many of the models, however, project significant variability in rainfall over the coming years. From results of some of such models, considerable variability in rainfall across all agro-ecological regions of Ghana is expected over the period 2010-2050 with coefficient of variation of annual rainfall in the country varying between -9% under Global wet scenario to -14% under Ghana dry scenario as observed by the World Bank (2010).

Annual rainfall in all parts of Ghana, except the High Rainforest Zone of southwest is projected to decrease by the year 2100 (AP, 2011). For instance, EPA (2001) has observed that annual rainfall will decrease by about 9 to 27% across the country by the year 2100 with the decreases varying spatially.

1.2.1.2.4 Projected impacts of climate change on water resources

As part of Ghana's fulfilment of her commitment to the United Nations Framework Convention on Climate Change (UNFCCC) and to take adaptive measures against the emerging negative impacts of CC, the preparation of the initial National Communication (NC) on CC was carried out in 2000. During the preparation of NC, CC impacts and vulnerability assessment studies on each river basin in Ghana was carried out. One of the major findings of these studies was that over a 30-year period from 1961 to 1990, streamflows dropped by 30%, a reflection of the sensitive nature of river discharge to changes in rainfall and temperature (EPA, 2000). Flow reductions of between 15% - 20% and 30% - 40% are projected to occur by 2020 and 2050 respectively in all the river basins in the country (EPA, 2000). The simulations also projected that CC could lead to reductions in groundwater recharge by between 5% and 22% by 2020, and between 30% and 40% by 2050 (EPA, 2000). Consequently, there will be a hike in water demand for irrigation with projected rise in demand of about 40% in 2020 and 150% in 2050 for the humid part of the country and as high as 150% in 2020 and 1200% in 2050 in the northern dry savannah (EPA, 2000).

As part of the manifestations of CC, frequent fluctuations in river discharges in the Volta Basin within Ghana pose more risk of droughts and/or floods in both urban and rural areas of the country (World Bank, 2010)**.** The EPA (2011) further observed that effects on streamflow in many of these rivers and other water resources are due to erratic and dwindling nature of rainfall in parts of the country, particularly the north, and observed reductions in water levels of Akosombo dam leading to supply of only 30% of Ghana's energy need instead of 70% is an example of such effects.

In view of these adverse effects of CC on water resources of Ghana, various adaptation measures centred on water conservation and improvements on efficient use of water have been suggested. *"They include practices to increase water supply (by using groundwater, building reservoirs and improving or stabilizing watershed management) and practices to decrease water demand (by increasing efficiency, reducing water losses, recycling water, changing irrigation practices, recycling domestic water for non-potable uses, improving or developing water management systems, and developing and introducing flood and drought monitoring and control systems)"* (AP, 2011). These are measures that ought to be pursued and encouraged from national to community/local farmer base level through research, sensitisation and support to local communities/farmers.

1.2.1.2.5 Projected impacts of climate change on agriculture and adaptation options

Ghana's agriculture is highly climate-sensitive as it is mainly rain-fed, yet contributes heavily to the nation's gross domestic product (GDP) thus rendering Ghana's economy very vulnerable to climate variability and change (World Bank, 2010). Particular reference could be made to the extreme drought in1983 that led to severe hunger and drastic reduction in GDP for that year showing manifestation of the threats on Ghana's development by CC (EPA, 2011). As a result of the dwindling rainfall amount coupled with its erratic and unpredictable nature, agricultural activities have become so difficult for farmers in parts of the country as they could no longer establish the rainfall pattern for crop production (EPA, 2011). This is particularly a major issue in the northern sector of the country.

Consequently, it is projected that agriculture production in Ghana will decrease by between 10.1% under Global wet scenario and 3.0% under Ghana wet scenario by 2050 (World Bank, 2010**).** Additionally, it is projected that CC will cause reductions in yields of several crops, including a decrease by 6.9% of maize yields by 2020 compared with yields in 2000 (EPA, 2001; Cited in: AP, 2011). The EPA (2011) further observed the impacts of CC on the production of root and tuber crops in Ghana and indicated that cassava yields are expected to decline by 3%, 13.5% and 53% in 2020, 2050 and 2080, respectively. Cocoyam yields will also decrease by 11.8%, 29.6% and 68% in 2020, 2050 and 2050, respectively (ibid).

It is observed that a rise in temperature by 0.1^{O}C poses serious consequences for the production of some crops and animals in parts of the country like in the northern sector (EPA, 2011). The implications are that the impacts of a rise in temperature by about 2 ^{O}C on Ghana's agriculture as projected by the results of the various models would be overwhelmingly detrimental. This is particularly so because the principal income earning and economic activities in the northern sector of Ghana, also noted as the bread basket of the country, is the rain-fed agriculture.

In spite of uncertainties associated with results of some models, consensus from multiple studies indicates that a general decline in yields of major crops in Ghana should be expected if adaptation measures are not taken (De Pinto *et al.* 2012). It is the reason agriculture sector was identified as one of the major adaptation priorities in Ghana's National Communication

(EPA, 2001). Some proposed adaptation measures for agricultural sector include *"educational and outreach activities to change management practices, a switch to different cultivars, and an improvement of pest and disease forecasting and control*" (AP, 2011). Although, national adaptation measures are crucial, the viability of such measures depends on national budget and resources. For instance, the World Bank (2010) observed that the whole of Ghana's adaptation resources approved is being spent on gradual expansion of irrigation since 2012. Nonetheless, farmers on their own do embark on several options of adaptation strategies aimed at reducing the adverse effects of CC (EPA, 2011) but often in dire need of external support.

1.2.2 Review of national policies on climate change, water resources, agriculture and irrigation

Since Ghana's independence in 1957, successive governments have pursued programmes aimed at accelerating economic growth and raising the living standards of the people with various degrees of success (IMF, 2012). This has resulted in several policy documents but with the return of constitutional rule in 1993, the nation has journeyed from vision 2020 to the current policy document – Ghana shared Growth and Development Agenda [GSGDA] (NDPC, 2010). The GSGDA together with other sectoral plans are providing the strategic direction for all sectors in Ghana. Although, the recently launched national policy framework on CC in 2014 is expected to derive its basis from the earlier main government sectoral document on CC, *"Ghana Goes for Green Growth: National Engagement on Climate Change"* (Sarpong and Anyidoho, 2012), its implementation is governed by the main national development plan, the GSGDA, just as other sectoral policy documents.

In order to assess the feasibility of the research recommendations, a policy review was conducted to ascertain whether there are adequate provisions for the implementation of all these proposed recommendations in this study.

1.2.2.1 National climate change policy

Climate data in Ghana from 1961 to 2000 indicates a clear and consistent rise in temperature and decrease in mean annual rainfall in all the six agro-ecological zones in the country (NCCAS, 2010). The national economy which depends heavily on agriculture is suffering and there is a certainty of further risk. This coupled with the nation's financial inadequacies among others, explains the need for a national policy on CC (MESTI, 2013). The Ghana

National Climate Change Policy (GNCCP) has been developed to help the nation to deal with CC related issues. *"The vision of this policy is to ensure a climate-resilient and climate-compatible economy while achieving sustainable development through equitable low-carbon economic growth for Ghana"* (MESTI, 2013). This is expected to be achieved through three main objectives, which are effective adaptation, social development and mitigation (IMF, 2012).

Four main policy themes have been outlined as key strategic focus areas to pursue in addressing the issues of adaptation in Ghana. These are agriculture and food security, disaster preparedness and response, natural resources management, and energy and infrastructure development (MESTI, 2013). Under each of these policy themes, several actions are intended to be carried out. Activities to be carried out under the first policy theme include researching into climate-smart agriculture, building the capacity of extension officers in climate-smart agriculture as well as developing climate resilient crop and livestock varieties. Promotion of diversified land use practices, preparing and enforcing spatial plans and improving farming technologies would also be pursued. The second policy theme is disaster preparedness and response. Here, actions such as carrying out public education on climate issues, ensuring existing infrastructure are climate-proof and making available financial support and insurance packages will be embarked upon. The focus on the third policy theme, natural resource management, is to ensure community based natural resource management through the introduction of monetary and social incentives to encourage effective and sustainable natural resource management such as conservation of forest through the use of alternative biofuel sources for domestic fuel needs among others. The final policy theme, energy and infrastructure development, seeks to minimize Greenhouse Gas (GHG) Emissions through research and development in the areas of low emission and clean energy technology such as wastes management technologies for generating energy. This includes embarking on improved energy efficiency and consumption.

A cross-cutting policy theme is equitable social development which seeks to ensure that the impact of CC does not alter the equity in social development but rather enhances equal access to it, regardless of gender, physical and socio-economic status. This is to be done in two main ways - that is dealing with the impact of CC on human health and access to water and sanitation. Also, CC gender issues relating to livelihoods and poverty are expected to be handled in this thematic area. Migration and other climate-change-related societal challenges would be tackled too.

Though clear and elaborate policies are identified to be carried out, what is critical for the realisation of these objectives is ensuring that they are integrated into sectoral programmes and actions for implementation by the various Ministries, Departments and Agencies (MDAs). It is to this effect that a ministerial body is proposed to perform the oversight role of developing detailed time-bound and implementation plans. The Environmental and Natural Resources Advisory Council (ENRAC) operates at cabinet level to coordinate among ministries and with several coordinating activities also carried out within ministries (CC DARE, 2011).

However, key constraints to the implementation of CC policies in Ghana in the past included the absence of clear cut roles for some institutions with CC related responsibilities, such as Town and Council Planning Department (CC Dare, 2012). Also, most of the institutions assigned responsibilities were not adequately equipped to perform their roles - example is the National Disaster Management Organisation (NADMO) (CC Dare, 2012). For the policy to adequately provide opportunities for the populations, particularly, farmers to adapt to the impact of CC, there is the need for these obstacles and several others to be addressed.

1.2.2.2 National agricultural sector policy

The nation's agricultural policies are contained in the Food and Agriculture Sector Development Policy (FASDEP), with the first document developed in 2002 (FASDEP I) as a continuation of what the Accelerated Agricultural Growth and Development Strategy (AAGDS) had initiated with emphasis on the private sector as engine of growth (MOFA, 2007). The current policy document for the agricultural sector is FASDEP II. The FASDEP II became necessary after Poverty and Social Impact Analysis (PSIA) showed that FASDEP I was not capable of accomplishing the desired impact on poverty. As a result, FASDEP II was developed to provide a level environmental ground for all categories of farmers with a special focus on the poor and vulnerable groups. The FASDEP II adopted wide range policies to address challenges within the agricultural sector in Ghana. These are human resource and managerial skills; natural resource management; technology development and dissemination; infrastructure; market access; food insecurity and irrigation development and management (MOFA, 2007). Six main policy strategies were identified to address challenges in the agricultural sector but for the purpose of this research, only policies related to this study were reviewed. Among the activities under the food security and emergency preparedness strategy are development of irrigation schemes, development of high yielding and short-duration crop varieties and promoting proper methods of managing harvest. Through this strategy, the nation seeks to enhance early warning systems and preparedness for disaster to avoid loss of harvest. Another key strategy is to increase farmers' incomes. Activities such as diversification of crops, vegetables, small ruminants and poultry are also considered in the strategy.

The policy, apart from the above, have plans to enact and enforce appropriate practices and plans to facilitate the development of agriculture in Ghana. To this end, community level land use plans are expected to be developed and enforced. Research into development and industrial use of indigenous stables and livestock by producing certified seeds and breeds for farmers to adapt are earmarked interventions. Extension service development and delivery is to be improved to identify appropriate methods of delivering equitable services to men and women. As noted above, this policy also seeks to create level playing environment for all farmers and one of the ways in doing this is to expand irrigation facilities and increase the production capacity of the current schemes. These are to be done in a way that promotes proper environmental practices.

Agricultural mechanisation and financing are major issues also captured in the policy. Here, initiatives such as developing appropriate machinery and equipment and promoting access to them would be all implemented. Financing access to credit by all categories of farmers is to be ensured at all levels through the implementation of several activities. The successful implementation of these policies however, requires the commitment of government and MDAs to ensure effective allocation of funds, and nurture the necessary linkages between stakeholders, particularly, to the private sector. More importantly, the response of the private sector and producers to the policy is critical for its success.

1.2.2.3 National irrigation policy

Under the agriculture sector, irrigation development and management stands out as a major strategy in the policy. The pertinence of this area has made it necessary for the nation to adopt separate policy and institutions to oversee its development. However, from independence until 2004, irrigation had no dependable and elaborate policy to direct its development and expansion. During this period, ad-hoc government agricultural strategies and programmes were basic interventions which determined irrigation development. However, in 2004, it was clear a practicable irrigation policy was a pre-requisite for the sustenance of agriculture (MOFA, 2011b). This realisation and several other processes finally resulted in the approval of an irrigation policy in 2010 known as the National Irrigation Policy, Strategies and Regulatory Measures (NIPSARP) to address challenges related to irrigation such as increasing the percentage of arable land irrigated, ensure effective management of existing schemes and increasing operation capacity of public schemes.

Another issue the policy was to promote is support for the informal sector irrigation so as to reduce the burden on the formal sector. The policy and the National Irrigation Development Master Plan (NIDMAP) together seek to implement strategies to expand irrigation to an area of 500,000ha in the medium term (MOFA, 2011b). Based on this background, the nation's policy direction is geared towards developing irrigation schemes, promoting reforms that will ensure equal access to land by everyone and ensure the use of meteorological information in agriculture at the grassroots. In the medium-term, the policy focus is ensuring that existing facilities and infrastructure are rehabilitated and expanded. Also, a conscious effort is intended to encourage the use of these facilities. To this end, expanding irrigation facilities, community-based valley-bottom irrigation schemes, ground water exploration and development for irrigation and the promotion of hand-fixed pumps will all be embarked upon (IMF, 2012). An elaborate institutional framework is proposed for the successful implementation of the policy initiatives. A major consideration of the policy is to create effective links within the Ministry of Food and Agriculture (MOFA) and beyond MOFA, particularly, with regulatory agencies such as Water Resources Commission (WRC), the Environmental Protection Agency (EPA) and local government. Other institutions incorporated in this linkage are Ghana Irrigation Development Authority (GIDA) and Ministry of Local Government and Rural Development (MLG & RD). The full decentralisation of GIDA and elevation of all its regional offices to departments is also planned to facilitate the presence of GIDA as close to the farmer as possible.

1.2.2.4 Wetlands and water resources policies

The nation's focus is ensuring sustainable use of wetlands through a wetland inventory and monitoring, to restore and rehabilitate badly altered wetlands. As a result, sustainable livelihood strategies are proposed at the grassroots level to avoid the dependence of these communities on the wetlands for a livelihood. This is particularly important as wetlands are a source of varied opportunities that include socio-economic, cultural and ecological values for the inhabiting communities and the nation at large (IMF, 2012).

The water resources potential of Ghana is divided into two forms as surface and groundwater sources and the policy of the nation is to ensure that the need of water does not pose a challenge to national development (MWRWH, 2007). The utilisation of water in Ghana is categorised into consumptive and non-consumptive uses. Projections of consumptive water demand for 2020 based on surface water resources alone is 5 x 10^9 m^3, representing only about 12% of the entire surface water resources (MWRWH, 2007). Despite the availability of sufficient water resources to meet diversified demands, deficits in coverage persist (MWRWH, 2007; Norström, 2009). On the other hand, major non-consumptive uses are inland fisheries, water transport and hydropower (MWRWH, 2007). However, with rapidly growing and diversified demands, water resources are becoming increasingly depleted in both quantity and quality (IMF, 2012). This concern and many others, made it necessary for policies to govern the sector and provide directions for the sustainable use of the resources.

Historically, national water policies in Ghana have always been informed by international development objectives such as Millennium Development Goals (MDGs), New Partnership for Africa's Development (NEPAD) and others. The current National Water Policy's goal is to *"achieve sustainable development, management and use of Ghana's water resources"* by focusing on three main themes which are community water and sanitation, urban water supply and water resource management (MWRWH, 2007). All policy objectives have been categorised under special focus areas to ensure coordination in the realisation of the goal of the policy. Integrated water resources management, access to water, water for food security, financing, climate variability and change, capacity building, public awareness creation, good governance, planning and research and international cooperation (MWRWH, 2007) are just a few of the focused areas identified in the policy. Clear actions and measures have also been outlined to be embarked upon in every focused area.

Based on the above, the following are expected to be seen at the grassroots; mainstreaming water resources planning into economic planning, ensuring cost recovery and sustainability of water resources and promoting public private partnership for protection and conservation of water resources. To make water available for food security, the policy also seeks to support micro-irrigation and valley bottom irrigation in communities, enhance the capacity of District

Assemblies (DAs) to support communities to operate and maintain irrigation facilities and promote the efficient use of fertilisers to reduce pollution of water bodies and ensure water conservation (MWRWH, 2007). Provisions are made for clear institutional and regulatory arrangements for the implementation of this policy. The Ministry of Water Resources, Works and Housing (MWRWH) is trusted with overall responsibility for the water sector. Others institutions are the Water Resources Commission (WRC), the Water Directorate (WD), the Environmental Protection Agency (EPA), the Ghana Water Company Limited (GWCL), the Community Water and Sanitation Agency (CWSA), and the Public Utilities Regulatory Commission (PURC) just to mention but a few. All these institutions are assigned clearly defined roles and jurisdiction at the various level of the decentralisation structure (MWRWH, 2007).

National policies of each of the sectors seem to have made adequate provisions for the implementation of most of the research recommendations. However, the commitment of the government and its stakeholders in terms of action, coordination and resources allocation remains critical for the realisation of these at the farmer level. Also, another important condition to be met to enable farmers benefit and take advantage of these policy interventions is mainstreaming these policies into the plans of the DAs.

1.2.3 Land use land cover changes

Land describes the basic life supporting natural resource for human and majority of other living forms in terms of being the source of space, energy and nutrients required by any organism (FAO, 1998; cited in: Beza, 2011). Land could be categorized into two different forms as land in its natural condition and land modified to meet a wide range of human needs and wants, in which sense, the land quality is determined by its natural suitability for a particular human activity and which then determines land use (Beza, 2011). Over the ages, land has been exploited to serve diverse human needs and wants, ranging from non-destructive form of watching landscape and traditional collection of herbs to a much destructive form of heavy machinery application and industrial use of land (Stolbovoi, 2002; cited in: Duadze, 2004). Land use is therefore, defined by the purposes for which the land cover is being exploited (Lambin *et al.* 2003).

Land usage has been conceived differently; to the World Conservation Monitoring Centre of the United Nations Environment Programme (UNEP-WCMC, 2001), land use refers to human activities carried out to obtain goods or benefits from the land. Importantly, land use has been widely recognized as a critical factor mediating socioeconomic, political and cultural behaviour and global CC (IPCC, 2001). The rising socioeconomic development is the major factor responsible for land use/cover changes (Wagner *et al.* 2013). This is directly linked to rapid population growth and the associated growth in consumption which is a key driver of environmental and water resource changes (Sirén, 2007 and Sun *et al.* 2008). For instance, the rising population growth/density and the associated socioeconomic development quest, technological and CC have been observed to be the leading drivers of the rapid land use/cover changes (UNEP, 2007). Land-use planning, particularly in developing countries where there are rapid demands for socioeconomic activities, is a necessary measure for sustainable benefits of such societal developments while ensuring that natural resources are being conserved (GIZ, 2012). However, land-use planning measures are virtually alien in most developing countries in sub-Sahara Africa of which Ghana is a part.

The realization that changes in land use/cover have impacts on climate and ecosystem attracted global concerns about these changes in recent times (Lambin *et al.* 2003). Land use/cover forms the lower boundary of the atmosphere and is thus a major component of climate variability and change. Human modification of the land surface therefore, affects regional to global climate processes, by changing the fluxes of mass and energy between an ecosystem and the atmosphere (Pielke *et al.* 2002). The effects of land use/cover changes extend beyond alteration of climatic system to the temporal and spatial determination of the state of water resources at the river catchment level. Evidence abounds of the effects of land use/cover changes on the hydrologic system and the resultant huge potential impacts on water resources (Wagner *et al*. 2013; Stonestrom *et al.* 2009). This occurs in different dimensions; including the influence on runoff and river discharge resulting from the induced changes in climatic system.

It is also established that land use/cover changes resulting from human activities have been the major driving force of high water resources exploitation (Nian *et al.* 2014). Land use/cover changes are also part of the leading causes of soil erosion (Wijitkosum, 2012) which can lead to siltation of water bodies and deterioration of water quality. The effects of land use/cover changes on water quality include, *"introduction of nitrogen compounds and other biologically active solutes"* (e.g., Schlesinger *et al.* 2006; Schlesinger, 2009; cited in: Stonestrom *et al.* 2009) and the "large-scale alteration of sediment budgets" (Hassan *et al.* 2008; Valentin *et al.* 2008; cited in: Stonestrom *et al.* 2009). Information on land use/cover has therefore become critical for informed policy formulation for natural resources management ranging from global to local community level (Duadze, 2004)

According to Dietz *et al.* (2004), land use/cover changes in the whole of the Upper East Region (UER) of Ghana are obvious. They identified the underlying causes as relocation of farms to valleys, population growth and its pressure for more land and the increased development of irrigation schemes. The others included the southward shift of the cotton belt which has led to more land put under cotton cultivation as well as intensification or expansion of farms as part of measures to off-set crop-failure risks (Dietz *et al*. 2004). Asante and Amuakwa-Mensah (2014) further disclosed that the depletion of the vegetation in the UER is a result of combined effects of overgrazing, intensive farming activities and climatic variability.

Any change in land use/cover has a potential of affecting water yield in a catchment and consequently, affect the hydrological regime of the catchment. Siltation of water bodies could be a major concern of any considerable land cover changes in a catchment. Besides, land use/cover changes affect evaporative water losses and variations in evapotranspiration, the key concerns in irrigated agriculture.

1.3 Research objectives

1.3.1 Main objectives

The present study is an attempt to forecast future water resources availability situation in the Vea catchment with regards to multi-sectoral water demands and water supply, particularly for irrigation, in the context of CC. The main objectives of this study, therefore, include the assessment of the impacts of predicted CC on the water resources of the catchment and the vulnerability of irrigated agriculture to these changes. This involves predictions of the future state of the water resources and water demands under CC and assessments of the vulnerability of irrigated agriculture and other water users (e.g. domestic) to climatic induced changes in water availability. The study also assessed the land use/cover changes in the catchment.

1.3.2 Specific objectives

The specific objectives were to:

- Estimate flux (runoff/flow) for Vea catchment

- Investigate the impact of CC on surface hydrology (runoff/flow and evapotranspiration) and reservoir storage in the Vea catchment
- Assess farmers' perceptions and adaptation practices to climate variability and change in comparison with the actual change and variations based on observed climatic data.
- Assess vulnerability of the Vea catchment to water stress conditions
- Assess land use/cover changes in the catchment

1.4 Research questions

The study was an attempt to find answers to the following questions:

- Can historical streamflow data for the ungauged Vea catchment be estimated using water mass balance method and reservoir bathymetry data?
- Are there changes in rainfall, streamflow, reservoir storage and evapotranspiration in the Vea catchment as a result of CC? If there are changes, are the pattern of the changes increasing or decreasing?
- Do farmers' views about CC and variability correspond with analyses from observed climatic data or differ?
- Are there any relationships between future adaptation measures planned to be taken by farmers in response to changing climatic conditions and increase water demand in the Vea catchment?
- Will future CC lead to inadequate water availability in the Vea catchment for future irrigation and domestic water supply?
- Have there been changes in the land cover categories in the Vea catchment over the past two decades? If there are changes, are the pattern of the changes increasing or decreasing?

1.5 Hypotheses

The following hypotheses were formulated and tested by this study:

- Historical streamflow data for the ungauged Vea catchment can be estimated using water mass balance method and reservoir bathymetry data.
- Rainfall, streamflow and reservoir storage in the Vea catchment are decreasing as a result of CC, while evapotranspiration is increasing for the same reason.

- Farmers' perceptions on CC and variability differ from the reality showed by the observed climatic data.
- Future adaptation measures planned to be taken by farmers in response to CC are related to increase future water demand in the Vea catchment.
- Future CC will relate to future inadequate water availability in the Vea catchment for future irrigation and domestic water supply.
- There have been changes in land cover categories of the Vea catchment over the past two decades.

1.6 Conceptual framework

The conceptual framework of a research study serves as a research protocol that "sets the stage" for the presentation of the research question that calls for the investigation being conducted based on the problem statement (McGaghie *et al*. 2001; Cited in: Regoniel, 2015). It plays an important role by serving as a "map" or "rudder" that guides the researcher in pursuing the investigation by identifying the key variables required in the research, illustrating the interconnections between these variables and mapping out the actions required in the course of the research towards achieving the objective of the study (Regoniel, 2015). In order to achieve the main goal of this study with the key focus on assessing the water availability situation in the study area for future irrigation, the investigation in the study is conceptualized as depicted by figure 1.5.

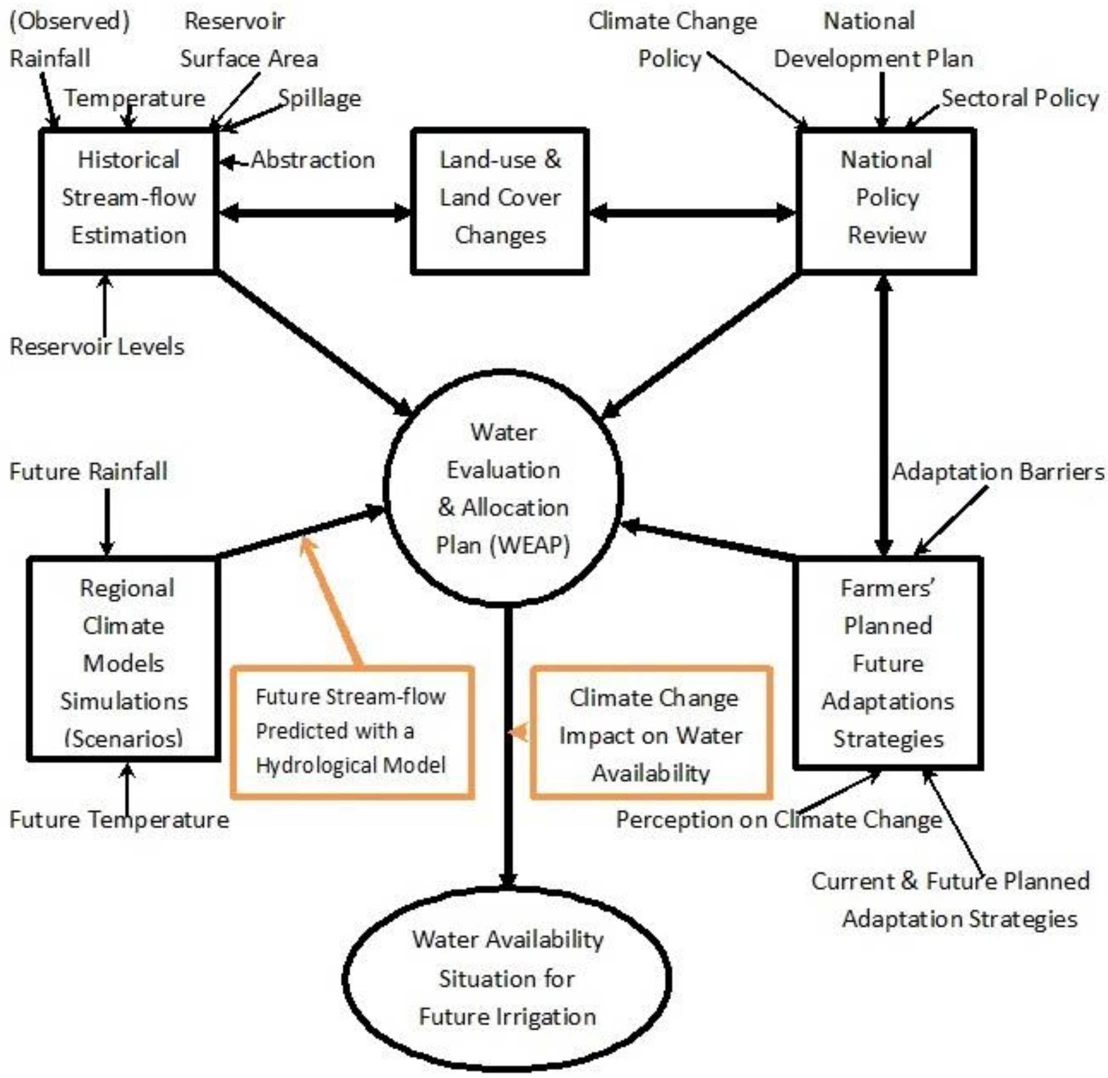


Figure 1.5: *Schematic diagram illustrating the interrelationships between the various components of the study*

Any attempt to assess the water availability situation in a catchment for future irrigation in the context of CC must take into consideration five major components (factors) of variables/scenarios. The five distinct components are namely, catchment historical stream-flow; future climate conditions (scenarios); existing national policy on CC; farmers' perception on CC and planned future adaptations strategies; and land use and cover changes in the catchment. These components will all influence the availability of water and the extent of water demand and water use in the catchment.

The relationship between these components and the set goal of determining the water availability situation in the area for future irrigation is conceptualised as shown in figure 1.5. It is generally a two stage relationship. The first level of relationship is where the five components are outputs of several variables which are identified and linked to these major components and the second stage involves a relationship in which the major components serves as inputs for the Water Evaluation and Allocation Planning model (WEAP), which in turn estimates the future water availability situation in the area for future irrigation in the context of predicted future climate conditions. These components include the future stream-flow time series predicted with a hydrological model IHACRES (identification of unit hydrographs and component flows from rainfall, evapotranspiration and stream-flow) using regional climate models simulations (scenarios) as inputs. Remarkably, the historical stream-flow time series is the most immediate required component in the estimation of catchment future water availability situation or status. It serves as a control input variable and is required for model calibration and as input for water availability comparative analysis between the past and the given future period. Notably also, a change or modification in any variable/scenario under any of the other components can result in different outcomes.

The changes or different scenarios may include the variable outcomes of the simulations of future climate conditions by the different climate models, national policy change/modification and the different planned future adaptations strategies by farmers. For instance, if more farmers plan to practice irrigated agriculture in the future as opposed to the status quo (rain-fed) or if those already practicing irrigated agriculture intend to increase their irrigated fields, the future water availability situation in the area could considerably be different from the present situation. Likewise, if there is any change in national policy on CC, for example, focus on irrigation development as an adaptation strategy to support farmers' adaptive capacity, there could be a rippling impact on the availability of water resource, particularly, at the catchment level. Nonetheless, the feasibility of any planned future irrigation as an adaptation strategy by farmers is determined or governed by provisions in the national policy on CC and adaptation strategies and sometimes, the reverse holds.

Land use land cover changes could be a result of the national policy (e.g. on environmental protection and resources conservation, water resources management, CC, and so on) or the lack of it. Effective national policy relating to environmental protection and resources conservation, could effectively regulate and control land use land cover changes at the catchment level and thereby serves as a key water resources management tool for protection of water resources in the context of CC. The lack of or the ineffectiveness of such national policy could be detrimental to the sustainability of water resources, particularly at the catchment level. Land use and cover changes could considerably affect water yield, streamflow, water availability and water quality in the catchment. In this study, the extent of changes in land use and cover in the study area is investigated and the relationship with other components has been identified as depicted in figure 1.5.

In summary, the research investigation entails a stepwise process that involves estimation of historical stream-flow time series; a review of national policy on CC; investigation of farmers' perceptions and adaptation practices to climate variability and change; and the acquisition of regional climate models simulations (scenarios), all of which serve as inputs and scenarios for the Water Evaluation and Allocation Planning model (WEAP), which in turn estimates the future water availability situation in the area for future irrigation in the context of predicted future climate conditions. In addition, the extent of changes in land use land cover in the study area is investigated and the result serves as support for drawing recommendations for water management in the study area.

1.7 Novelty

The novelty of the present study resides in the maiden approach employed that offered the possibility of assessing the impact of CC on the water resources of the ungauged Vea catchment. The maiden approach involved the use of water mass balance method for estimating streamflow for the catchment that has no observed historical streamflow as well as the use of an integrated method of assessing future water availability situation through modelling with different scenarios drawn from the various sectors that influence water demand/use. By an integrated method used, scenarios drawn from the review of national and sectorial policies on CC and water resources as well as farmers' planned future CC adaptation strategies and the associated future likely irrigation water demand were incorporated in the modelling process of assessing future impact of CC on water availability for irrigation. This approach of assessing future impact of CC on the water resources of the catchment is first of its kind and we believe the new research approach used in the present study as well as the findings will greatly be beneficial to managers of the water resources in the study area and other policy makers. The research approach of assessing future impact of CC on the water resources of an ungauged catchment as employed in the present study is expected to be novel and of interest to managers of other such ungauged catchments, especially, in the West Africa sub-region.

Significant amount of research have been carried out in Ghana over the past decade to assess the impact of CC on water resources in Ghana, particularly water resources within the Volta

Basin. However, literature has shown that no such research has explicitly been carried out on the Vea catchment of the White Volta Sub-Basin obviously due to lack of streamflow data. Nonetheless, the Vea irrigation reservoir remains a single most important water resource in the catchment and to the people in the area as it serves a dual purpose of water supply for domestic use and irrigation which has become the main livelihood for the surrounding communities. The present study was a result of the conviction that the study of the impact of CC on the water resources of the catchment was crucial; hence lack of observed streamflow data should not be a barrier once there was a possibility of an innovative study approach.

1.8 Scope of the study

Spatially, this study covered only the Vea catchment of area 305 km^2 in the Upper East Region of Ghana. In the present study, the impact of CC on only the surface water resource availability in the catchment was investigated due to lack of ground water data. The assessment of the influence of siltation of the irrigation reservoir on future water availability situation in the area was excluded in this study due to lack of sedimentation data. The study period covered between 1972 and 2012, which was the period of available observed meteorological data, reservoir bathymetry data (daily height, surface area and storage) and the daily water abstraction data required for this study.

Six out of eleven agricultural enumeration areas in the catchment were chosen for the survey data collection carried out in this study. Only adult farmers of age group of 50+ years with at least 30 years of farming experience were sampled as respondents to the household survey questionnaire administered. The sample sizes for the household questionnaire survey was 466. Eight stakeholder institutions in agriculture, water and environment sectors in the study area were also interviewed during this study. The daily observed rainfall, temperature and evaporation data were the only primary climate parameters used in this research owing to lack of observed data for the other climate parameters. While both rainfall and temperature data were obtained from four meteorological stations, the evaporation data for only one meteorological station could be obtained. The outputs of an ensemble of 16 different Regional Climate Models (RCMs) - simulated temperature and rainfall time series for the catchment were used. However, only the two extreme streamflow time series (lowest and highest) derived from conditions simulated by these 16 RCMs and the streamflow time series averaged over all the 16 conditions were used as inputs into water allocation and planning model (WEAP) to assess future water availability situation in the catchment. The Landsat

ETM satellite images used in this study were those of 04 January 1990, 02 January 2000 and 02 January 2010 covering the study area with resolution, 30mx30m.

The theories and models applied in the analyses of data and interpretations of results were:

1) The Thiessen Polygons interpolation method used to determine the catchment areal rainfall.
2) The delta-change bias correction method used for correction of biases in the RCMs simulations.
3) The reservoir mass balance equation used to estimate the catchment historical streamflow.
4) The Mann-Kendall test statistics (Mann 1945, Kendall 1975), Pettitt test (Pettitt, 1979) and Hubert Segmentation test (Hubert *et al.* 1989) used for the change-point detection and examining the long-term trends in rainfall and temperature time series data of the catchment.
5) F-ratio and F-distribution method used for rainfall variability analysis.
6) Thornthwaite (1948) method used in estimating evapotranspiration.
7) The CROPWAT/CLIMWAT model used in determining the annual irrigation water demand/requirement.
8) The IHACRES rainfall-runoff model used for future streamflow prediction and
9) The WEAP model used for assessing future water availability situation in the catchment.

1.9 Expected results and benefits

The future operations of the VEA irrigation project could face serious challenges if, besides the foreseeable competing water demand on the water resources of the catchment, there exists any significant CC impact. An estimation of historical streamflow for the ungauged Vea catchment coupled with establishment of a modelling system consisting of a simple and effective rainfall-runoff model, an integrated watershed-based water use and supply planning model and a couple of Regional Climate Models as a basic decision support tool for management and assessment of CC impact on VEA irrigation project is the primary expected upshot of this study. This system will help decision makers to undertake regular assessment and design policies and measures that will enhance a long-term optimal operation of VEA irrigation project. In other words, a call could be made to responsible institutions, particularly, the Ghana Irrigation Development Authority (GIDA) and the management of

VEA irrigation project to recognize and accept this established scientific tool for assessment and management of the water resources in the catchment.

Besides, the study will also provide information with regards to the future state of climatic, environmental, social and economic systems, future water demands under CC and the vulnerability of the water users to climate induced changes in water availability that is of significant importance in respect of policies and strategies of the government of Ghana and the Upper East Region in planning future developments on the VEA dam project. It is also expected that by the end of the study, a reliable and well collated data for the Vea catchment such as climate data, streamflow data and land use maps would have been established.

In conclusion, the upshot of the study is expected to help the managers of Vea irrigation project formulate water management policies that will optimise water use by abating the impact of projected climatic changes on the water resources of the Vea catchment, as well as to develop adaptation programs. The findings from this study are expected to have a broader relevance to other agricultural areas, especially, in the West Africa sub-region or in other places with similar agro-ecological and climatic characteristics as in the Vea catchment. It is therefore expected that larger lessons will be inherent in the findings of the present study and should be of interest to the larger scientific community, hence should merit publication of those findings in good peer review scientific journals.

1.10 Outline of the thesis

This thesis is organised into eight chapters in the following way.

Chapter 1 presents a general introduction and background of the study which include the overview of CC projections and impacts on water resources and agriculture as well as policy guidelines on CC and adaptation. The objectives are also defined in this first chapter.

Chapter 2 provides an overview of the study area that includes the description of the study region (i.e. Upper East) and the catchment in terms of location and demographic features, soil and drainage, vegetation, climate, geology and hydrogeology and water resources utilisation.

Chapter 3 presents detailed description of the data types that were used in the study and the materials and methods used in analysing these data. This includes description of data preparation processes, how secondary data were derived or estimated from the primary data and all the processes involved in the analysis of each data type, including the selection and description of each software (model) used.

Chapter 4 presents the results of the analysis of the current status and future development of climatic variables and water components in the study area. These include the results of the statistical analysis of the meteorological data of the area, the estimation of the catchment historical streamflow, the hydrological predictions of the catchment future streamflow and assessment of the impact of CC on streamflow in the catchment.

Chapter 5 presents the results of the analysis of the qualitative data collected using household survey questionnaire and institutional interviews as well as focus group discussions. These include the findings on perceptions of changes in long-term temperature and rainfall as well as perceptions of vulnerability level of livelihoods, adaptation practices and future adaptation plans, external adaptation supports and barriers to adaptations. The results of the analysis of perceived changes in land use and land cover in the study area are also included in this chapter.

Chapter 6 presents the results of the analysis and assessment of the impact of future CC on water resources and water allocations in the study area. These include the results of the assessment of the future situation of water availability for irrigation, domestic supply and livestock watering in the study area.

Chapter 7 presents the classification results of the analysis of Landsat ETM satellite images of land use and land cover in the study area.

Chapter 8 presents the general conclusions and recommendations of the study.

CHAPTER 2: THE STUDY AREA

2.1 Introduction

This chapter of the study provides an overview of the study region (i.e. Upper East) and catchment area (i.e. Vea). The study region captures the location, soil and drainage, vegetation and climate and geology of the area. The rest are: hydrogeology, water resources and population characteristics. The study catchment area also presents a brief description of the site (i.e. Vea), map of Vea showing Vea dam irrigation reservoir as well as the topographic, soil and land use maps.

2.2 The Study Region

2.2.1 Location, Population and Socio-economic Characteristics

Upper East Region (UER) is one of the three regions of Northern Ghana (Upper East, Upper West and Northern Region) and located in the north-eastern corner of the country (Fig. 2.1) between longitudes 1^0 15′ W and 0^0 5′ E and latitudes 10^0 30′ N and 11^0 8′ N (Ofori-Sarpong, 2001). It is situated in the centre of the Volta Basin (van de Giesen *et al*. 2002) and bordered by Burkina Faso in the north and Togo in the east. Within Ghana, the Region is bordered to the south by the West Mamprusi District of Northern Region and by the Sissala District of Upper West Region in the west (GSS, 2013a).

The UER lies in the transitional area of the Guinea and the Sudan savannah zones of annual rainfall of about 1000 mm and between 500 – 700 mm respectively (Issaka *et al.* 2012). The rainfall in the Region is mono-modal and the peak of the rainy season is between July and September (Badmos *et al.* 2015). UER is characterized by consistently high temperatures and erratic rainfall (Blench, 2006; Amegashie *et al*. 2012). The Region records the highest temperatures in Ghana (MOFA, 2011a) with the highest value of 43.9°C so far experienced in Ghana recorded in the Region which also experienced the highest annual mean maximum temperature of 34°C (GMet, 2016). The mean annual value for the Region revolves around 28.6^{o}C (Gyasi *et al.* 2006; Amegashie *et al*. 2012).

The total land area of UER is about 8,842 km^2, representing 3.7% of Ghana’s total land area (GSS, 2013b) and has a relatively flat landscape with the East and southeast characterized by a few hills (Donkoh *et al.* 2012). The current population of the Region stands at about 1,046,545 people (51.6% females and 48.4% males), with population growth rate of 1.2% and a population density of 118.4 inhabitants/km^2 well above the national average of 103.4

inhabitants/km^2 (GSS, 2013a). There is rising scarcity of land in the Region due to population pressure (Karbo and Agyare, 2002). Nonetheless, the Region is losing population through out-migration at a high rate (GSS, 2013a). The high rate of out-migration in the Region is due to the combined effects of poverty, land scarcity and population pressure (Kwesi, 2003).

The UER is largely dominated by people living in rural areas constituting over 80% of the Regional population (Birner *et al.* 2005). It is economically the poorest among the ten administrative Regions of Ghana (Gyasi *et al.* 2006) and yet it is the region where efforts to reduce poverty have failed to yield positive results (Kwesi, 2003). With as high as 88% of the population living in poverty as of 1998/99 (GSS, 2000) the Region has the largest proportion of poor people in Ghana (Liebe, 2002). The UER is also one of the most deprived regions in Ghana (Hagan, 2007).

Agriculture forms the main source of livelihood for majority of the people in the region (Liebe, 2002). About 68.7% of the Region's economically active population aged 15 years and above are engaged in agriculture and related activities (GSS, 2013a). Additionally, about 77.9% of working children (aged 7-14 years) are also engaged in agriculture and related activities (GSS, 2005). The Region records the highest proportion of agricultural households (83.7%) in Ghana (GSS, 2013b).The people in the Region practice largely peasant (subsistent) agriculture with relatively small farm sizes due to high population density which is also responsible for the over exploited and impoverished soils in the area (Kwesi, 2003). The availability of land and other resources are the determining factors of the size of each farmer's farm in the Region, whilst the climate, vegetation, soil and drainage systems are factors that determine the types of crops cultivated by the farmers in the area (GSS, 2013a). The five major crops cultivated by farmers in the Region are millet, groundnut, rice, maize and beans accounting for 82.3% of total farms in the Region (GSS, 2013a).

Besides crop farming, livestock production has been the second most important income activity for the people in the Region (Kwesi, 2003) by serving as a critical means of building household resilience to food insecurity (Quaye, 2008). Of all the agricultural households in the Region, 96.7% are in crop farming and 82.8% are in livestock rearing (GSS, 2013b), indicating that most of the agricultural households engage in a combination of crop farming and livestock rearing. The major traditional livestock in UER include cattle, sheep, goats and pigs (GSS, 2013a). The Region accounts for about 18% of Ghana's cattle production (GSS, 2005) and has the highest cattle population density in the country (Gyasi *et al.* 2006).

On account of the critical and immense role of agriculture as the main livelihood source for the majority of the population in the Region, improvement in agriculture is necessary for the economic development of the area.

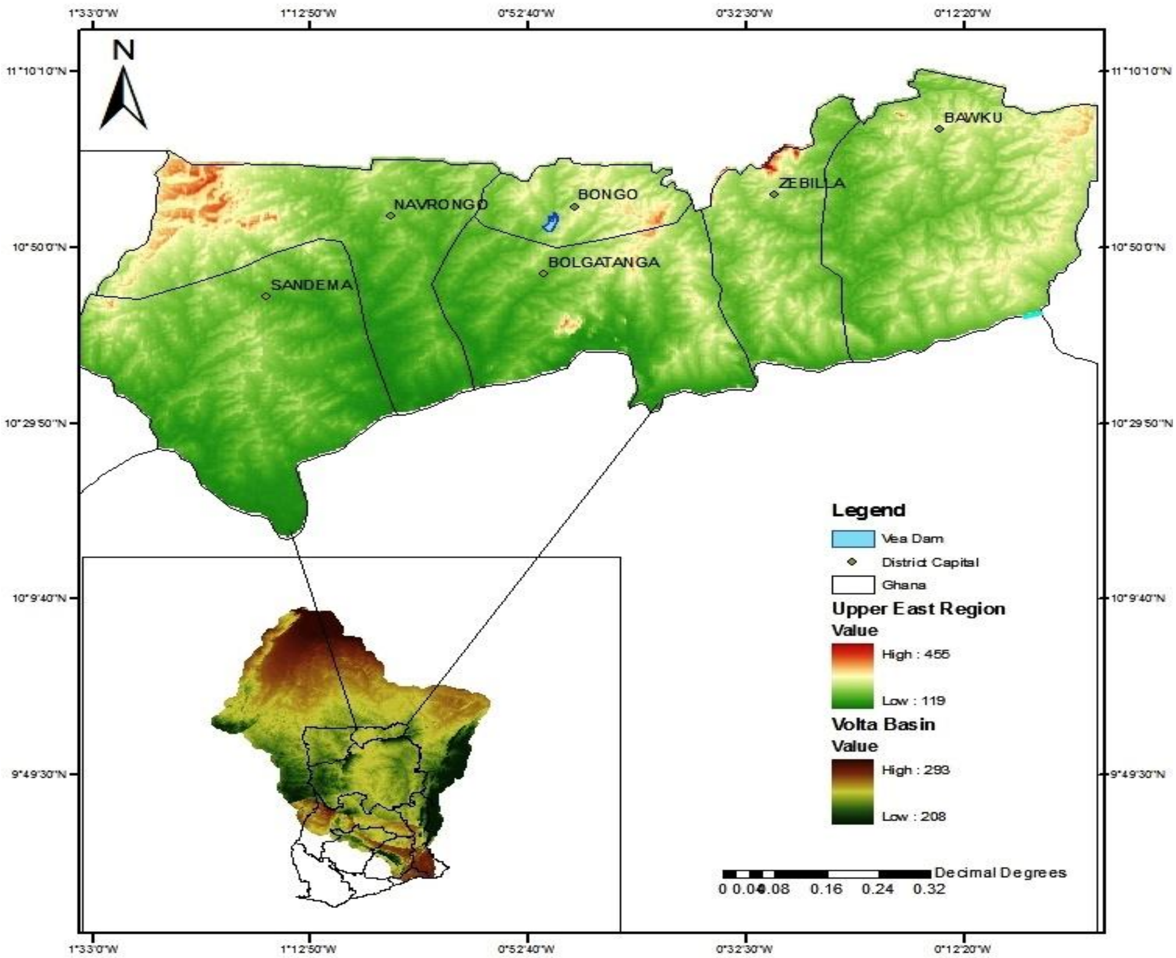


Figure 2.1: *The Upper East Region (UER), showing its location in Ghana and Volta Basin*

2.2.2 Soil and Drainage

The soils in the UER are largely the formations from granite rocks (Mdemu, 2008; GSS, 2013a). Generally, the vast area of the Region is dominated by *Lixisols* (Fig.2.2) but the *Fluvisols* are the most found along the White Volta sub-basin including ephemeral rivers (Mdemu, 2008) such as the Yaragatanga of the Vea Catchment. These soils of granite rocks origin in the Region are shallow with complex basement, by which nature they have low fertility (Ofori-Sarpong, 2001) with low organic matter content, coarse textured and prone to erosion (GSS, 2013a). The low land areas are covered by heavy and silty clay soils with higher natural fertility but are difficult to till and also prone to floods due to seasonal water logging (Ofori-Sarpong, 2001; GSS, 2005; GSS, 2013a). The White Volta River is the main drainage of the UER and receives runoff from all river networks that drain the Region with the Red Volta, the Sisili and the Tono Rivers as its major tributaries (Mdemu, 2008).

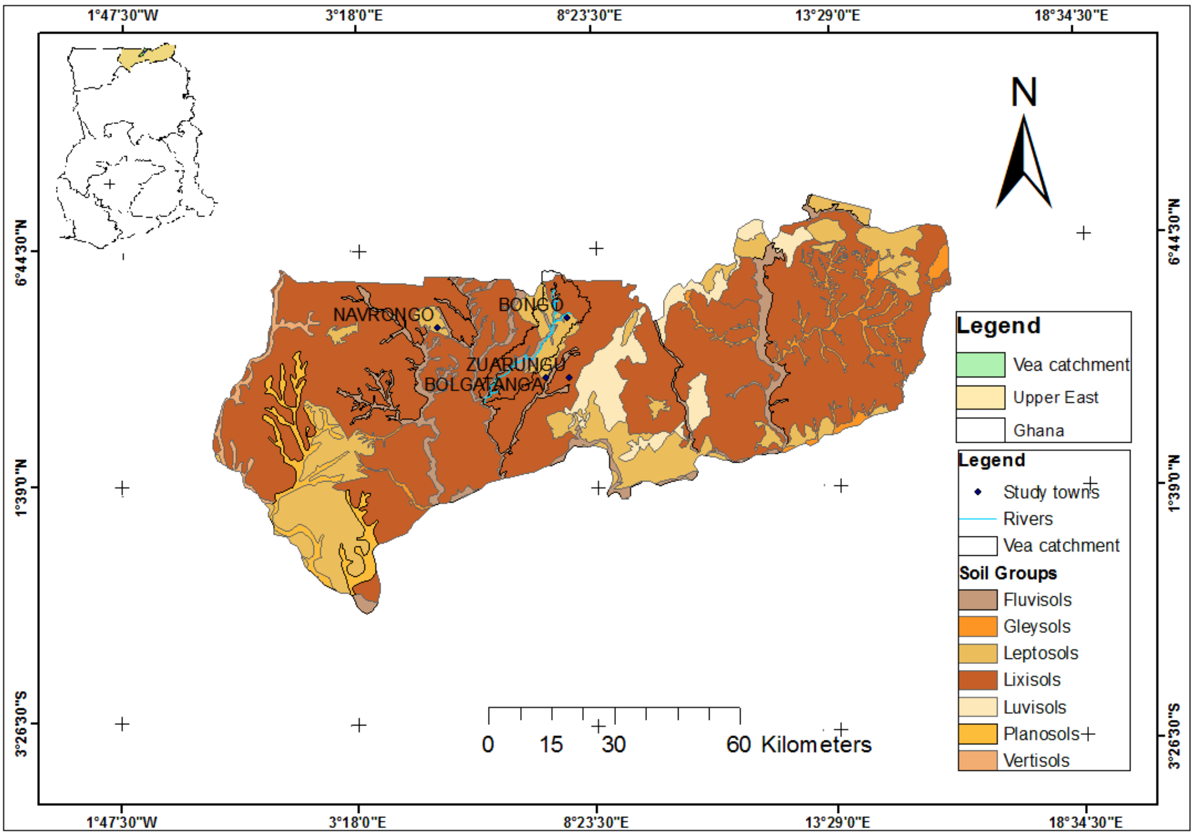


Figure 2.2: *Soils of the Upper East Region of Ghana, showing the study catchment*

2.2.3 Vegetation and land use

Blench (2006) observed that little is known of state-of-the-art environmental evolution in UER with much of the literature being obsolete. The known natural vegetation is predominantly the savannah woodland cover that consists of sparsely populated short and drought-resistant trees and perennial grass cover that deflagrate by bushfire during the dry season (GSS, 2013a). These tree species include the locust ('dawadawa') (*Parkia biglobosa.*), shea (*Vitellaria paradoxa.*), kapok (*Ceiba pentandra.*), baobab (*Adansonia digitate.*) and whitethorn (*Faid herbia albida.*) while the perennial groundcover of grasses is mainly the *Andropogon gayanus* species (Blench, 2006). The sheanut, dawadawa, boabab and acacia remain the most valuable economic fruit trees in the Region (GSS, 2013a) and this perhaps explains why they remain dominant and protected. The vast area of UER is under extreme pressure of anthropogenic activities. A tiny fraction of the natural vegetation cover that could be found in the Region relatively closer to settlements is mainly due to the traditional preservation of sacred forests, aside which are some afforested Mango and neem trees outside settlements (Blench, 2006). Deforestation in the Region is pervasive due to the pressure of human activities such as felling of trees for fuel wood and farming activities and, these are contributing factors to the growing desertification, land degradation and droughts in the region (Ofori-Sarpong, 2001). Persistent annual dry season bush fires are also the contributing factor to the reduction in forest trees such that only young trees are found in even remote areas (Blench, 2006).

2.2.4 Climate

The general climate of UER, just as other parts of northern Ghana, is driven by the movement of the two air masses: North East (NE) trade winds (or harmattan) and South Westerly (SW) monsoon winds with the associated movement of the Intertropical Convergence Zone (ITCZ) (Mdemu, 2008) as described in chapter 1. The UER is a semi-arid area (Ofori-Sarpong, 2001; Liebe *et al.* 2005) characterized by a uni-modal rainy season that occurs between April/May and September/October (Mdemu, 2008). This period accounts for 90% of an annual rainfall in the area with the peak occurring in August (Ofori-Sarpong, 2001). The rainfall intensities during this period are often high and exceed the soil infiltration rates leading to high surface runoff to the detriment of soil moisture and groundwater replenishment (Liebe *et al*. 2005). The annual rainfall ranges between 700-1200 mm (Blench, 2006). The Region is characterized by erratic and unpredictable rainfall that is also spatially variable (GSS, 2005). This often results in farmers having to plant seeds twice or thrice in each growing season before they meet reliable rains (Blench, 2006). Between one rainy season and the next (November to April) is the dry season which is often marked by the dry and dusty harmattan winds from the Sahara Desert, often severe between November and February.

Except in the heart of the rainy season (July to September), the potential evapotranspiration (PET) in the region is higher than rainfall in the rest of the year (Fig. 2.3) (Obuobie & Ofori, 2014). This makes the annual PET approximate double the annual rainfall, necessitating the culture of water storage in reservoirs for uses in the dry season (Mdemu, 2008). Obuobie & Ofori (2014) further observed that owing to this high evapotranspiration coupled with the high spatial and temporal rainfall variability in the region; water is often scarce in most part of the year. The storage reservoirs are also very necessary for capturing the high seasonal surface runoff resulting from high rainfall intensities and low soil infiltration rates for both domestic and irrigation purposes (Liebe *et al*. 2005). The relative humidity in the region fluctuates largely and is less than 30% in the rainy season (Ofori-Sarpong, 2001). It is also observed that the growing period for the dominant rainfed crops in the region is less than 60 days (Ofori-Sarpong, 2001).

The region often records high temperatures with up to between 40°C and 45°C experienced in the months of March to April, while the absolute minimum temperatures of between 15°C and 18°C are experienced in December with mean annual temperature between 28°C and 29°C (Mdemu, 2008). According to the Ghana Statistical Service [GSS] (2013a), the Region falls entirely within both the "Meningitis Belt" of Africa and the onchocerciasis zone. However, large areas of farmlands that were previously abandoned due to these diseases are now declared suitable for settlement and farming activities owing to the successful control of the diseases (GSS, 2013a).

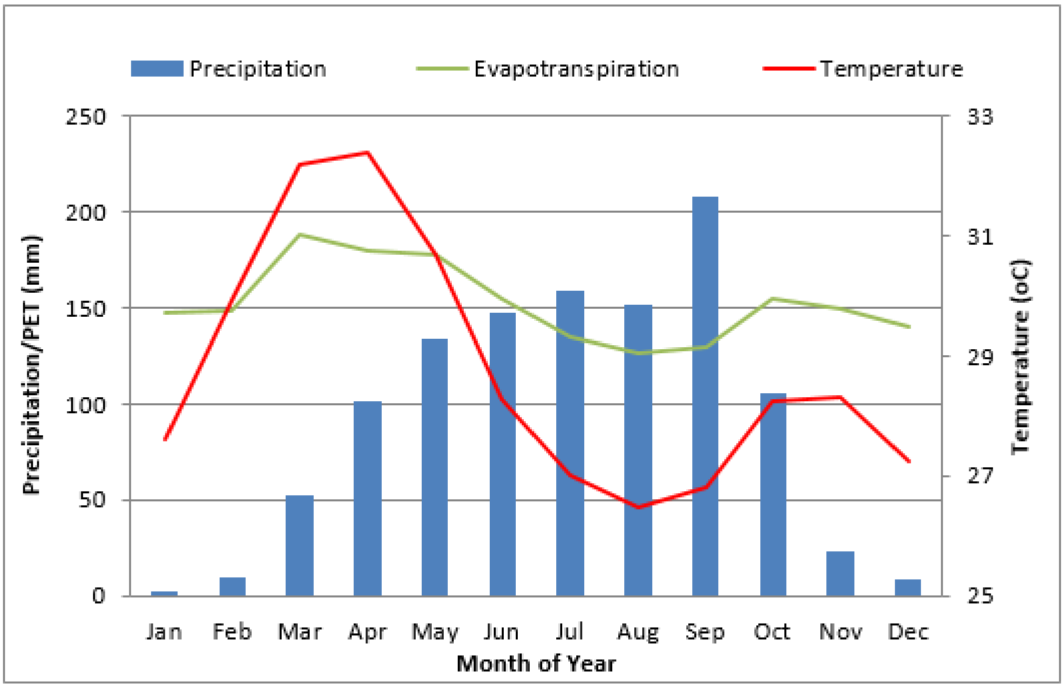


Figure 2.3: *Long-term (1975-2014) mean rainfall, PET and temperature at Bolgatanga (in UER) (Source: Obuobie & Ofori, 2014)*

2.2.5 Geology, hydrogeology and relief

The Upper East Region (UER) is underlain by two main geological formations: the Pre-Cambrian Basement Complex rocks and Palaeozoic consolidated sedimentary rocks (Obuobie & Ofori, 2014). The Pre-Cambrian Basement Complex rocks which underlie the major (92%) parts of the region consist of mainly the Dahomeyan, Birimian and Tarkwaian formations (Obuobie & Ofori, 2014; Fig. 2.4). The Palaeozoic consolidated sedimentary rocks (Voltaian formation) consist of 3 sub-groups: basal sandstones (Lower Voltaian), Obosom and Oti Beds (Middle Voltaian) and Upper Voltaian formations and are found in the extreme south east part of the region (Obuobie & Ofori, 2014; Fig. 2.4).

Averagely, the thickness of the regolith in the region is less than 30m and may rise as high as 140m (Dapaah-Siakwan and Gyau-Boakye, 2000; cited in: Carrier *et al*. 2008). The thickness of the regolith that covers Barimian and the Tarkwaian rocks in the Bongo and Bolgatanga districts ranges between 12m to 33m with an average of 23m, while its thickness over granitoid intrusions varies between 3m and 37m with an average of 20m (Carrier *et al*. 2008).

There are two main hydro-geological formations in northern Ghana of which UER is part: the Voltaian and Pre-Cambrian Basement formations (Carrier *et al*. 2008). The main determining factors of occurrence of groundwater in the region include the geology, topographic features, structural features, thickness of the overburden and the degree of interconnectivity (Obuobie & Ofori, 2014). There are three main types of aquifers in the region: the weathered, fractured and bedrock–weathered zone interface, with aquifers found in areas underlain by granites offering higher yields than areas underlain by consolidated formation (Obuobie & Ofori, 2014). The detail description of the geology and hydro-geological of the region is discussed by Obuobie & Ofori (2014).

The relief of the UER is identified to be associated with the geology of the area, with elevations of a number of Birimian greenstone hills which dominate the north eastern corridor along the border with Burkina Faso and in the southwest along the White Volta River reaching about 457m above sea level (Adu, 1969; Cited in: Mdemu, 2008). While the mean elevation of the region is 197m above sea level, the areas underlain by granites and Voltain rocks are similar, with low relief of between 122m to 260m above sea level except few escarpments underlain by Voltain rocks which has relief above 518 m in the eastern part along the border with Togo (Liebe, 2002; Cited in: Mdemu, 2008)

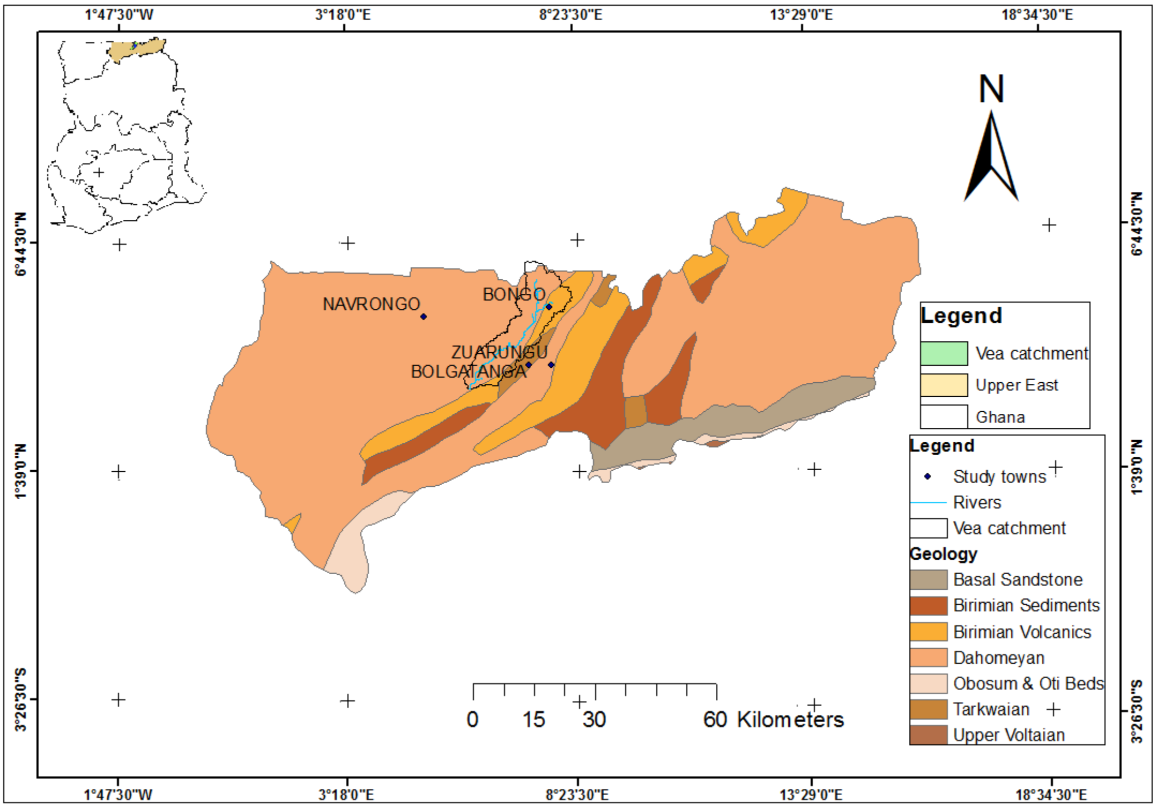


Figure 2.4: *Geological Map of Upper East Region of Ghana*

2.2.6 Water resource utilization

The Region is endowed with major surface water resources consisting of the river system of White Volta River with the Red Volta, the Sissili and the Kulpawn (Tono) rivers as its tributaries (Birner *et al.* 2005). These include a number of small rivers such as Yaragatanga of the Vea catchment and streams that flow through the region, although many of these small rivers are ephemeral and often dry up or reduce to a series of pond during the dry season (Birner *et al.* 2005).

Often the runoff drained by these river networks comes as floods and require water storage reservoirs to store such water for use in the long dry season period in the Region. Liebe *et al.* (2005) observed that the availability of small reservoirs for storage of such flood waters in the Region has been crucial for reducing the effects of minor droughts in the rural communities. Several reservoirs have been constructed and dotted around the Region over the past five decades. Birner *et al.* (2005) reported that many of the small reservoirs in the Region were constructed during the 1960s and later followed by the construction of the two large-scale irrigation reservoirs, the Tono and the Vea catchment irrigation schemes. The two major irrigation reservoirs constructed between 1975 and 1985 are very important water storage infrastructure in the Region with both serving multi-purpose of crop irrigation and livestock watering as well as major sources of domestic water supply to both urban and rural communities. Besides these two major irrigation schemes, several small reservoirs and dug-outs developed across the Region have been critical water sources for dry season irrigation, domestic and livestock water needs (Birner *et al.* 2005; Mdemu, 2008).

Some studies have made estimations of the total number of reservoirs in the Region. Liebe *et al.* (2005) reported from their estimation that, excluding the Tono and the Vea irrigation reservoirs, there are 154 small reservoirs with a total acreage of 999.54 ha, ranging from 1 to 35 ha. From that estimation, Liebe *et al.* (2005) indicated that with Tono (1894 ha) and Vea (435 ha) reservoirs added, the current total number of reservoirs in UER stands at 156 giving the total surface area of 3408 ha where the two major reservoirs (Tono and Vea) take sixty-nine percent (69%) of this area and thirty-one percent (31%) by the 154 small reservoirs. In another study by GTZ (2005) (cited in: Birner *et al.* 2005), it is reported that the total number of reservoirs in the Region is 184, while acknowledging that not all of these reservoirs are still functioning.

The reservoirs in the Region play a crucial role in the socio-economic development of people, particularly in the rural communities, where they act as the main governing factor of water availability and water use in the long dry season.

2.3 Overview of the study catchment

The research was conducted in the Vea Catchment (Fig. 2.5) which is one of the sub-catchments within the White Volta Sub-basin. Vea Catchment covers a total area of about 305 km^2. It is a transboundary catchment with about 80% of its total area in Ghana and the remaining smaller portion in the south-central part of the neighboring Burkina Faso (Ofosu *et al.* 2014). The Ghanaian section of the catchment lies across two administrative Districts of the Upper East Region (UER) – Bolgatanga and Bongo, with a forest reserve at the extreme lower/downstream part of the catchment. The catchment area is located between longitudes 0º45′0″ to 1º0′0″ W and the latitudes 10º42′30″ to 11º02′30″ N. It falls within a semi-arid agro-climatic domain and across three agro-ecological zones: Savanna and Guinea Savanna zones in Ghana and the North Sudanian zone in Burkina Faso (Ibrahim *et al.* 2011). The area is marked by only one rainfall/growing season from May to October and peaks in August characterized by erratic rainfall and often associated with floods and droughts, followed by a long dry season that often spans from November to April (Gyasi *et al.* 2006). The average temperature within the catchment ranges between 28-29ºC with the average annual rainfall and annual average evapotranspiration about 950 mm and between 2000-2050 mm respectively (Ibrahim *et al.* 2011).

The catchment area, just as most other parts of the UER is characterized by intensive farming activities, overgrazing, bushfires, hunting, charcoal burning and firewood harvest. The catchment hosts the Vea irrigation dam, constructed in 1980 and one of the two major irrigation dams (Vea and Tono) in the UER. Vea irrigation scheme is a valuable facility for the farming communities in the area as it offers farmers the opportunities for all-year-round agricultural production (Badmos *et al.* 2014), though it faces numerous challenges in recent times that includes dilapidated infrastructure, encroachment, water shortages due to climate change (CC) effects and siltation. Siltation in the Vea irrigation reservoir due to poor farming practices, overgrazing and other human activities with associated poor vegetative cover within the catchment should be of concern (Adongo *et al.* 2014). Adequate empirical evidence of the state of water resources and land use land cover changes within the catchment is therefore necessary for policy direction on water resources conservation, sustainable activities and land recovery programs in the area. The maps of the topography, soil and land use of the study catchment are as shown in figures 2.6, 2.7 and 2.8 respectively.

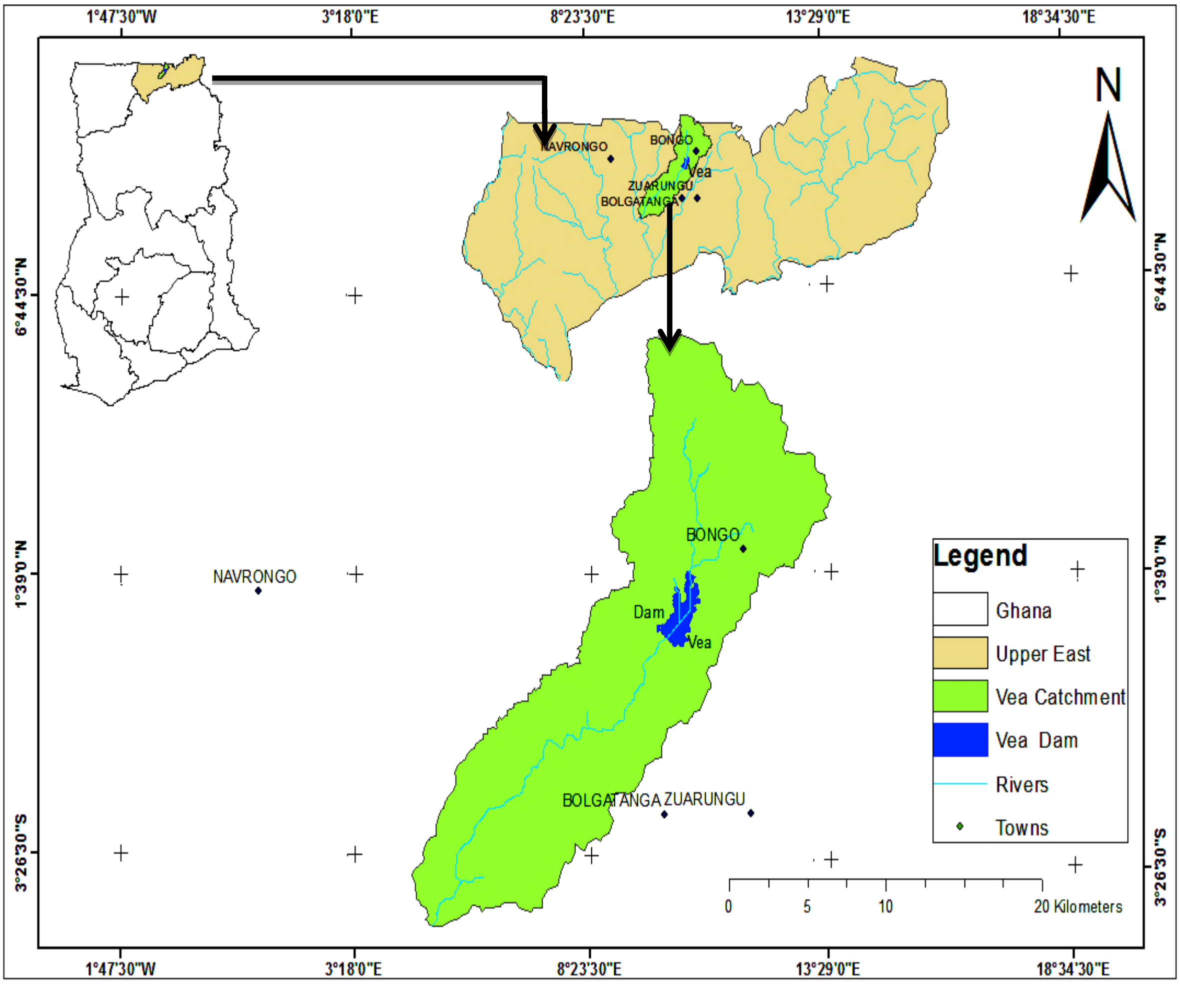


Figure 2.5: *The Vea Catchment, showing meteorological stations (towns) and its location in UER and Ghana*

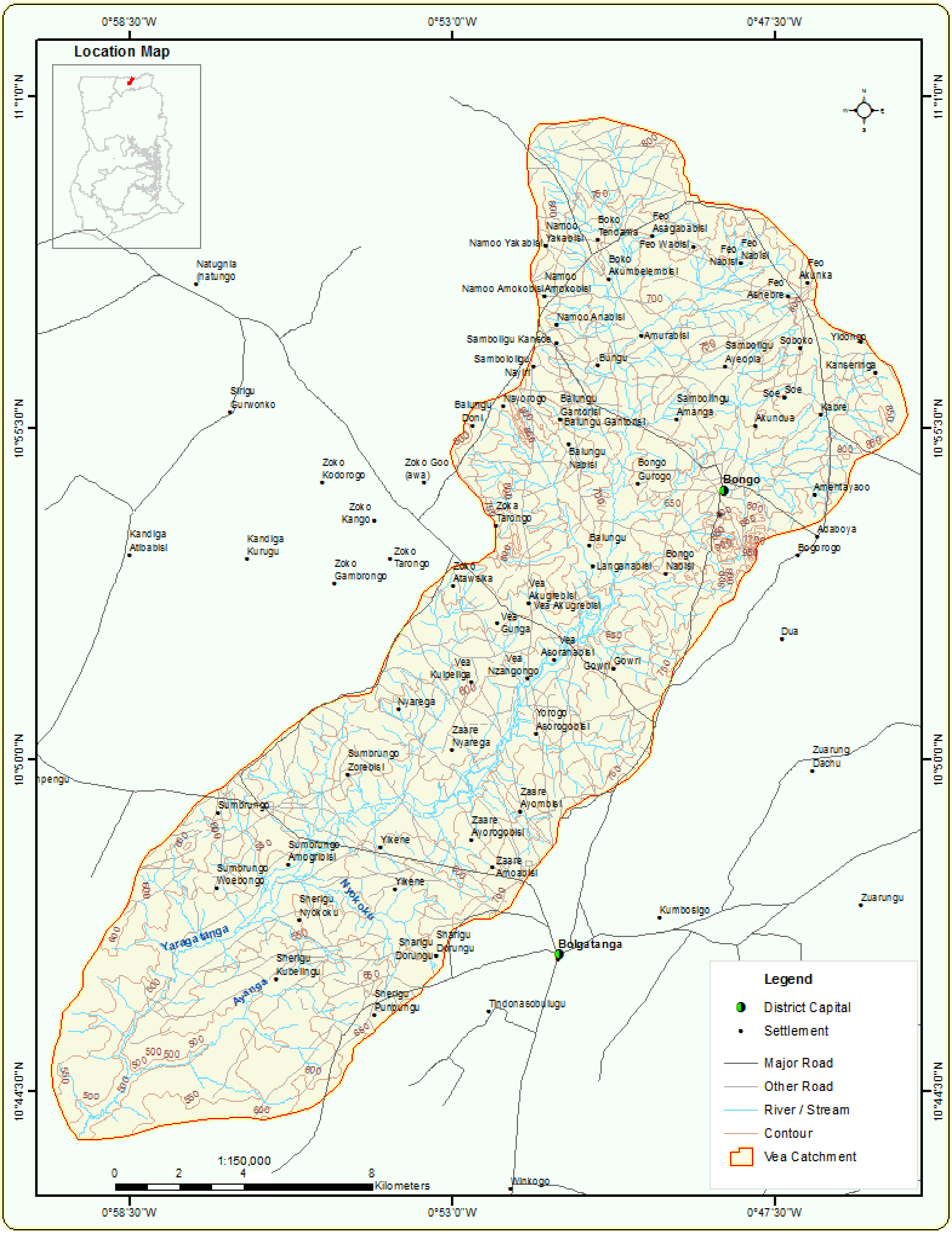


Figure 2.6: *Topographic map of the study area*

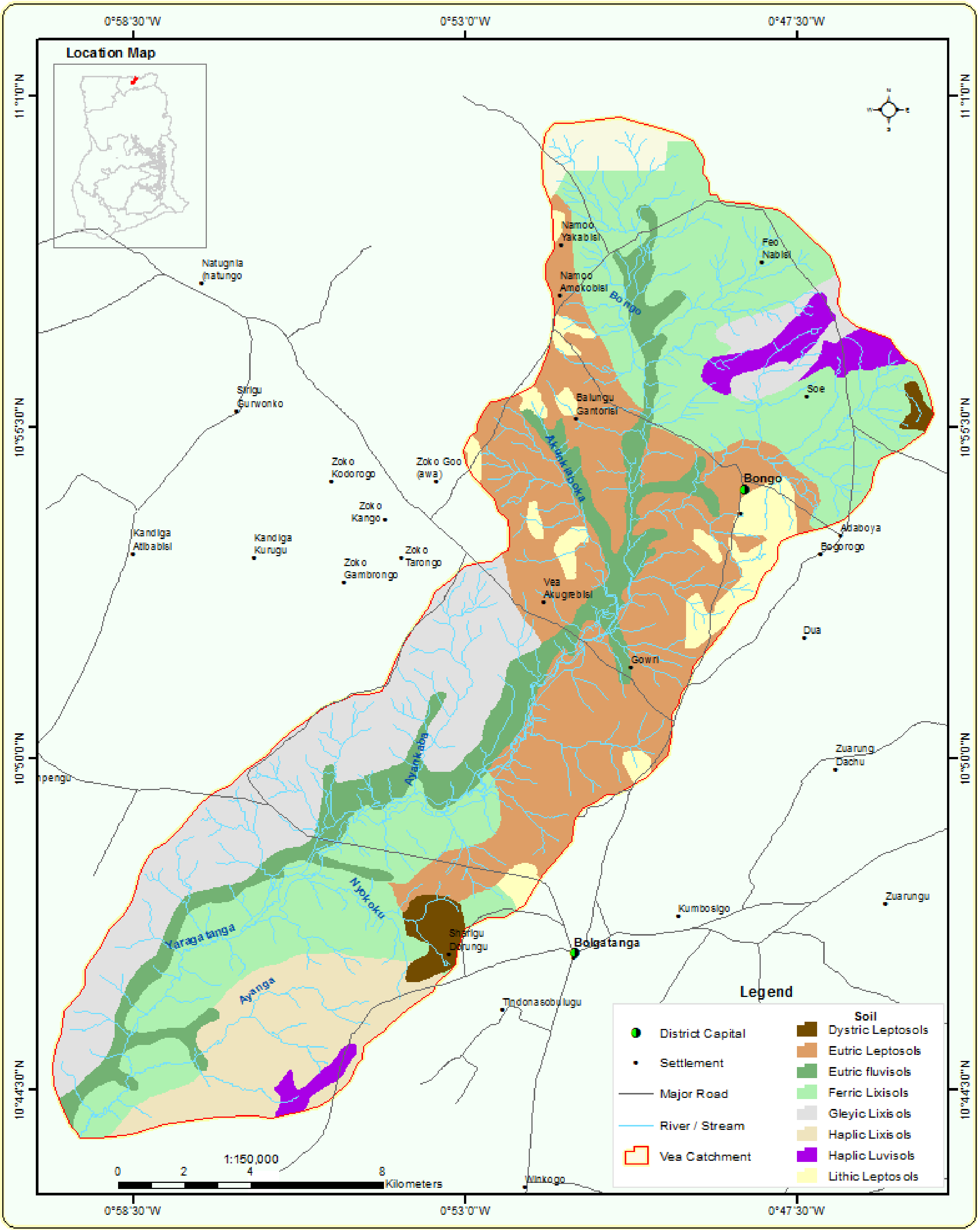


Figure 2.7: *Soil map of the study area*

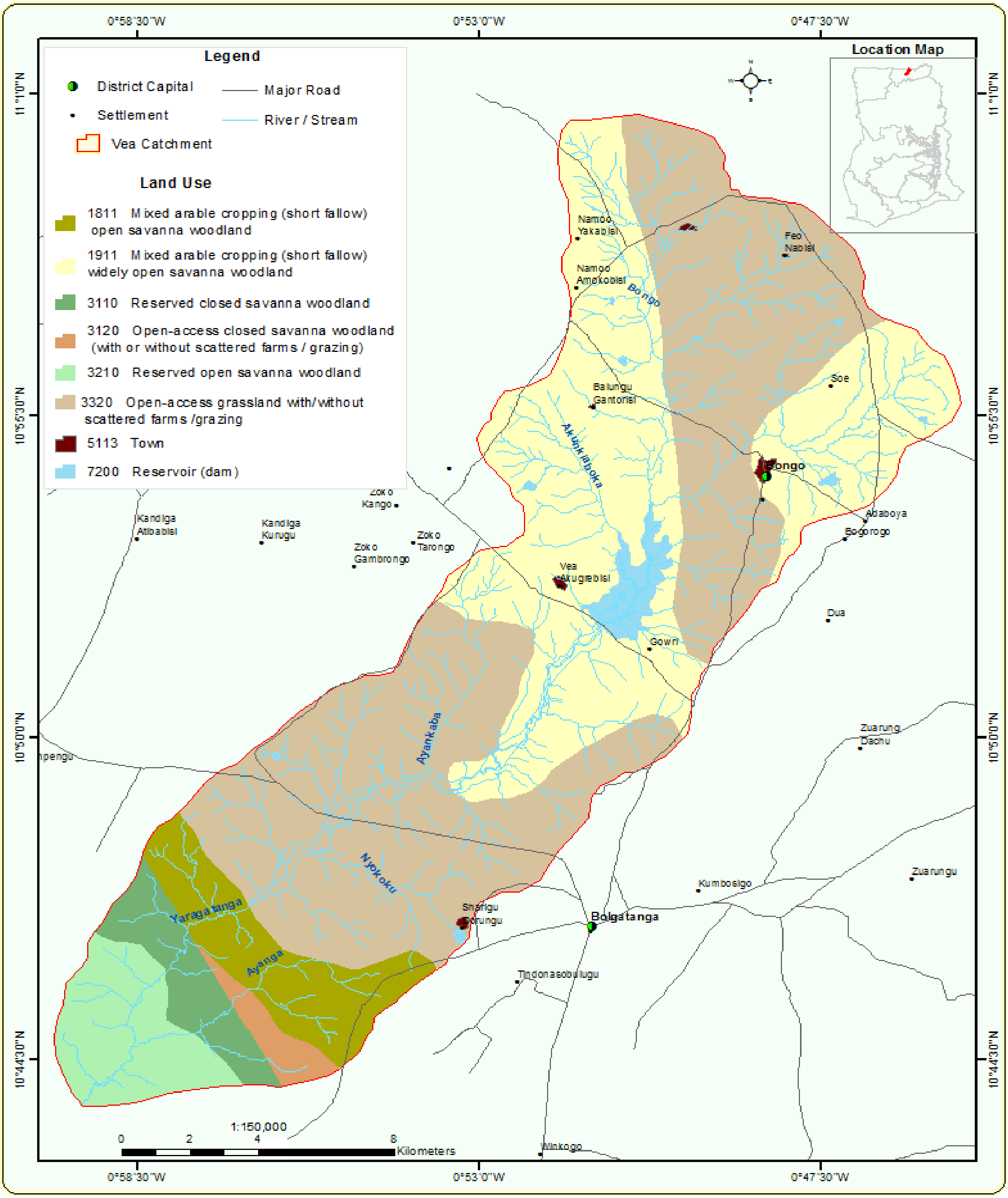


Figure 2.8: *Land use map of the study area*

2.4 Conclusion

In this chapter, a general overview of the study area (i.e. Vea) and the Upper East Region (UER) of Ghana in which the area is located was provided. The areas reviewed included the population and socio-economic characteristics of the UER and for that matter the study catchment, the soil and drainage, vegetation and climate and hydrogeology as well as water resource utilization of the area. The area is characterized by high population density with high level of poverty among the inhabitants who are predominantly small holder farmers living in rural areas. Only one rainfall/growing season (May to October) is experienced in the area which is characterized by unpredictable rainfall, frequent floods and droughts, followed by a long dry season (November to April). The rain-fed agriculture predominantly practiced in the area is therefore unreliable due to vulnerability to these climate incidences. The only major irrigation scheme in the area, Vea irrigation project, is therefore of significant importance to the people in the area as it serves as a multi-purpose project of crop irrigation, livestock watering and source of domestic water supply to urban and rural communities. There are, however, fears about the future of this irrigation project in view of possible effects of both CC and siltation due to land cover changes associated with anthropogenic activities. The assessment of the current and future state of the water resources in the context of CC as well as examining the land use land cover changes within the catchment are therefore necessary for policy direction on water resources conservation, sustainable activities and land recovery programs in the area.

CHAPTER 3: DATA, MATERIALS AND METHODS

3.1 Introduction

This chapter describes the data types that were used in the study, the steps employed in collecting the raw data, processing and analysing these data. This involves detailed description of the data collection methods as well as the materials, methods and the theories used for the analysis and interpretation of these data. The chapter therefore consists of the various subsections that present the description of the various types of data used, its extent, and period considered, and all the processes involved in the analysis of each data type, including the selection and description of each software (model) used. This includes description of how secondary data were derived or estimated from the primary data.

3.2 Data

To achieve the set objectives, several different types of primary data (quantitative and qualitative) were collected and prepared for use in the current study. These included meteorological data (rainfall, temperature and evaporation), reservoir bathymetry data (daily height, surface area and storage), data on water abstraction for domestic supply by Ghana Water Company Limited (GWCL), ensemble climate scenario data, survey data (household, focus group discussions and institutional interviews) and Landsat ETM satellite images. The secondary data derived from these primary data included streamflow time series and actual evapotranspiration (ET_a). The preparation and usage of these data are as shown in the following subsection on methods.

3.2.1 Acquired meteorological data

The daily observed data of both rainfall and temperature covering the study period between 1972 and 2012 at four meteorological stations, located in Vea, Bolgatanga, Zuarungu and Navrongo, were obtained from Ghana Meteorological Agency (GMet) and used in this study. The daily observed evaporation data for only Navrongo meteorological station was obtained and used in this study due to unreliable evaporation data or the lack of it at the other stations.

3.2.2 Acquired reservoir bathymetry data (daily height, surface area and storage)

The time series of reservoir surface area, storage and spillage were require for the estimation of streamflow. Observed reservoir height (level) data was necessary for deriving these time series using the storage-area-height relationship (function) at the reservoir site. The observed daily reservoir height (level) data covering the study period (1972 – 2012) was therefore separately obtained from two institutions that operate on the Vea irrigation reservoir, namely the Irrigation Company of Upper Region (ICOUR) and Ghana Water Company Limited (GWCL). Obtaining the separate daily reservoir height (level) data from the two separate institutions were for the purpose of comparison and filling in any missing observations.

3.2.3 Water abstraction data

The daily reservoir water abstraction for domestic supply covering the study period (1972 – 2012) was obtained from GWCL for the estimation of streamflow. Since the river is an ephemeral type and irrigation only occurs during the period of zero or no flow (Oct/Nov to Dec/Jan), the daily reservoir water abstraction for irrigation was not needed and therefore not obtained.

3.2.4 Acquisition of ensemble climate scenario data

The climate simulations were particularly required in this study as inputs to the rainfall-runoff model (IHACRES) and Thornthwaite (1948) evapotranspiration (ET) tool for investigation of impact of climate variability/change on future surface hydrology (runoff and evapotranspiration) of the catchment. The streamflow outputs from IHACRES also served as inputs to the Water Evaluation and Planning (WEAP) model for investigation of impact of climate variability/change on future water availability for irrigation in the catchment.

As observed by Muerth *et al*. (2013), the determining factors for choice of climate simulations for any study are not just limited to the research questions posed or initial proposal of the study, but most especially the accessibility of data and the capacity to process it within the given period of the study. The latter factor is most influential in an academic research such as the current study in which time is most crucial. The climate simulations for all the Regional Climate Model (RCMs) that participated in the Coordinated Regional Downscaling Experiment (CORDEX), and provided data for the CORDEX Africa domain (Table 3.1) were therefore used for the current study based on relatively easy accessibility. All the simulations are based on IPCC's RCP4.5 and RCP8.5 scenarios, at a grid box resolution of 0.44 x 0.44 degrees and at daily time step. These are available over the periods of 1951 – 2005 (control run) and 2006 – 2100 (scenario), except a few that has control run ranging between 1949-2005, 1950-2005 and 1970 - 2005.

The data for the study catchment was extracted from these simulations under the RCP8.5 scenario by raster package in R programming using the catchment shape file. The study catchment was found to be well captured by only a single grid box owing to its small size, thus the RCMs simulations (temperature and rainfall series) for the catchment were extracted from this grid box in a similarly procedure as by Teutschbein and Seibert (2012). The outputs of an ensemble of 16 different RCM-simulated temperature and rainfall time series were obtained and used in this study – four (4) RCMs simulations from outputs of eleven (11) GCMs (Table 3.1).

Table 3.1: *List of GCMs and RCMs*

GCMs (RCP8.5)	RCMs				SUM
	SMHI-RCA4	CLMcom-CCLM4	ICTP-RegCM4	KNMI-RACMO22T	
CCCma-CanESM2					1
CNRM-CERFACS					2
HadGEM2-ES					1
ICHEC-EC-EARTH					3
IPSL-IPSL-CM5A					1
MIROC-MIROC5					1
MOHC-HadGEM2-ES					2
MPI-ESM-MR					1
MPI-M-MPI-ESM-LR					2
NCC-NorESM1-M					1
NOAA-GFDL-GFDL-ESM2M					1
SUM	9	4	2	1	16

3.2.5 Acquisition of survey data (qualitative data)

Survey data on perception of climate change (CC) and future adaptation plans at the farmer and institution levels were required for the assessment of future water demand and availability situation in the study catchment. These were gathered through household questionnaire survey, focus group discussions and institutional interviews.

3.2.6 Acquisition of land use/cover satellite imagery

Landsat ETM satellite images of 04 January 1990, 02 January 2000 and 02 January 2010 covering the study area, with resolution, 30mx30m, was obtained from the Centre for Remote Sensing and Geographical Information System (CERSGIS) of the University of Ghana, Accra and used for this study. Cloud cover effect during this period of the year in the area, is usually non-existence or at its lowest. Since the images were obtained within the same season of the year and within the same month, errors associated with seasonal differences are also minimised (Enaruvbe & Atafo, 2014).

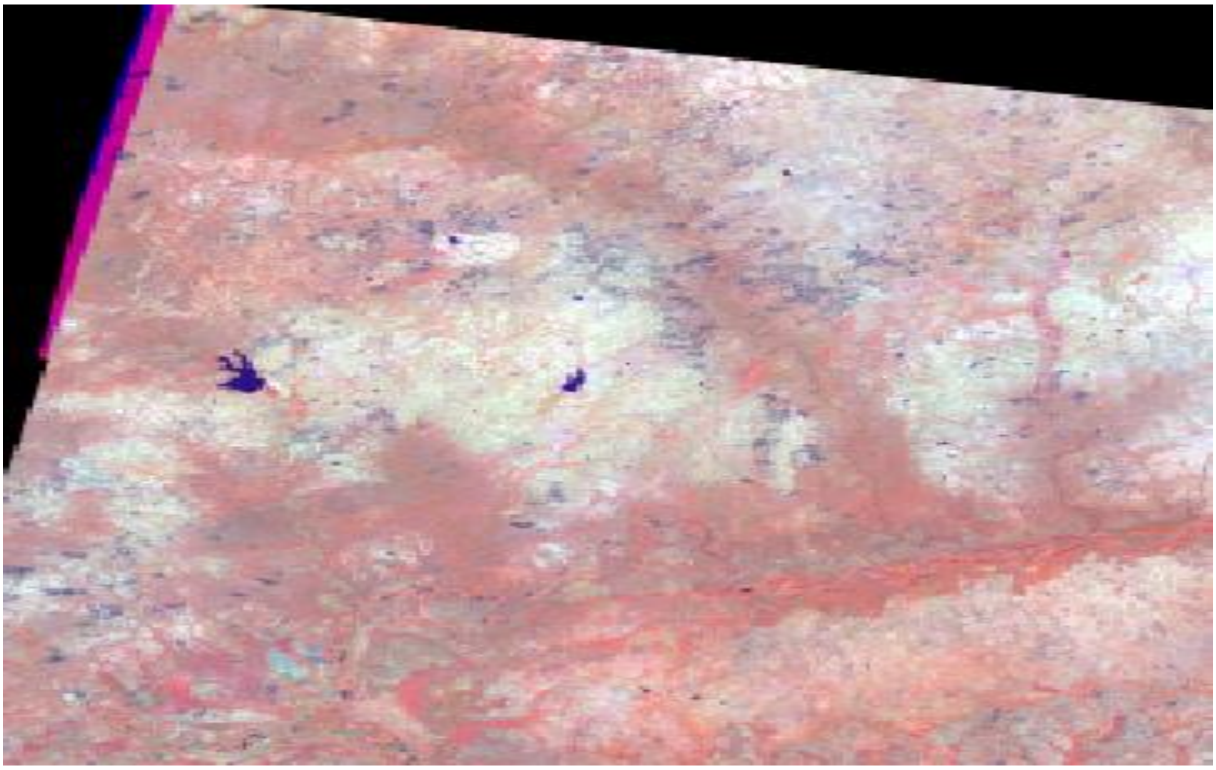


Figure 3.1: *Acquisition of raw satellite image*

3.3 Materials and Methods

3.3.1 Data preparation

3.3.1.1 Rainfall data (filling in missing data and determining catchment areal rainfall)

There are several methods available for determining average rainfall over any area of interest, but selecting any of these methods depends on its suitability for a particular study or the distribution of the rain gauge stations in the study area (Ward & Elliot 1995). The Thiessen Polygons method is commonly preferred for study areas where rain gauges are not evenly distributed (Ward & Elliot 1995) as in the current study. The missing observations in rainfall data and the daily areal rainfall used as input for the IHACRES model application were therefore computed using the obtained daily data from the four meteorological stations (shown in Fig. 3.2) for the study catchment area by Thiessen Polygons interpolation method.

The daily areal rainfall for the study catchment was determined as a weighted average of the observed daily rainfalls of the four selected stations in the following relation as described by Ward and Elliot (1995):

$$P = \frac{\sum_{i=1}^{n} A_i \, x \, p_i}{\sum_{i=1}^{n} A_i}$$

where P represents the average depth of rainfall in the catchment of total area of $\sum_{i=1}^{n} A_i$, and $A_i$being the area of the i^{th} polygon with rainfall depth of $p_i$in that polygon.

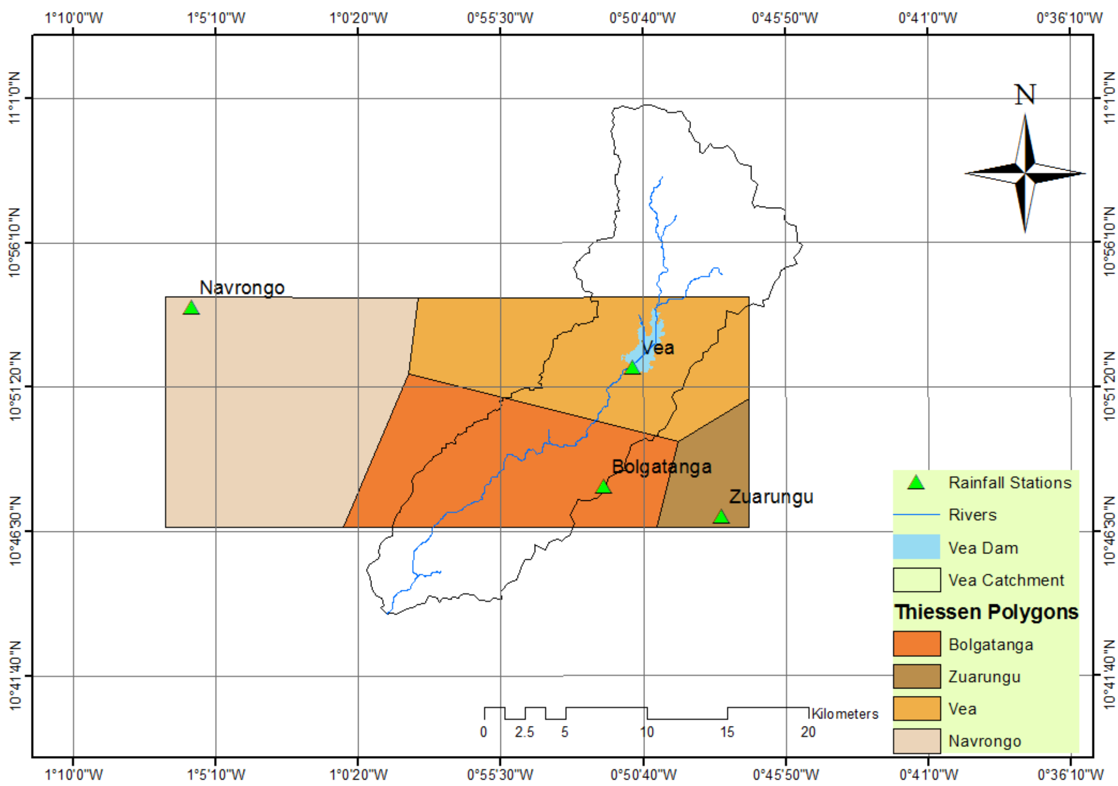


Figure 3.2: *Map of gauge network, showing Thiessen Polygons of the four selected rainfall stations of the Vea catchment area*

3.3.1.2 Temperature and evaporation data (filling in missing data and determining catchment areal temperature)

The missing observations in temperature data and the daily areal temperature used as inputs for the IHACRES model application were determined using the obtained daily data from the four meteorological stations for the study catchment area by Simple Arithmetic average method. However, since evaporation data for only one meteorological station (Navrongo) could be obtained, the moving average method of simply averaging within a given window in the data time series was used to fill missing observations in the evaporation data. No outliers were identified in both the temperature and evaporation data time series, thus no corrections on the data were made in that respect.

3.3.1.3 Reservoir bathymetry data (daily height)

Preparing the obtained reservoir height (level) data involved filling in missing observations and correcting any possible outliers or abnormal observations. This was done by comparing the separate reservoir height (level) data obtained from the two separate institutions (ICOUR and GWCL). The two separate reservoir height (level) data were comparatively the same with few missing data and outliers in each at different dates, thus missing observations in one data time series was filled with the corresponding observations in the other data according to the observation dates. Few outliers identified in the two separate data were corrected in a similar manner as missing observations.

3.3.1.4 Water abstraction data (filling in missing data)

Missing water abstraction data were mainly due to faulty meter. Days of no water abstraction were also mainly due to electrical power failure and in few cases plant shut down for routing cleaning maintenance. With known pumping rates of the pumps used and the pumping duration on each day, each missing water abstraction data was easily determined by multiplying the pumping rate of the pump by the pumping duration. Just as with rainfall and temperature data, no outliers were identified in the water abstraction data, thus no corrections on the data were made in that respect.

3.3.1.5 Bias correction of climate scenario data

There are often risks of considerable biases in RCMs simulations making the application of such raw simulated data in hydrological climate-change impact studies unreliable (Teutschbein & Seibert 2012). Bias corrections are very necessary to be carried out on such climate simulations in order to achieve reliable future climate data (Dhanya & Gupta, 2014). Several methods of bias correction, ranging from simple to sophisticated techniques, have therefore now been developed, and that include the linear scaling of rainfall and temperature, local intensity scaling of rainfall, power transformation of rainfall, variance scaling of temperature, distribution mapping of rainfall and temperature and delta-change correction of rainfall and temperature (Teutschbein & Seibert 2012). After a review of these bias correction techniques, the delta-change method was selected and used in the current study for bias correction of all the 16 different RCM-simulated temperature and rainfall time series used.

The delta-change correction method which allows for direct comparison of different model simulations with different error characteristics is widely used, particularly in hydrological climate-change impact and water planning studies (Hamlet *et al*. not dated). The method simply involves the use of future climate signals (correction factors) of the climate simulation for perturbation of observed data to represent the future conditions rather than applying the simulated conditions directly (Teutschbein & Seibert 2012). In that case, the classical delta-change method as employed in this study, simply involve the application of average monthly anomalies or climate signals in the RCM-simulated temperature and rainfall time series to the observed temperature and rainfall time series that will then serve as inputs to the hydrologic model (Hamlet *et al*. not dated). This is done by simply averaging the variables (temperature and rainfall) of the RCM simulation *"over a historic period from a control simulation and a future period from a scenario simulation to estimate the changes"* (Hamlet *et al*. not dated). Teutschbein and Seibert (2012) illustrated this by the following equations:

$P^{x}{}_{contr}(\mathrm{d}) = P_{obs}(\mathrm{d})$

$P^{x}{}_{scen}(\mathrm{d}) = P_{obs}(\mathrm{d}).\left[\frac{\mu_{m(P_{scen}(\mathrm{d}))}}{\mu_{m(P_{contr}(\mathrm{d}))}}\right]$

$T^{x}{}_{contr}(\mathrm{d}) = T_{obs}(\mathrm{d})$

$T^{x}{}_{scen}(\mathrm{d}) = T_{obs}(\mathrm{d}) + \mu_m(T_{scen}(\mathrm{d})) - \mu_m(T_{contr}(\mathrm{d}))$

Where;

$P_{contr}(\mathrm{d})$ = daily rainfall of the RCM simulated historical data (1981-2010)
$P_{obs}(\mathrm{d})$ = daily observed rainfall (1981-2010)
$P_{scen}(\mathrm{d})$ = daily rainfall of the RCM simulated future data period
$P^{x}{}_{scen}(\mathrm{d})$ = final bias-corrected daily rainfall of the RCM simulated future data period
$T_{contr}(\mathrm{d})$ = daily temperature of the RCM simulated historical data (1981-2010)
$T_{obs}(\mathrm{d})$ = daily observed temperature (1981-2010)
$T_{scen}(\mathrm{d})$ = daily temperature of the RCM simulated future data period
$T^{x}{}_{scen}(\mathrm{d})$ = final bias-corrected daily temperature of the RCM simulated future data period
$\mu_{m(P_{contr}(\mathrm{d}))}$ = monthly rainfall mean of RCM simulated historical data period (1981-2010)
$\mu_{m(P_{scen}(\mathrm{d}))}$ = monthly rainfall mean of RCM simulated future data period
$\mu_{m(T_{contr}(\mathrm{d}))}$ = monthly temperature mean of RCM simulated historical data period (1981-2010)
$\mu_{m(T_{scen}(\mathrm{d}))}$ = monthly temperature mean of RCM simulated future data period

In this study, bias correction factors were derived from a 30-year window of 1981-2010 and applied to two future 30-year windows of 2021-2050 (the near future) and 2071-2100 (the distance future).

The resultant bias corrected RCM-simulated temperature and rainfall times series of all the 16 models were used as inputs for the IHACRES rainfall-runoff model for hydrological simulations of daily streamflow under the climate conditions of the two future time slices, 2021-2050 (the near future) and 2071-2100 (the distance future). The impacts of CC on the catchment streamflow, based on projected climate conditions of the near future (2021–2050) and the distance future (2071–2100), were compared using all the 16 RCM-simulated (CORDEX) data. Finally, with the WEAP model, the impacts of CC on water availability for domestic and irrigation within the study catchment, based on climate conditions of the two future times slices (2021-2050 & 2071–2100), were compared using the reference streamflow time series (1983-2012) and three different streamflow time series derived from the 16 RCM-simulated conditions as discussed in sub-section 3.3.13 below (see also chapter 6).

3.3.2 Flux estimation

In view of lack of adequate and reliable streamflow data for the study catchment, it became necessary to carry out flux estimation using the available bathymetry data as part of this research study. Based on the geometry of the Vea dam reservoir on the catchment river (Yaragatanga), expressed as a storage-area-height relationship, inflows (runoff) were computed from these data using a simple reservoir mass balance equation. It involved the following procedure:

- First, the time series of the observed reservoir height (level) data and the storage-area-height relationship (function) at the reservoir site were obtained from ICOUR.
- The time series of the releases from the reservoir, the time series of the open water evaporation at the site and the time series of the direct rainfall contribution into the open water surface of the reservoir were also accessed.

With these available, the required inflow time series was estimated as follows:

1. The storage-area-height function was used to convert the time series of the height into time series of reservoir storage (S) and reservoir surface area (A).

2. The surface area was used to convert the evaporation depth and direct rainfall into evaporation volume and direct rainfall contribution respectively.
3. The reservoir mass balance equation was then sequentially applied to the data to get the inflows as follows:

$$Q_{in}(t) = S(t+1) - S(t) + Q_{out}(t) + E(t) – P(t) + q(t)$$

Where $Q_{in}(t)$ is the required inflow in period t, $S(t+1)$ is the storage at the end of t, $S(t)$ is the storage at the beginning of t, $Q_{out}(t)$ is the total release (including any spills and compensation) during period t, $E(t)$ is the volumetric evaporation during period t, $P(t)$ is the direct rainfall contribution during period t, and $q(t)$ is the volumetric seepage during period t (this term was, however, eliminated because literature indicated that seepage is negligible in the area).

3.3.3 Statistical analysis of meteorological data

3.3.3.1 Trend test and change-point detection for the meteorological data

Pettitt test (Pettitt, 1979) which is based on comparing two samples, i.e., two segmentations of the original data time series (Bru *et al.* 2011), is widely employed for detecting changes in hydro-meteorological time series data (Ma *et al*. 2008; Mu *et al*. 2007). This was employed in this study and then followed by examining the long-term trends in climatic time series data of the study catchment using the Mann-Kendall test statistics (Mann 1945, Kendall 1975). The Mann-Kendall test statistic was used because it is more robust than parametric tests when dealing with skewed data and outliers in a data series (Onoz and Bayazit, 2003). Mann-Kendall analysis method was particularly used to detect linear trends in temperature and rainfall time series. Additionally, Hubert Segmentation test (Hubert *et al*. 1989) was also used as a means of cross-validating results from Pettitt test by change-point detection for both temperature and rainfall time series of the study area. The Hubert Segmentation test considers the squared difference between the data time series and a fixed segmentation in which process, all possible segmentations of the time series are tested and the optimal segmentation selected (Bru *et al.* 2011). Hubert Segmentation test detects multiple change-points in time series. The software package, KhronoStat, developed at the Science House of water (ESM) of Montpellier (Lubès *et al.* 1998), within which the three tests (Pettitt test, Mann-Kendall test and Hubert Segmentation test) are embedded, was used for this study.

Our interest was in analysing annual mean temperature time series and different aspects of the rainfall time series. For that reason, fourteen different data scales (annual scale and monthly scale for the growing season) were derived from the primary daily dataset for analysis of different aspects of the rainfall time series. These include the time series of both annual total rainfall amount and annual total number of rainy days, as well as time series of both monthly rainfall amount and monthly number of rainy days of each of the six months in the growing season of the catchment (May-October).

3.3.3.2 Rainfall variability analysis by sample variance: F-ratio and F-distribution method

A test for an increasing (or decreasing) variance trend was carried out to assess changes in variability of rainfall time series over the study period. Fourteen different data scales (annual scale and monthly scale for the growing season) of rainfall time series of the study period obtained as described in the preceding sub-section above were each divided into two arbitrarily parts (e.g. 1972-1992 and 1993-2012) and changes in variances between the two samples examined using F-ratio (ratio of variances) and F-distribution test (comparing the variances of two independent samples by testing whether or not the two sample variances are equal) as described by Foltz (2013). The question was, is the variance (S_x^2) of the first data sample (1972-1992), the same as that (S_y^2) of the second sample (1993-2012) or different? That is: $S_x^2 = S_y^2$?

Calculation of the sample variances for comparison will involve sampling error, hence the need to know if the difference is statistically significant or just related to the sampling error. We first compared the relative size of the two variances using an F-ratio with the largest of the two sample variances as numerator and the smaller of the two sample variances as denominator.

F = $\frac{S_x^2}{S_Y^2}$; the F-ratio, where S_x^2 = larger sample variance and S_y^2 = smaller sample variance

This was then followed by testing to find out if statistically, significant difference exists between the two sample variances using F-distribution test. Notably, when independent random samples, n_X and n_y are taken from two normal populations with equal variances, the sampling distribution of the ratio of those sample variances follows the F-distribution – the distribution of ratios.

Each of the numerator and denominator of the F-ratio has degrees of freedom given as, n-1, where n represents the sample size of each of the two samples. Thus the degrees of freedom of both the numerator and denominator are n_X-1 and n_y-1 respectively. The critical F-value on the F-distribution which marks the boundary between the lower 95% (non-rejection region) and the upper 5% (rejection region) is determined using the F-table (or digitally) with chosen significance level (α), numerator degrees of freedom (df_1) and denominator degrees of freedom (df_2). In this study, we used the digital F-table of the Excel (2010) F.INV.RT function due to its relatively easy usage and precise result. Notably, we used the F-distribution with $\alpha = 0.05$, and confidence level of 95%.

Having obtained the critical F-value, the hypothesis testing for equality of variance was carried out and in which process; the hypotheses formulated and tested were straight forward as:

H_0: $S_x^2 = S_y^2$

H_a: $S_x^2 \neq S_y^2$

Because we placed the large sample variance in the numerator, the F-ratio, in that case, is an upper-tailed test/distribution - testing for equality of variance is an upper/right-tailed test in which the null hypothesis (H_0) is rejected or accepted when the result of F-ratio is greater than or lesser than the critical F-value respectively.

3.3.4 Estimation of evapotranspiration

The trend of evapotranspiration (ET) over the study period (1972-2012) and two future periods (2021-2050 and 2071-2100) was examined. Thornthwaite (1948) method of estimating ET was employed as follows:

$$\mathrm{PET}_t = 16\left(\frac{10T}{I}\right)^a$$

Where, PET_t is the monthly potential evapotranspiration (mm); T is the monthly mean air temperature (°C); $a = (6.75\ x\ 10^{-7})I^3 - (7.71\ x\ 10^{-5})I^2 + (1.79\ x\ 10^{-2})I + 0.49239$; and I is the annual heat index computed from monthly indices as follows:

$$I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}$$

T_i is the mean air temperature (°C) for month i; i = 1,.....,12.

Remarkably, $\mathrm{PET}_t$is the theoretical evapotranspiration based on 30 days and 12 hours of sunshine per day. Thus actual evapotranspiration (ET_a) for a particular month with mean temperature T°C was obtained by:

$$ET_a = \mathrm{PET}_t \left(\frac{DL_d}{360}\right)$$

Where, D is the number of days in the month and L_d is the average number of hours between sunrise and sunset in the month. Finally, annual actual evapotranspiration (ET_a) for each year was obtained by summing up $ET_a$for all the twelve months in the year.

3.3.5 Hydrological model selection

The selection of the rainfall–runoff model was based on the factors and criteria by WMO (2008, 2009) as being relevant in selecting a model. These factors and criteria include a critical consideration of the type of system to be modelled (i.e. small catchment, river reach, reservoir or large river basin), the hydrological element(s) to be modelled (e.g. daily average discharge) and model simplicity as far as ease of application is concern (Vaze *et al*. 2011). The other key considerations in the model selection were parsimony and robustness.

Simple rainfall–runoff models are more satisfactory in their application when considering the above factors. By virtue of their simplicity, they have been observed to offer more robust results over complex models in streamflow predictions (Perrin *et al.* 2001; Nalbantis *et al.* 2011; Cited in: Ivkovic *et al*. 2014). In recent times, several of these rainfall–runoff models have been employed around the world for predicting future flow conditions (Nicholson, 2012). They include NAM (Nielsen and Hansen 1973), Sacramento (Burnash *et al.* 1973), HBV (Bergström & Forsman, 1973), HYMOD (Moore, 1985), IHACRES (Jakeman *et al.* 1990; Jakeman & Hornberger 1993), HYSIM (Manley, 1993), TANKMODEL (Sugawara, 1995) and SIMHYD (Chiew *et al.* 2002) just to mention but a few.

After a review of a number of these rainfall–runoff models, the IHACRES model was selected for this study based on its conformity with the above enumerated factors, particularly the study catchment characteristics, and its simplicity with fewer parameters as well as its notable suitability for predicting flows in ephemeral catchments as in the current study. The IHACRES model is more appropriate considering the smaller size of the study catchment in which the assumption of the homogeneity of the catchment characteristics could be more justified. It has been successfully applied worldwide in several catchments of different sizes and different climatic conditions, notably for streamflow prediction (Schreider *et al*. 2000).

Following an impressive performance of the IHACRES model compared with other conceptual rainfall-runoff models, Ye *et al.* (1997) concluded that if the objective is to model runoff in ephemeral catchments with areas between 0.82 to 517 km^2, then there is no need for a model with more than six parameters once an appropriate model structure to handle the nonlinearities is employed. Typically, the linear unit hydrograph routing module of the IHACRES model has only three parameters, thus allowing a more easy modification of its routing module for desired output results (Ivkovic *et al*. 2014).

The modern version of the IHACRES model employed in this study is part of an R software package termed Hydrological Model Assessment and Development (Hydromad). The overview of the Hydromad and the IHACRES model are as provided in the following sub-sections.

3.3.6 Hydrological Model Assessment and Development (Hydromad)

The hydromad is an open-source software package for the R statistical computing environment that provides a modelling framework for catchment hydrology including water balance estimation and flow routing in spatially aggregated catchments (Andrews, 2011). It is designed for hydrological modelling and associated data analysis with emphasis on a top-down, spatially lumped, empirical approach to catchment hydrology (Andrews, 2011). It does these by using a set of functions which work together to construct, manipulate, analyse and compare hydrological models, specifically dynamic, spatially-aggregated conceptual or statistical models that take daily time step data as inputs (Andrews, *et al.* 2011). "*These models are usually calibrated to a period of observed streamflow, and the parameters defining the modelled relationship between rainfall, evaporation and flow are assumed to be stationary in this period"* (Andrews, *et al.* 2011). Generally, the core supports of hydromad package include simulation, estimation, assessment and visualisation of flow response to time series of areal rainfall and other drivers (Andrews, 2011).

Hydromad package is designed as a general model framework consisting of a two-component structure: Soil Moisture Accounting (SMA) module and a routing or unit hydrograph module (Fig. 3.3) (Andrews, *et al.* 2011). It works on the basis or principle of this general two-component structure, in which the two components: SMA and the routing components can be arbitrary functions and a method can be specified for fitting the dependent routing component (Andrews, 2011). The SMA module estimates effective rainfall from input rainfall and temperature which is then routed to catchment outlet as streamflow by the routing module or the unit hydrograph module (Andrews *et al.* 2011; Andrews, 2011). Hydromad package is an ensemble of several models that are consistent with this framework, notably the IHACRES Catchment Wetness Index (CWI) (Jakeman and Hornberger, 1993) and Catchment Moisture Deficit (CMD) (Croke and Jakeman, 2004), all with SMA modules and unit hydrograph transfer functions for the routing (Andrews, 2011). "*The hydromad function can be used to specify any of the models within the package with the model equations, data, parameters and settings"* (Andrews, 2011).

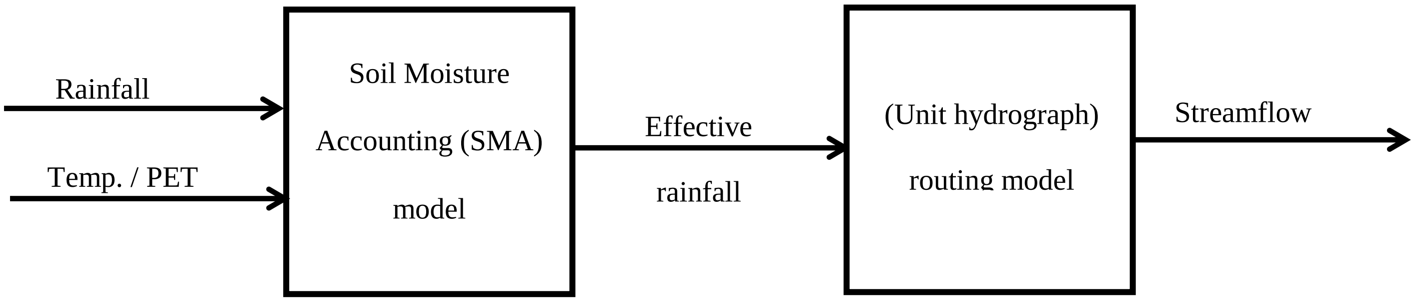


Figure 3.3: *The hydromad model framework, based on unit hydrograph theory (Source: Structure modified from Andrews et al. 2011)*

Detailed description of the hydromad package is provided in Andrews *et al.* (2011) and Andrews, (2011). In this study the hydromad version 0.9-18 on R version 2.15.0 (Andrews, 2011) was used in which IHACRES CWI model was specified. The IHACRES model requires daily rainfall and temperature as input data in the case of CWI specification, and daily rainfall and evapotranspiration as input data in the case of CMD (Fig. 3.3). However, all these hydromad package rainfall runoff models can be calibrated to time series of observed streamflow data (Andrews, 2011). Observed streamflow is used during calibration and validation only.

3.3.7 IHACRES model description

The IHACRES (Identification of Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data) is a six-parameter catchment-scale rainfall-runoff model that is designed to support in characterising the dynamic relationship between catchment areal rainfall and streamflow (Croke *et al*. 2005). The initial version of IHACRES (Version 1.0) was developed in 1994 by Institute of Hydrology (IH), Wallingford; UK (Littlewood and

Jakeman, 1994) and upgraded to Version 2.1 by the Centre for Resource and Environmental Studies (CRES) of the Australian National University, Australia (Croke *et al.* 2004; Cited in: Sriwongsitanon and Taesombat, 2011). The latest version, (Version 2.1) was used in the current studies. It is part of the ensemble conceptual rainfall-runoff models in the hydromad package and runs on R statistical computing environment. Thus, IHACRES Version 2.1 comprises of a two-module structure (Fig. 3.4): a non-linear loss module that transforms input rainfall r_k and temperature t_k into effective rainfall u_k at each time step k (usually daily time step as in this study) and a linear routing model that translates the effective rainfall into streamflow x_k on account of a total unit hydrograph approximation (Schreider *et al.* 2000; Croke *et al.* 2004). The non-linear loss module, estimates the amount of rainfall that is lost through evapotranspiration and soil absorption in the first stage of the two-module structure, giving the remaining amount of rainfall termed effective rainfall, which is then linearly routed to the catchment outlet by the linear unit hydrograph routing module in the second stage (Anderson and Goodall, 2006).

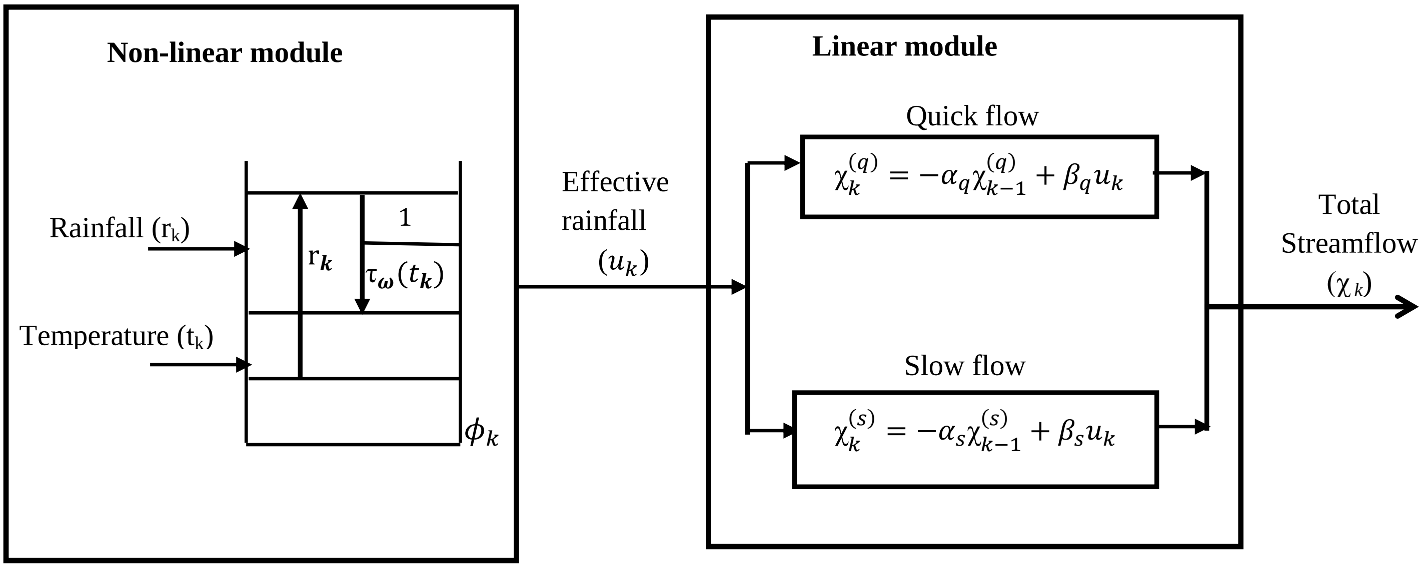


Figure 3.4: *IHACRES model structure (Evans and Jakeman, 1998; Cited in: Sriwongsitanon and Taesombat, 2011)*

The non-linear loss module estimates the effective rainfall from incident rainfall and storage index through an equation proposed by Ye *et al*. (1997). This equation is further described by Sriwongsitanon and Taesombat (2011) as in Table 3.2.

Table 3.2: *IHACRES Loss Model (Modified from: Sriwongsitanon and Taesombat, 2011; Anderson and Goodall, 2006)*

Equations	
$u_k = [c(\emptyset_k - l]^p\, r_k$................(Eqn. 1) $\emptyset_k = r_k + (1 - \frac{1}{\tau_k})\, \emptyset_{k-1}$............(Eqn. 2) $\tau_k = \tau_w e^{(0.062 f(t_r - t_k))}$.............(Eqn. 3)	
Variables	
k	Time step = 1 day
$\emptyset_k$	Soil Moisture
l	Soil moisture index threshold for producing flows
p	Non-linearity to the wetness index response term
τ_k	Drying rate
t_r	Reference temperature set to local average air temperature (°C), i.e. 20°C
t_k [°C]	Input temperature (°C)
r_k [mm/day]	Input (observed) rainfall in mm on day *k*
u_k [mm]	Effective rainfall (rainfall excess) (mm)
Parameters	
τ_w [days]	Time constant of wetness decline at 20 °C (drying rate at reference temperature)
f [1/°C]	Temperature modulation parameter
c [1/mm]	Index of catchment wetness capacity

The parameters *p* and *l* are particularly necessary when dealing with low-yielding catchments (Ye *et al*. 1997) or ephemeral catchments (Carcano *et al.* 2008; Sriwongsitanon and Taesombat, 2011) as in the current study. If the value of *p* is 1, then it means a linear relationship. The parameter *l* is the threshold for generating effective rainfall. If the value of *l* is less than l, then no effective rainfall is produced. Empirically, the parameter *f* sets the sensitivity of the drying rate (τ_w) to temperature, thus influenced by seasonal changes in evapotranspiration and consequently the climate, land use and land cover, whereas τ_w influences the soil drainage, infiltration rates and the amount of effective rainfall produced (Sriwongsitanon and Taesombat, 2011).

The routing module has a structure governed by transfer function theory that translates effective rainfall into streamflow by linear transformation equations (Young, 1974; Whitehead & Young, 1975; Cited in: Ivkovic *et al*. 2014). The routing module consists of two parallel flow paths, one illustrating a quick flow pathway to the catchment outlet with a short response time, and the other, a slow flow pathway with a long response time (Ivkovic *et al*. 2014; Anderson and Goodall, 2006) as show in figure 3.4. The quick flow pathway refers to the surface runoff and interflow or subsurface contributions to streamflow, whereas the slow flow pathway represents the baseflow or groundwater contributions to streamflow (Ivkovic *et al*. 2014). Each of the two parallel flow paths is characterised by a time constant that can be viewed as the rate of its unit hydrograph recession (Croke *et al*. 2004). As illustrated by the equations in figure 3.4 and Table 3.3, $x_k^{(q)}$and $x_k^{(s)}$ represent the modelled quick and slow flow volumes at time-step *k*, while x_k represents the modelled total streamflow (the sum of modelled quick and slow flow).

Table 3.3: *IHACRES Routing Model (Modified from: Sriwongsitanon and Taesombat, 2011; Anderson and Goodall, 2006)*

$x_k = x_k^{(q)} + x_k^{(s)}$.....................................(Eqn. 4)	
$x_k^{(q)} = -\alpha_q x_{k-1}^{(q)} + \beta_q u_k$..........................(Eqn. 5)	
$x_k^{(s)} = -\alpha_s x_{k-1}^{(s)} + \beta_s u_k$..........................(Eqn. 6)	
VARIABLES	
Δ	Sampling interval = 1 day
α , β	Polynomial transfer function coefficients
PARAMETERS	
$\tau_q = -\Delta/\ln(-\alpha_q)$ [days]	Quick response time constant
$\tau_s = -\Delta/\ln(-\alpha_s)$ [days]	Slow response time constant
$v_q = \beta_q/(1+\alpha_q)$ [unitless]	Quick volumetric throughput
$v_s = \beta_q/(1+\alpha_s)$ [unitless]	Slow volumetric throughput

The parameters α_q and α_s each represent the rate of unit hydrograph recession of the quick and slow flow paths, respectively, whereas β_q and β_s determine the height of the unit hydrograph peaks of the two parallel flow paths respectively (Ivkovic *et al*. 2014). "*The proportional volume of the quick flow* (v_q) *to slow flow* (v_s) *storage response completes the parameterisation of the linear routing model" (*Croke *et al. 2004).* Notably, the parameter v_s is the partitioning between quick and slow flow and lies between 0 and 1, where 0 is an indication of no base flow and 1 indicates that all effective rainfall goes to slow flow (i.e. no quick flow component).

A detailed description of the IHACRES model and its applications is available in Jakeman *et al.* 1990, Jakeman and Hornberger 1993, Andrews, 2011, Andrews *et al.* 2011, Sriwongsitanon and Taesombat, 2011, and many others in literature.

3.3.8 IHACRES model development

3.3.8.1 Sensitivity analysis

Sensitivity analysis of the IHACRES model was carried out to access the effects of each of the six parameters on the catchment runoff. This was done by varying the values of each parameter individually while keeping the rest of the parameters constant.

3.3.8.2 Calibration and validation

The hydromad package has several optimisation functions for calibrating of the IHACRES model to observed data where the choice of each technique depends on the problem at hand (Andrews *et al.* 2011; Andrews, 2011). The general optimisation function with pre-sampling, fitByOptim, with the "PORT" sampling method was used for calibrating IHACRES model in this study, after tests and comparisons with other methods were carried out. Detailed description of the fitByOptim optimisation function is available in Andrews *et al.* (2011). The model was calibrated on a ten-year period from January 1, 1982 to December 31, 1991 (mix of dry & wet years) of the estimated runoff data then followed by validation over two ten-year periods, January 1, 1972 to December 31, 1981 (dry period) and January 1, 1992 to December 31, 2001 (wet period). The model performance in the catchment was further and finally verified with the entire data set of the period under review (January 1, 1972 to December 31, 2012).

3.3.8.3 Model performance assessment

Four different performance assessment statistics which are part of a set of built-in statistics within the hydromad were used to assess the performance of the IHACRES CWI model. These are as described in the following equations:

- Bias as a fraction of the total observed flow (rel.bias):
  rel.bias $= \Sigma (X - Q) / \Sigma Q$ (excluding any time steps with missing values).

- R Squared (Nash-Sutcliffe Efficiency) (r.squared):
  r.squared $= 1 - \Sigma (Q - X)^2 / \Sigma (Q - \bar{Q})^2$

- R Squared using square-root transformed data (less weight on peak flows) (r.sq.sqrt):
  r.sq.sqrt $= 1 - \frac{\Sigma |\sqrt{Q} - \sqrt{X}|^2}{\Sigma |\sqrt{Q} - \bar{\sqrt{Q}}|^2}$

- R Squared using log transformed data, with an offset (r.sq.log):
  r.sq.log $= 1 - \frac{\Sigma |\log{(Q+\varepsilon)} - \log{(X+\varepsilon)}|^2 }{\Sigma |\log{(Q+\varepsilon)} - \bar{\log{(Q+\varepsilon)}}|^2}$

where Q is the observed data, X is the modelled data and ε is the 10 percentile (i.e. lowest decile) of the non-zero values of Q.

3.3.9 Survey

As a preliminary measure to achieve the set objectives, an intensive reconnaissance field survey of the study area was carried out between June and July, 2013. This was to obtain first-hand information on geographic, hydro-graphic and physical characteristics of the area and most importantly the various farming systems/methods and any adaptation measures practiced. The reconnaissance field survey was to also obtain information about the farm locations, crop types; land use and land cover types prior to a detailed survey. Three methods of survey data collection were employed in this study (Fig. 3.5).

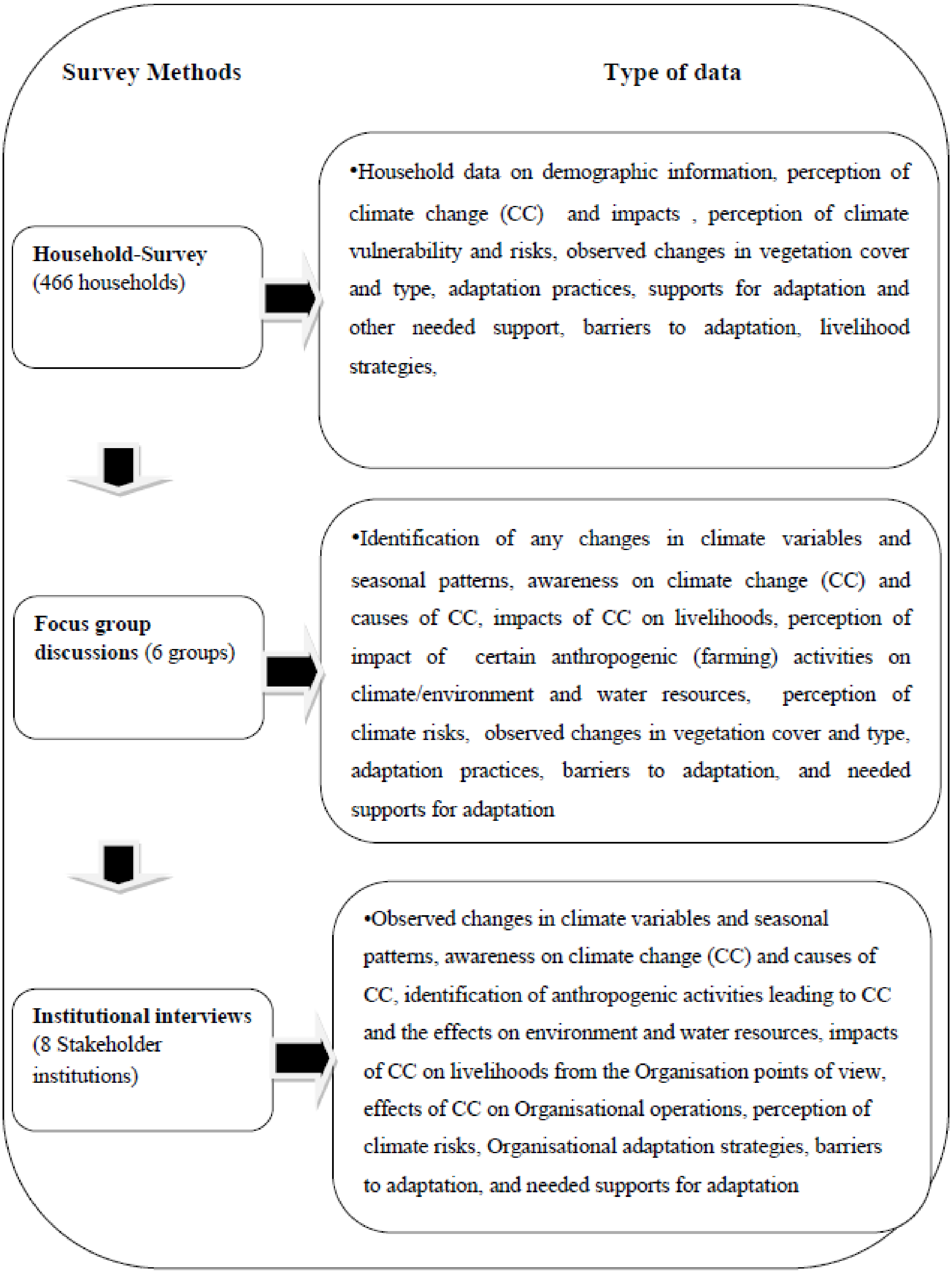


Figure 3.5: *Concept of data collection (Source: Structure modified from Below et al. 2011)*

A structured household questionnaire was designed into five main sections and covered information on demography, farming systems, farmers' perceptions on CC, concerns for changes in climate, their adaptation practices and external support for adaptation, barriers to adaptation, future adaptation plans as well as their required support to build resilience.

Sections of the questionnaire designed for this study were adopted from a farm household's questionnaire by Gbetibouo (2009). It was administered with the help of Agricultural Extension Agents/Officers (AEAs) of the Ministry of Food and Agriculture (MOFA) in the Bolgatanga municipal and Bongo District.

Just as other parts of Ghana, the study area is divided into agricultural operational areas supervised by an AEA. The operational areas consist of enumeration areas (EAs), i.e. [special areas where intensive data collection is carried out with the farmers for annual agricultural performance assessment. Six out of eleven such EAs were chosen for this study in a stratified manner that maximized representation and generalizability to farmers in the area. The selected EAs include two each from upstream, middle and downstream of the catchment. Farmers within each EA are registered (listed) by AEA and constitute a farmers' group who share ideas and resources.

The questionnaire survey was conducted by both purposive and random sampling methods in which adult farmers of age group of 50+ years with at least 30 years farming experience were selected in each EA using MOFA's holders list. This method of selecting a sample frame was preferably employed based on the idea that it is one of the ways of getting the best information through selecting people most likely to have the experience to provide quality information on the research topic (Denscombe, 2010). The age group of 50+ was targeted because the focus of this study interval spans over the last 30-year period as required for meteorological data time series analyses. Over the last 30 years means an adult in the Ghanaian context must have been at least eighteen (18) years or above. However, a preliminary survey in the area revealed that 30 years ago, most persons of age 18 who were not in school were most likely to be cattle herders and may have little knowledge about climatic conditions as at then, until at about age 20 or more when he/she actively engaged in farming activities. Thus, ages 50+ were considered most appropriate for this study.

The farm holders list (inclusive of both sexes) from the MOFA in the Bolgatanga and Bongo districts showed that the total number of registered farmers in all the 11 EAs of the catchment is 2,921. A total number of 1,102 of these farmers are aged 50+. From this population of farmers aged 50+ in each EA, the sample size for each of the selected EAs was then determined using online sample size calculator as recommended by Denscombe (2010). With the online sample size calculator by Creative Research Systems (2012), which applies the formulae (equations 1 and 2) by Jerrold (1984), the sample sizes of the entire listed farmer population (2,921) and farmers aged 50+ (1,102) were found to be 340 and 285 respectively at confidence level of 95%. However, the sum of the sample sizes of farmers aged 50+ in all the selected EAs was 466, which is well above the sample size (340) of the entire listed farmer population of the catchment. To maximize generalisability and minimize potential challenges with non-response, 466 was selected as the target number. Determining sample size separately at each of the selected EA was done to ensure uniformity and representativeness of the responses at all the selected EAs and the catchment at large.

ss =$(Z^2 * (p) * (1 - p))/c^2$..(1)

Where:

ss = sample size
Z = Z value (e.g. 1.96 for 95% confidence level)
p = percentage picking a choice, expressed as decimal
c = confidence interval, expressed as decimal

Correction for finite population gives:

new ss = $ss/[1 + (ss - 1/pop)]$...(2)

Where: pop = population

The structured questionnaire was then administered by random sampling technique using random number generator software used by MOFA for similar surveys. The random generator was applied to each of the 6 selected EAs for selection of the respective number of respondents in each EA. Farmers that make up the sample size in each EA were randomly selected based on their serial numbers in the list and then the names and houses of the randomly selected farmers to be interviewed in each EA were identified by these randomly selected serial numbers. This strategy enabled the AEAs who already know all the communities and the houses of these farmers in each EA to easily reach them for interview.

A field survey approach of face-to-face interview method of questionnaire administration was adopted to maximize the response rate (Denscombe, 2010). A total of 466 household questionnaires were administered to farmers in the study area. To obtain reliable responses on climatic information, the questionnaire administration was conducted using appropriate local terms in the common local language (Frafra) spoken by the people in the study area. From a household of more than one farmer, only one farmer was interviewed to avoid bias as a cue from Kemausuor *et al.* (2011). The farmers in the area include mainly those who practiced rain-fed only and those who practiced both rain-fed and irrigated agriculture. The questionnaires surveys were conducted between August and September, 2013. The data gathered were processed and statistically analysed using the Statistical Package for the Social Scientists (SPSS 16.0) software and the results interpreted.

On the other hand, focus group discussions were carried out immediately following the questionnaire administration in each of the six (6) selected EAs. These were conducted using an interview guide questionnaire designed to gather concise information that serves as the basis for cross-validation of information obtained through household questionnaires as well as complement it. Beside, eight (8) stakeholder institutions in agriculture, water and environment sectors in the study area were interviewed using a formulated interview guide questionnaire. This was a measure to obtain a fairly all round information in the study area regarding perception on CC, concerns for changes in climate, adaptation strategies, barriers to adaptation, future adaptation plans and needed supports for adaptation. These institutions include Ghana Water Company Limited (GWCL), Community Water and Sanitation Agency (CWSA), Ghana Irrigation Development Authority (GIDA), Irrigation Company of Upper Region (ICOUR), Water Resources Commission (WRC), Hydrological Service Department (HSD), and Environmental Protection Agency (EPA), Ministry of Food & Agriculture (Bolgatanga Municipal MOFA and Bongo District MOFA). This information was required to assess the future pressure on the water resources in the catchment due to adaptation measures by farmers and these stakeholder institutions.

3.3.10 Model selection for assessing impacts of climate change on future water resources

As an appropriate tool uniquely used globally for water resources planning and management, particularly regarding water allocation for multiple users and prioritisation, Water Evaluation and Planning (WEAP) model (SEI, 2012) was preferably chosen for this part of the study. Its main application was to investigate the impacts of CC on water resource availability in the catchment by examining the dynamics of water availability, water demand and supply for multiple uses in the context of projected CC. In doing so, the WEAP model was used to assess the adequacy of the catchment water availability to meet current and projected water demand by examining and predicting the future trend of the catchment water demand and supply based on current and projected future conditions of the catchment. Finally, potential water stress conditions are assessed through comparison of the outcome of the WEAP model with standard definitions of water stress conditions in literature.

3.3.11 Water Evaluation and Planning (WEAP)

The WEAP model was developed by Stockholm Environment Institute (SEI) for integrated water resources planning through a comprehensive framework for policy analysis (SEI, 2012). The core application of WEAP involves the use for examining whether or not the available water resources can meet the current and future demand given the various scenarios of long term mean, extreme and projected future climate conditions as well as assumptions of policy and socio-economic changes and other likely future evolutions (IUCN, 2007). It is a unique policy tool for assessing a wide range of alternative water development and management strategies while taking into account the various multiple and competing uses of the water resources (SEI, 2012). The following sub-sections provide summary of the approach and structure of WEAP.

3.3.11.1 The WEAP Approach

The WEAP model operates on the basic empirical approach of a mass balance accounting principle that makes it applicable to a wide range of water resource systems that include irrigation and municipal water supply systems, single catchments and large transboundary river basins (SEI, 2012). It computes water mass balance for every node and link along a river system on a monthly time step (SEI, 2007). The computation is done by allocation of water to each demand site which includes in-stream or environmental water needs and all sectorial requirements (e.g. irrigation, municipal supply, livestock, and so on) based on the analyst-assigned demand priorities and supply preferences to those demand sites. Using such priority allocation technique, WEAP allocates water at each time step to satisfy higher priorities first before consideration is given the lower priorities in decreasing order. Where water is limited, allocation to demand sites with lower priorities are restricted accordingly (McCartney *et al.* 2012). By that approach, the WEAP model is capable of being used to address a wide range of issues that include *"sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and streamflow simulations, reservoir operations, hydropower generation, pollution tracking, ecosystem requirements, vulnerability assessments, and project benefit-cost analyses"* (SEI, 2012).

The application of WEAP model typically involves the following steps as outlined by SEI (2007 & 2012):

- ***Study definition*** that involves defining the time frame of the study, spatial boundary, system components and configuration of the problem.
- Establishing ***Current Account*** which presents a snapshot of the water system as it currently exists. It provides the prevailing situation of the water system in the study area which includes specifying the actual water demand, available water resources and supplies for the system. It is a calibration step in the development of the WEAP model application and the starting year for all scenarios.
- Building of ***scenarios*** on current account which gives the user the opportunity to explore the impact on future water availability of different assumptions of how future conditions of the water system, climate, policy and technological development might evolve in the study area.
- ***Evaluation*** of the scenarios with regards to water availability and its productivity in the study area.

3.3.11.2 WEAP model structure

WEAP model is structured in a form of five main views of the user's study area (SEI, 2007 & 2012):

- **Schematic view:** This gives the starting point for any application in WEAP and contains GIS-based tools for easy configuration of the study system.
- **Data view:** This provides an environment for the user to create data structures and relationships as well as build assumptions using mathematical expressions. It is dynamically linked to Excel giving access to data in Excel.
- **Results view:** This provides detailed and flexible display of all model outputs of the study system in a wide variety of charts and tables.
- **Overviews view:** This allows for simultaneous display of a group of result charts on the screen for quick viewing. This is often typically used to highlight key aspects of the results in charts for a quick glimpse of the simulated system.
- **Notes view:** This provides a place for the user to enter documentation and references for data and assumptions.

A detailed description of the WEAP model and its applications is available in SEI (2007 & 2012).

3.3.11.3 WEAP model set-up

A review of literature revealed that the hydrological modelling component of WEAP model was relatively weak compared with other lumped rainfall-runoff models. For that reason, WEAP model was configured for only the modelling of water allocation with a good representation of the dynamics of water availability and water requirements of the Vea catchment in this study (Fig. 3.6). The head-flows for the catchment used in WEAP model set-up were derived from the output of the flux estimation, while future flows were simulated using IHACRES rainfall-runoff model as described in chapter 4. The model was configured to represent the surface water resources availability and water demand/uses dynamic response characteristics of the catchment which include the catchment area characteristics; the rainfall characteristics; hydrological characteristics (runoff/streamflow); the reservoir characteristics (storage); the water requirements/uses and return flows as well as the catchment water losses. The groundwater characteristics could not be taken into account, due to the lack of data.

The focus was on how water availability and demands will evolve over two 30-year future periods of 2021-2050 and 2071-2100 in the context of projected climatic change and irrigation development, human and livestock population growth. The period from May to April was designated the water year for the study area as noted by Ofosu (2011). The year 2010 was set as the current account year which was created using the data for the 2010/2011 water year. However, the streamflow data (head-flow) entered for the current account, was the average over the 30-year period (1981-2010). The current account serves as the base on which scenarios are built. The last year of scenarios was set as year 2100. The reference scenario by default, projects forward all the properties of the current accounts throughout the specified period under investigation (i.e. 2010-2100 in this study). The modelling time step was monthly and the time step boundary set to base on calendar month with time step per year of 12. The actual catchment river, Yaragatanga, with about two smaller tributaries upstream was represented by one main river system in the WEAP model setup (Fig. 3.6). The Vea irrigation reservoir developed on the river (Vea Dam) was positioned it.

Three water demand sectors (irrigation, municipal supply and livestock) in the catchment were identified and their respective demand nodes were each connected to the water supply source. The return flow (in the case of irrigation) was also appropriately returned to the receiving supply source. Based on the outcome of the stakeholder institutional interviews as discussed in chapter 5, the water allocation priorities for the demand sites were appropriately set within the catchment. All the demand sites (municipal supply, irrigation and livestock) were each given first priority. The water consumption, percentage consumption, monthly variations and the annual demand pattern were also set by means of key assumptions for each of the three demand sites. The monthly variations in percentage of the annual demand at all demand sites were derived from the available historical data obtained on each demand site. The inclusion of the environmental water requirements was not explicitly done in this study, in the same way as was done by McCartney *et al.* (2012).

Table 3.4: *Water availability in terms of 30-year monthly mean flows at the VEA irrigation reservoir (m^3/s): 2021-2050*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
Cu. Ac. 2010	0.00	0.01	0.03	0.11	0.29	0.46	0.80	3.79	6.43	1.59	0.03	0.01	**1.13**
Ref. Sce.	0.00	0.01	0.03	0.11	0.29	0.46	0.80	3.79	6.43	1.59	0.03	0.01	**1.13**
High RCMs flow	0.01	0.00	0.03	0.10	0.48	1.51	1.96	4.03	4.65	1.56	0.21	0.03	**1.22**
Lowest RCMs flow	0.00	0.00	0.02	0.02	0.03	0.21	0.37	0.32	0.10	0.01	0.00	0.00	**0.09**
Average RCMs flow	0.00	0.03	0.14	0.18	0.33	0.86	1.24	1.57	1.14	0.41	0.06	0.01	**0.50**

Table 3.5: *Water availability in terms of 30-year monthly mean flows at the VEA irrigation reservoir (m^3/s): 2071-2100*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
Cu. Ac. 2010	0.00	0.01	0.03	0.11	0.29	0.46	0.80	3.79	6.43	1.59	0.03	0.01	**1.13**
Ref. Sce.	0.00	0.01	0.03	0.11	0.29	0.46	0.80	3.79	6.43	1.59	0.03	0.01	**1.13**
High RCMs flow	0.00	0.00	0.00	0.02	0.17	0.91	1.54	7.33	26.73	7.45	0.59	0.04	**3.73**
Lowest RCMs flow	0.00	0.01	0.04	0.06	0.07	0.28	0.70	0.43	0.09	0.01	0.00	0.00	**0.14**
Average RCMs flow	0.00	0.06	0.13	0.16	0.27	0.80	1.23	1.89	2.58	0.65	0.07	0.02	**0.66**

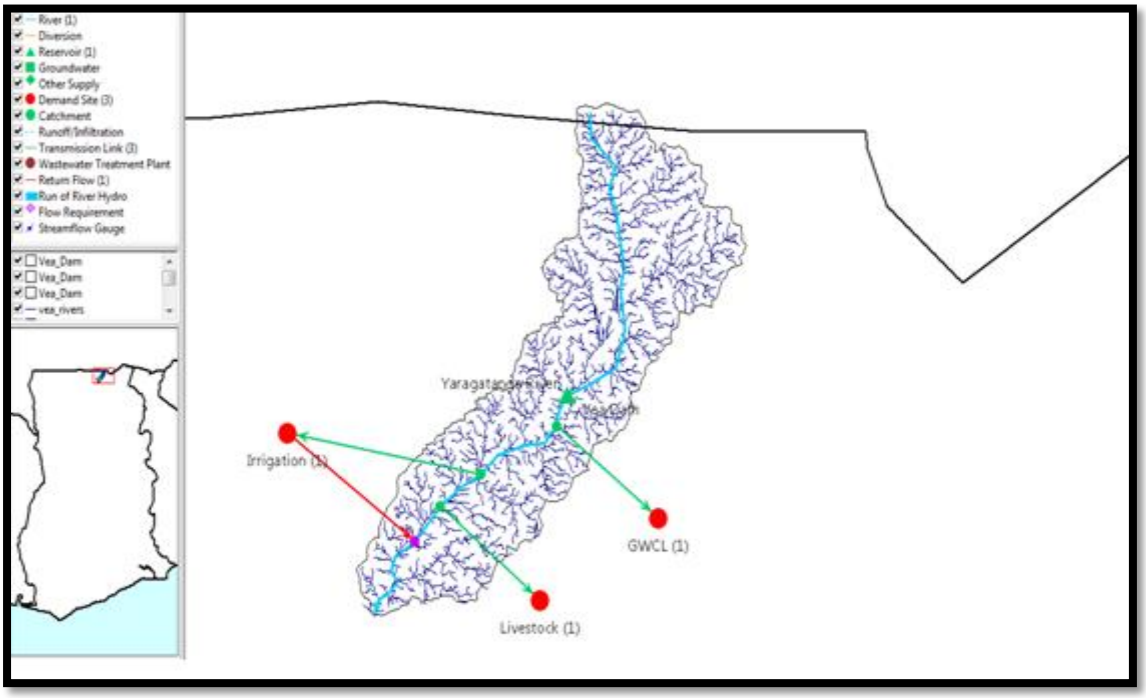


Figure 3.6: *Schematic layout of the Vea catchment as configured within the WEAP model*

3.3.12 Water demands

Water withdrawal from the catchment is mostly for domestic, irrigation and livestock watering purposes. The total water demand in the catchment is the sum of water required to meet the demands of these three sector uses - domestic supply, irrigation and livestock.

3.3.12.1 Domestic supply requirement

The main source of domestic water supply for the catchment populace is the surface water drawn from the Vea irrigation reservoir situated on the catchment river, Yaragatanga by Ghana Water Company Limited (GWCL). The current GWCL supply area population at the study area is 65176 (UNEP-GEF, 2008) with 6978 supply/source points. Data on long-term daily water withdrawal (1984-2012) was obtained from GWCL in Bolgatanga. The average per capita water consumption of the catchment was therefore found to be about 1.64 m^3 per day (54.5 litres per day) which is higher than an average per capita water consumption of the entire Volta Basin observed by McCartney *et al.* (2012) to be 35 litres per day. For the purpose of this study, the average per capita consumption of the catchment was assumed to be constant over time. The catchment population for 2010 baseline was derived from the 2010 Population and Housing Census data for the area, while the average annual population growth rate was derived from the past five consecutive annual inter-censal growth rates since 1960.

3.3.12.2 Irrigation requirement

The available records on irrigation water abstractions from the catchment were poor due to considerable missing data. However, adequate annual data on crops cultivated, areas of land cultivated and the irrigation efficiency were available over the period of 1985-2012. With these data, historical annual irrigation water demand/abstractions from the Vea reservoir were determined using the CROPWAT/CLIMWAT model by the Food and Agriculture Organization that had been configured for the catchment by Kusi (2013).

3.3.12.3 Livestock watering requirement

The surface water resources of the catchment serve as the main source of water for livestock watering, particularly for large ruminants including cattle and donkeys which are relatively populous in the area because of their crucial role in agricultural activities in the entire region – ploughing, carting of goods as well as commercial purposes. Although, other smaller ruminants such as sheep and goat may often source their water needs from a few troughs provided at wells and boreholes as observed by Allwaters Consult Limited (2012), it was noted during focus group discussions that these smaller ruminants as well as the swine largely source their water needs directly and indirectly from the surface resources, particularly the Vea reservoir. This is partly because most of these wells and boreholes dry up during much part of the year attributable to low ground water level in the area.

Regional livestock data for the area were not available, thus ten year district records (2001-2010) obtained from the Bongo district office of the Ministry of Food and Agriculture (MOFA), which shares the larger part of the catchment were used to estimate the population density of each type of livestock (Cattle, Donkeys, sheep, goats and swine) for the district and inferred for the catchment. The population of each type of livestock was then determined by multiplying the respective population density to the catchment area (305 km^2). The standardised estimates of livestock per capita water consumption of different livestock types at an average air temperature of 25 ^oC as provided by the Food and Agricultural Organization of the United Nations (Steinfeld *et al.* 2006) (Table 3.6) were used to determined livestock water demand for the study area (Table 3.7). The population of each type of livestock in the catchment was multiplied by the respective livestock per capita water consumption and the totals for all the livestock types summed up to give the total livestock water demand for the catchment. In this study, it was assumed that per capita water consumption for Camel was the same for Donkey. The average annual livestock growth rate (2.5%) for the Volta basin as observed by McCartney *et al.* (2012) was used in this study.

Table 3.6: *Drinking water requirements for livestock*

Species	**Physiological condition**	**Average Weight**	**Air temperature (^oC)**		
			15	25	35
			Water requirements		
		(kg)	(litres/animal/day)		
Cattle	African pastoral system-lactaring-2 litres milk/day	200	21.8	25.0	28.7
	Large breed - Dry cows - 279 days pregnancy	680	44.1	73.2	102.3
	Large breed - Mid lactation - 35 litres/day	680	102.8	114.8	126.8
Goat	Lactating - 0.2 litres milk/day	27	7.6	9.6	11.9
Sheep	Lactating - 0.4 litres milk/day	36	8.7	12.9	20.1
Swine	Lactating - daily weight gain of pigs 200g	175	17.2	28.3	46.7
Camel	Mid-lactating - 4.5 litres milk/day	350	31.5	41.8	52.2

Sources: Luke (1987); National Research Council (1985; 1987; 1994; 1998; 2000); Pallas (1986); Ranjhan (1998); Cited in: Steinfeld *et al*. (2006).

Table 3.7: *Vea Catchment livestock population and water requirements*

Type of Livestock	**Population density**	**Total population in the catchment**	**Per capita water consumption (litres/day)**	**Annual water requirement (m^3/year)**
Cattle	49.7	15143.6	25.0	9.1
Sheep	52.5	15998.5	12.9	4.7
Goats	58.8	17941.6	9.6	3.5
Swine	21.6	6573.4	28.3	10.3
Donkeys	2.3	692.4	41.8	15.3
TOTAL	184.8	56349.6	117.6	42.9

3.3.13 Scenarios development

Scenarios are assumptions of how the future might evolve with regards to policy changes, technological and other developmental changes as well as CC. It serves as an indispensable tool when modelling and assessing the impacts of anthropogenic activities and CC on natural resources, particularly on water availability as is the case in this study. In WEAP, scenarios development consists of three main steps: (1) “Current Accounts”, which serves as the base year of the model; (2) “Reference” scenario, which projects the properties of the Current Accounts to simulate likely evolution of the system without intervention; and (3) “what-if” scenarios which are created by altering the “Reference” scenario (SEI, 2012). In this study, a wide range of “what if” scenarios of future possibilities were considered under four main CC scenarios and simulated for assessment of future situation of water availability in the catchment. The CC scenarios were based on the reference climate and the 16 RCMs simulations based on the RCP 8.5 as discussed in chapter 4 and sub-section 3.2.4 of this chapter 3. The focus was on the possible situations in the near future (2021-2050) and the distance future (2071-2100). WEAP was set up for 2010 baseline water demand and for each of the two future time slices the following scenarios were analysed:

- Reference scenario: no CC - climate time series from 1983 to 2012 was used.
- Future highest extreme climate conditions: the highest of the 16 RCMs simulated conditions.
- Future lowest extreme climate conditions: the lowest of the 16 RCMs simulated conditions.
- Future average climate conditions: the average of the 16 RCMs simulated conditions.

In simple terms, the above four scenarios refer to a possible future with rainfall as has been over the past three decades (1983-2012) – reference streamflow; and future with the highest rainfall (highest streamflow), lowest rainfall (lowest streamflow) and average rainfall (average streamflow) from the 16 RCMs simulations respectively. For the purpose of convenience, these four climate scenarios investigated are herein referred to as: “reference”, “wet”, “dry” and “average” scenarios, respectively.

The ‘what if’ scenarios considered under the analysis of each of the above four climate scenarios were developed based on results of the survey study analysed in chapter 5 and the observed on-going developments as well as other likely future development options in the catchment. These include the on-going and projected possible irrigation development as well as the planned development in the domestic water supply infrastructure in the area. Eight types of ‘what if’ scenarios were elaborated and mainly emphasised on population and irrigation growth rates, with and without improved irrigation efficiency (from the current 50% to 70%). These include analysis to assess the water availability situation in the near future (2021-2050) and the distance future (2071-2100) if:

- Irrigation continues to expand at the current rate of 1.1%/a in the present (1981-2010) under business as usual (BAU) (current % proportion of each crop).
- Irrigation expands at a rate of 2.3%/a under BAU.
- Potential irrigable area (1400 ha) is developed under BAU.
- Only rice is used for total developed irrigable area (850 ha).
- Only rice is used for total potential irrigable area (1400 ha).

- Only tomato is used for total developed irrigable area (850 ha).
- Only tomato is used for total potential irrigable area (1400 ha).
- Vea dam serves domestic water supply to only Bongo District (Bongo and its environs).

3.3.14 Assessing land cover changes in the vea catchment - analysis of satellite imagery

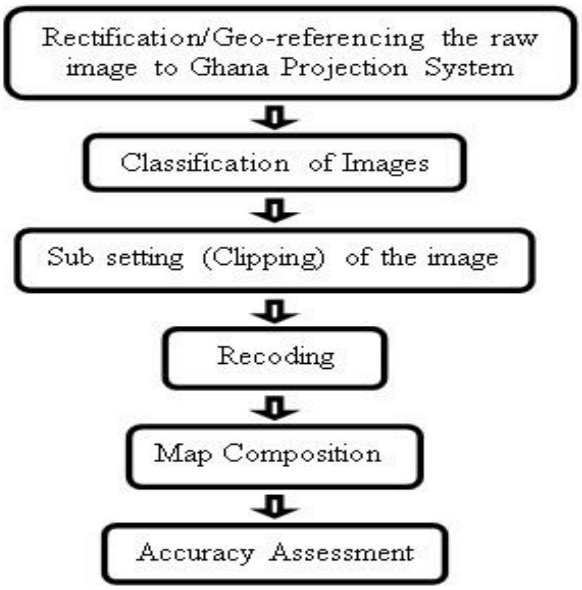


Figure 3.7: *The procedure used for satellite imagery analysis*

In a procedure as illustrated by figure 3.7, the raw image was rectified/geo-referenced to Ghana Projection System in a process which involves assigning Ghana Coordinates to the image using 1:50000 Ghana Topographic data. Hydrological data from Survey Department which is already referenced to the Ghana Coordinates System was used (i.e. to identify riverine vegetation). ArcGis software was used to carry out the rectification.

Classification of images was carried out using the supervised classification method in the ERDAS IMAGINE software. In this process, pixels that represent patterns that could be recognized or identified with help from other sources were selected. Having identified patterns in the imagery, the computer systems were "trained" to identify pixels with similar characteristics. By setting priorities to these classes (classes of unique Spectral Reflectance), the classification of pixels was supervised as they are assigned to a class value. Initially, however, the unsupervised classification option was used and then, the classified images validated using Global Positioning System (GPS) for the purpose of orientation in the field.

The delineated catchment boundary of the project area was used to subset (clip) the classified image. In recoding, new class value numbers were assigned to all classes, creating a new thematic raster layer using the new class numbers. Some of the classes were combined through this process. After recoding, the raster attribute table was exported as .dat. The statistics of all the various classes that were generated was opened in excel. Once the size of a pixel was known, i.e., Landsat 30m x 30m = 900m, the pixels per class was multiplied by 900 to get the total area in meters per class. This was divided by 10000 to get hectares, then divided by 100 to get square kilometre (km^2).

The various maps were finally composed showing the changes in the land cover types with statistics indicating the changes from 1990, 2000 and 2010.

To ascertain the reliability of the Land use/cover classes analysis method used, accuracy assessment was carried out. A total of 100 points were randomly selected: closed savanna woodland (15), open savanna woodland (20), dense herbaceous/grass /fallow agriculture (15), grass/herbaceous/agricultural lands (20), bare surface/built up area (15) and water body (15) with sum total (100). When we visited the field to check the accuracy 13 was really closed riverine whilst 2 was open riverine vegetation, and so on. To calculate the accuracy of the closed savanna woodland, the formula was thus: 13/15*100. This same formula was applied to all the classes to derive the matrix below (Table 3.8).

Table 3.8: *Accuracy assessment table based on error matrix of the pixel-based method*

CLASS	Closed savanna woodland/ dense herbaceous cover	Open savanna woodland/ dense herbaceous cover	Dense herbaceous/ grass (fallow agriculture)	Grass/ Herbaceous (agricultural lands)	Bare surface/ built up area	Water body	Sum
Closed savanna woodland/dense herbaceous cover	13	2	0	0	0	0	15
Open savanna woodland/dense herbaceous cover	2	14	1	1	0	2	20
Dense herbaceous/ grass (fallow agriculture)	0	1	12	2	0	0	15
Grass/herbaceous (agricultural lands)	0	1	1	14	2	2	20
Bare surface/built up area	0	0	1	1	13	0	15
Water body	0	2	0	2	0	11	15
Sum	15	20	15	20	15	15	100
Accuracy (%)	86.67	70.00	80.00	70.00	86.67	73.33	
Overall Accuracy (%)	77.78						

3.4 Conclusion

This chapter described the data types that were used in the study as well as the materials and methods used for the analysis of these data. The different types of data used in this study were the quantitative data that included meteorological data (rainfall, temperature, evaporation and evapotranspiration), reservoir bathymetry data (daily height, surface area and storage), data on water abstraction for domestic supply by Ghana Water Company Limited (GWCL) and ensemble climate scenario data. The qualitative data used were mainly the survey data collected using the structured household questionnaire, focus group discussions and institutional interviews. Landsat ETM satellite images were also used in this study. The quantitative data were prepared (corrected/cleaned) by filling missing data and carrying out bias correction on the ensemble climate scenario data.

Several software tools were used in the study including the Statistical Package for the Social Scientists (SPSS 16.0) software used for analysing the household questionnaire survey data, the KhronoStat software package used for the statistical analysis of the meteorological data and the CROPWAT/CLIMWAT model used in determining irrigation water requirement (irrigation water demand) for the catchment. Other software tools used included the ArcGis and ERDAS IMAGINE software used for analysis of satellite image, the IHACRES model used for prediction future streamflow and the WEAP model used for assessing the impact of CC on future water availability to meet demand in the catchment. The overall objective for the analyses of all the data collected for this study was to investigate the impact of CC on future water availability for irrigation in the catchment. The analysis of the survey data collected, for instance, was to help draw the scenarios of the future likely evolution of activities, developments and water demands in the catchment which were required as input into the WEAP model for assessing the future water availability situation in the catchment. The future streamflow time series predicted by IHACRES were also required as input into the WEAP model. The study period for the meteorological data analysed was between 1972-2012 and the future time slides considered for assessing the future water availability situation in the catchment were 2021-2050 (near future) and 2071-2100 (distance future).

CHAPTER 4: CURRENT STATUS AND FUTURE DEVELOPMENT OF CLIMATE AND WATER COMPONENTS

4.1 Introduction

This chapter presents the findings of the analysis of the current status and future development of key climate parameters and water components in the study area. This embodies the results of: (1) statistical analysis of the meteorological data of the area, (2) the estimation of the catchment historical streamflow, (3) the hydrological predictions of the catchment future streamflow and (4) the assessment of the impact of climate change (CC) on streamflow in the catchment.

4.2 Temperature trends

The time series analysis of annual temperature for the study area for the period 1972-2012 (Fig. 4.1) indicates that temperature has continuously been on the increase. The lowest and the highest of the mean annual temperatures within the period (1972-2012) were 27.9°C and 29.7°C and occurred in 1975 and 2006 respectively; whiles the long-term (1972-2012) average annual temperature was 28.9°C. The lowest and the highest of the mean monthly temperatures within the period (1972-2012) were 25.1°C and 34.4°C and occurred in January 1983 and March 2005 respectively, whiles the long-term (1972-2012) average monthly temperature remains 28.9°C, the same as long-term average annual temperature. The long-term (1972-2012) averages of mean monthly minimum temperatures and mean monthly maximum temperatures were 22.7°C and 35.0°C whiles the lowest of the mean monthly minimum temperature and the highest of the mean monthly maximum temperature were 16.7°C and 40.9°C and occurred in January 1975 and March 2005 respectively.

It was observed that, the highest temperatures occurred in March and April with mean values of 39.3°C and 38.5°C respectively and the lowest were observed to occur in December and January, with long-term (1972-2012) average values of mean monthly minimum temperatures of 19.2°C and 19.7°C respectively.

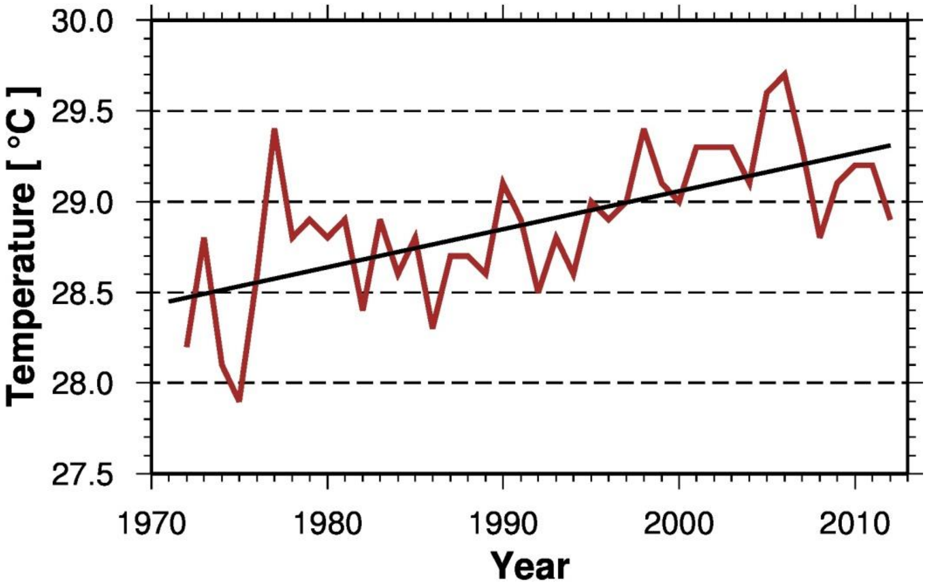


Figure 4.1: *Mean annual temperature trend in the catchment (Data source: Ghana Meteorological Agency)*

4.2.1 Pettitt test, Hubert Segmentation test and Mann-Kendall test of temperature data

The statistical analysis of temperature data for the catchment using non-parametric tests, further confirms the rising trend in temperature of the area. Both Pettitt test and Hubert Segmentation test detected change-points in temperature time series at 1994 (Pettitt test), 1975 and 1996 (Hubert Segmentation test) at confidence level of 99%. Mann-Kendall test likewise detected an increasing trend in temperature time series of the area at confidence level of 99%.

4.3 Rainfall trends

4.3.1 Rainfall amount time series

The mean annual rainfall for the catchment for the 41-year period 1972-2012 was 957 mm, while the lowest and highest annual rainfall amounts for the same period, were 664 mm and 1269 mm and occurred in 1977 and 1999 respectively. For the past 30-year period, 1983-2012, the lowest and highest annual rainfall amounts recorded in the area were 728 mm and 1269 mm and occurred in 1984 and 1999 respectively. The study found that between 1972 and 1988, 10 out of the 17 years recorded total annual rainfall below the long term mean of 957 mm. Between 1989 and 2012, 11 out of 24 years also recorded rainfall figures below the average. In all, across the two time periods, there were 21 out of 41 years in which total annual rainfall fell below the long term mean as shown in figure 4.2. Since 1989, however, rainfall exceeded the long-term mean excessively in a few sporadic cases which may have resulted in floods, especially in 1989, 1996, 1999 and 2007. The worst drought year in the study period occurred in 1977 followed by 1984 and 1981, whiles 1999 was the wettest year followed by 2007 and 1989.

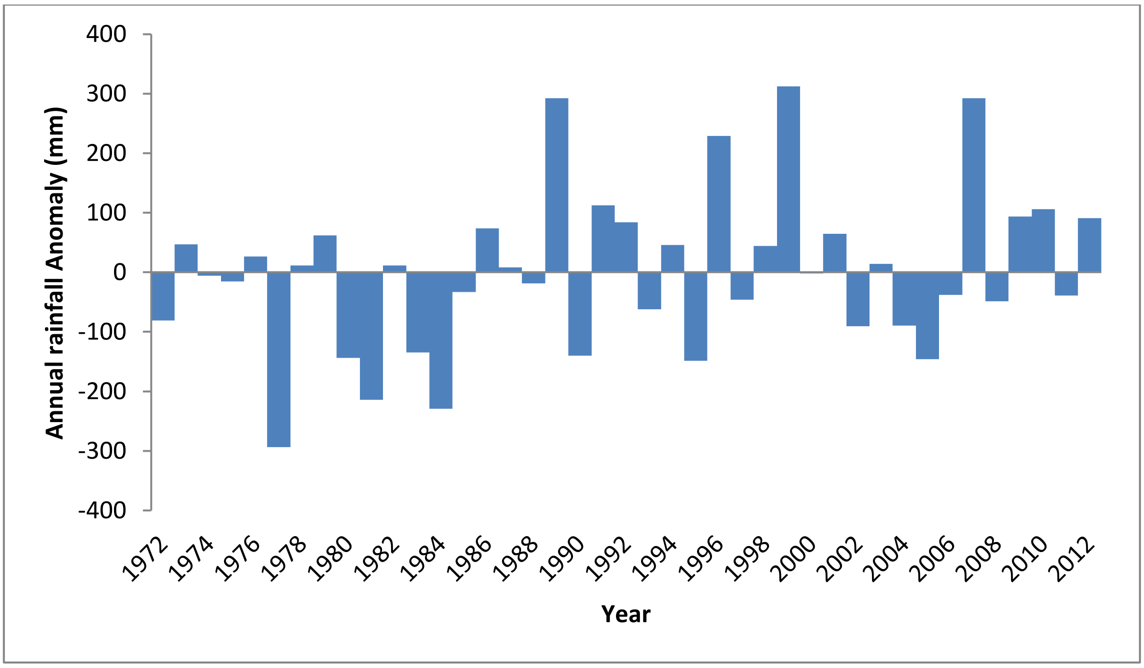


Figure 4.2: *Inter-annual rainfall anomaly (deviation from long-term mean) showing variability within the study period (1972 - 2012) (Data source: Ghana Meteorological Agency)*

The maximum and minimum rainfall amounts of the peak month (August) of the wet season were 485 mm and 102 mm in 2007 and 1986 respectively, whiles the average amount was 249 mm. The anomalies for individual months within the growing/cropping period (May-October) (Fig. 4.3) indicate a general fluctuation trend in intra-seasonal rainfall distribution since 1972 with largest anomalies occurring in August and September. On average, the seasonal (May-October) rainfall totals accounted for 93% of the total annual rainfall in the catchment over the study period. The maximum percentage contribution of the seasonal rainfall to annual totals was 99% and occurred in 1985 while the minimum was 81% and occurred in 2004 with respective annual totals of 923.7 mm and 867.6 mm.

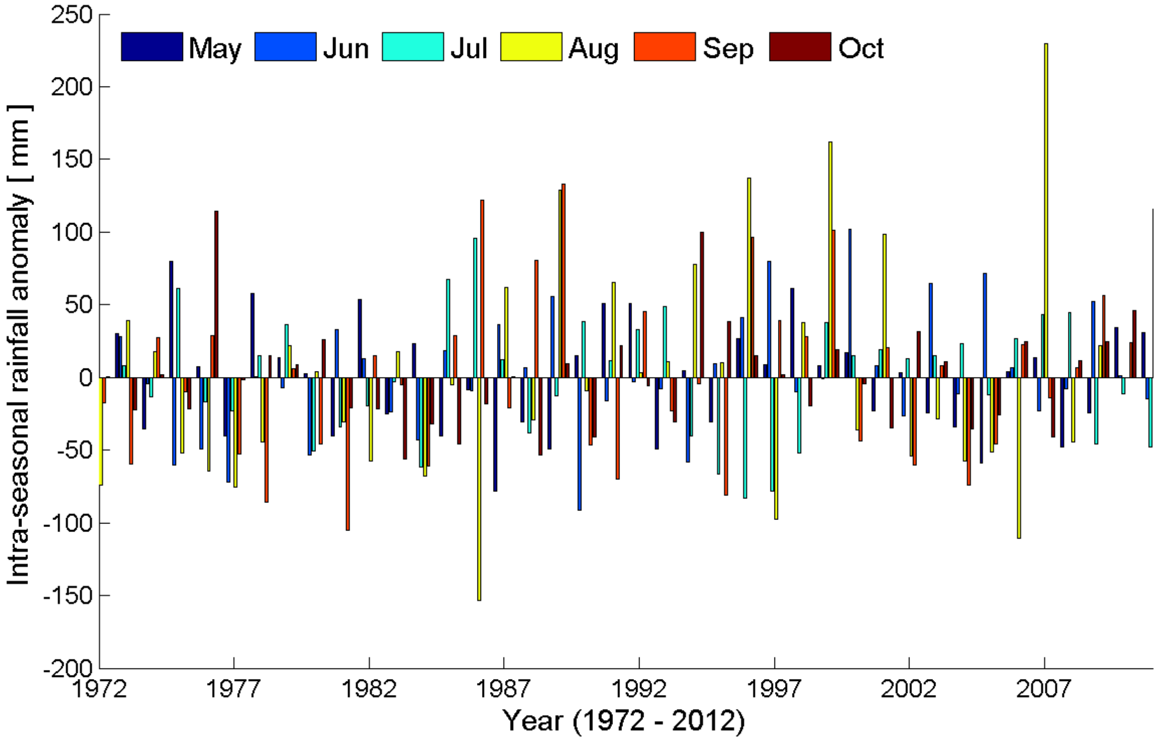


Figure 4.3: *Intra-seasonal rainfall anomaly showing variability during cropping season (May to Oct) in the study catchment (1972 - 2012) (Data source: Ghana Meteorological Agency)*

4.3.4 Rainfall events (rainy days)

The average number of annual rainy days for the catchment for the 41-year period (1972-2012) was 69 days. It is the same average number of annual rainy days (69 days) if we consider only 30-year period (1983-2012). Figure 4.4 illustrates annual rainfall events (rainy days) in the study area over the study period, 1972-2012 in terms of annual rainy days anomaly. The lowest and highest numbers of annual rainy days recorded in the area within the study period were 55 and 80 rainy days respectively. While the lowest of 55 rainy days occurred in 1983, the highest of 80 rainy days occurred both in 1994 and 1999.

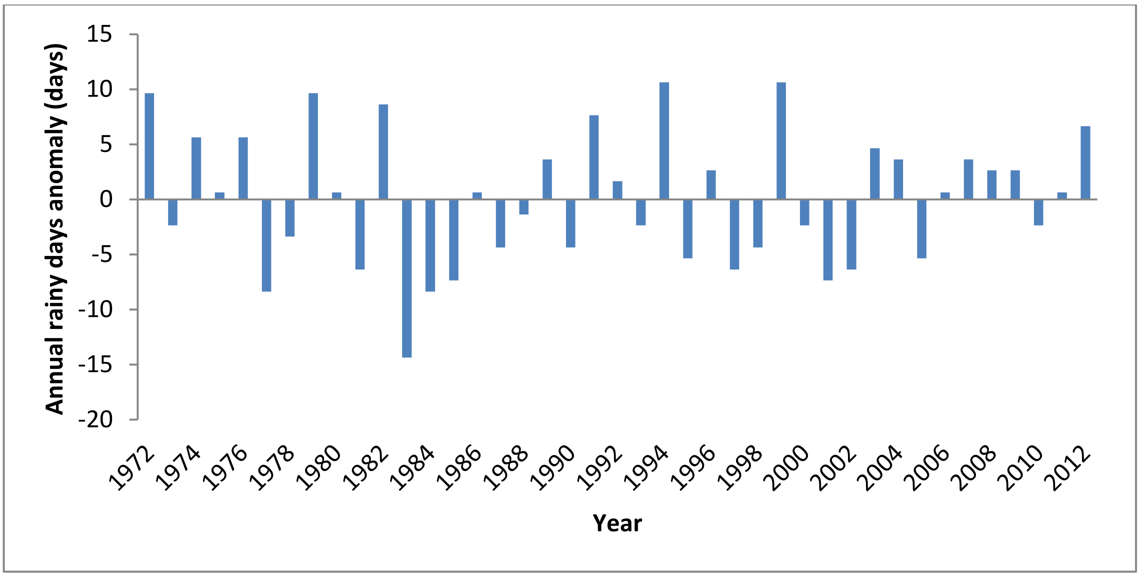


Figure 4.4: *Inter-annual rainy days anomaly (deviation from long-term mean) showing variability within the study period (1972 - 2012) (Data source: Ghana Meteorological Agency)*

Figure 4.5 presents a picture of the intra-annual rainfall events distribution in the study area in terms of monthly rainy days anomaly. The pattern of intra-annual rainy days over the study period is much similar to that of intra-annual rainfall amounts (Fig. 4.3), showing a general variability with no clear trend. The maximum number of 22 rainy days also occurred in the peak month (August) of the wet season and in the same year 2007 as observed for rainfall amounts (Fig. 4.3), whiles the average rainfall days was 15 for the peak month over the study period. However, the minimum of 11 rainy days of the peak month (August) occurred in 1997 and not in 1986 as was the case of rainfall amounts.

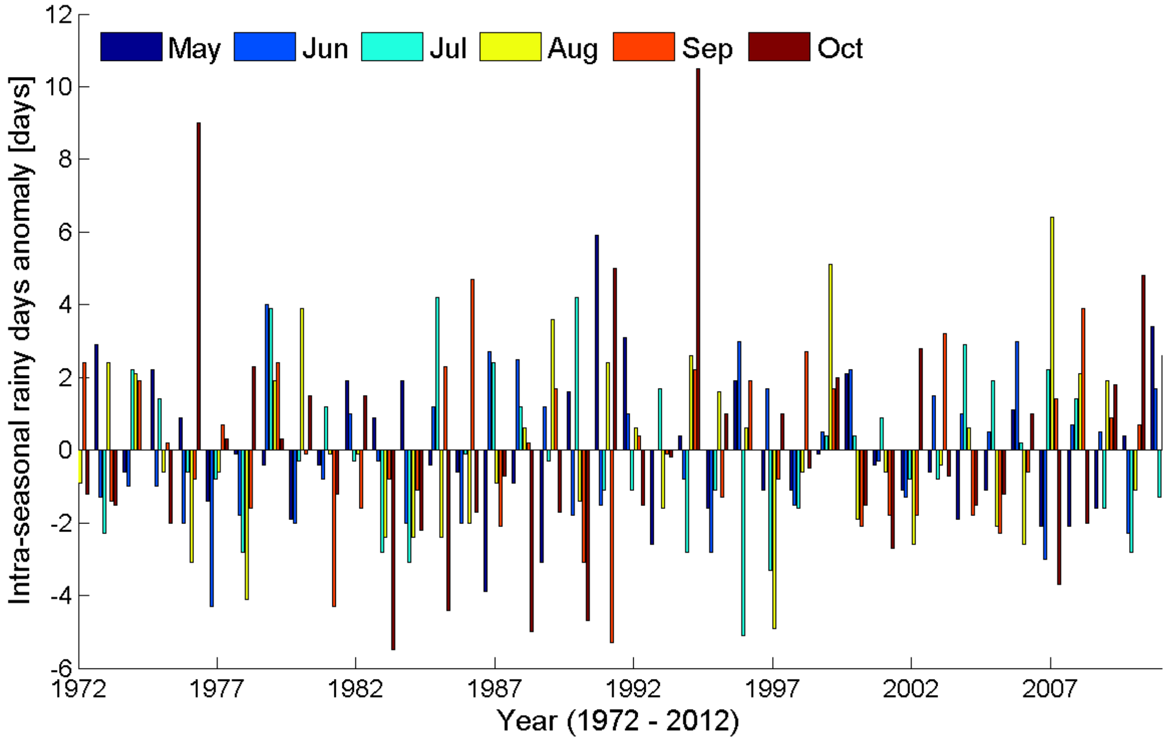


Figure 4.5: *Intra-annual rainy days anomaly showing variability during cropping season (May to Oct) in the study catchment (Data source: Ghana Meteorological Agency)*

4.3.4 Trend test and statistical analysis of rainfall data

Both Pettitt test and Hubert Segmentation test detected no change-points in all the fourteen datasets (annual plus monthly rainfall for May through October) of rainfall time series at confidence level of 99%. Similarly, Mann-Kendall test detected no trends in all these datasets of rainfall time series of the area at confidence level of 99%. Additionally, no significant change in variability of each of the fourteen datasets of rainfall time series was detected. In each of the analyses for individual time series, the value of F-ratio was lower than the critical F-value and falls in the lower 95% (non-rejection region) of the F-distribution. These further confirm the results of trend analysis above.

4.4 Flux estimation

The estimated streamflow for the catchment is as illustrated in figures 4.6, 4.7 and 4.8. The estimated streamflow shows an intermittent flow (Fig. 4.6 & Fig. 4.7) and that is because the area is an ephemeral catchment. The highest flows of about 20 m^3/s and 19 m^3/s in the entire time series occurred on the September 6th, 1999 and September 3rd, 1992. These are followed by a flow of about 16 m^3/s on September 17th, 1989, indicating that September marks the peak streamflow month in the catchment. The least flow years in the time series were 1977 and 1984 with annual highest flow of about 5 m^3/s each.

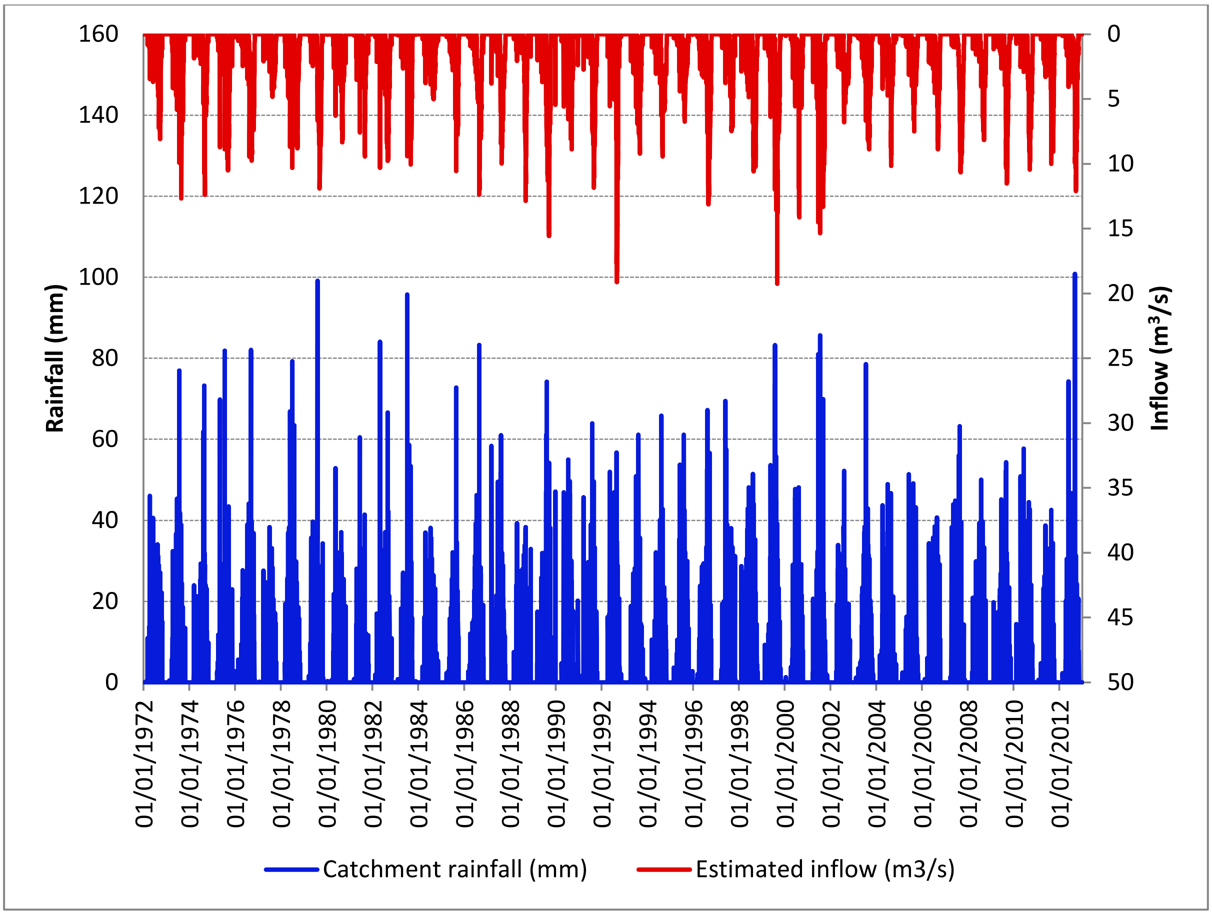


Figure 4.6: *Catchment areal rainfall and estimated streamflow in cubic meters per second for the Vea Catchment*

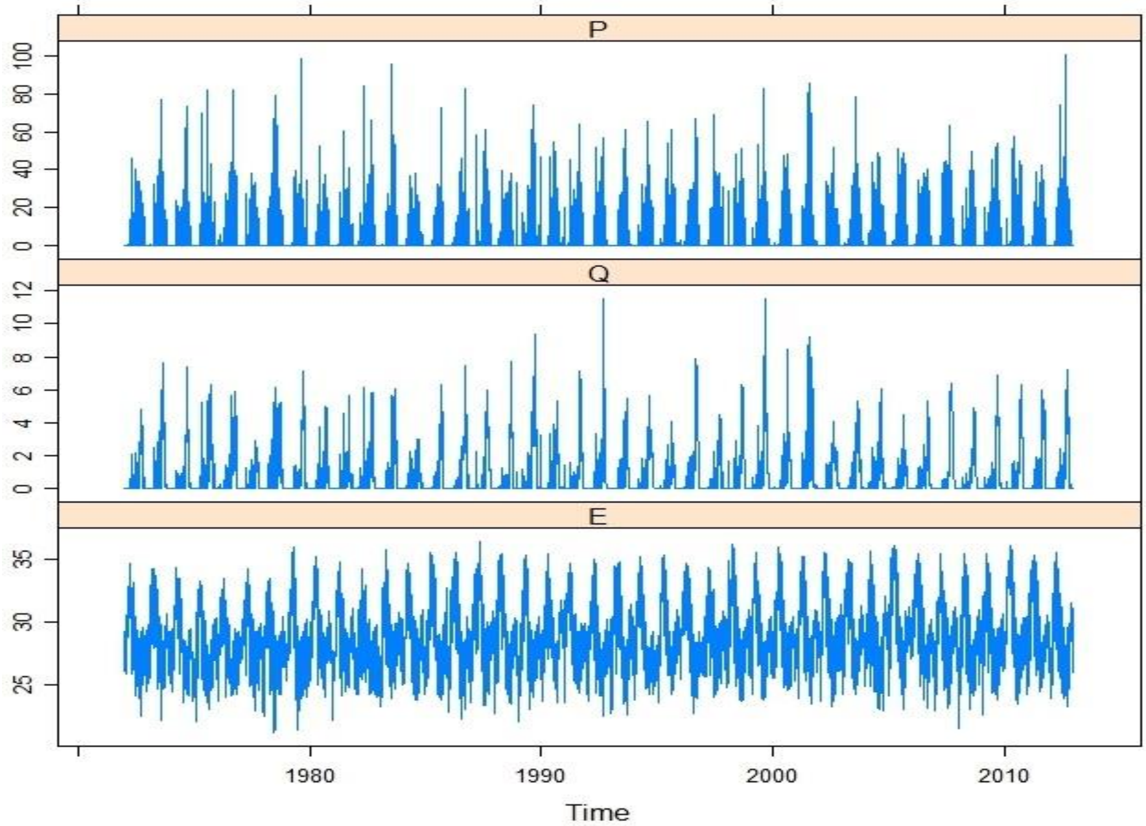


Figure 4.7: *Catchment areal rainfall, estimated streamflow in millimetres per day and temperature for the Vea Catchment*

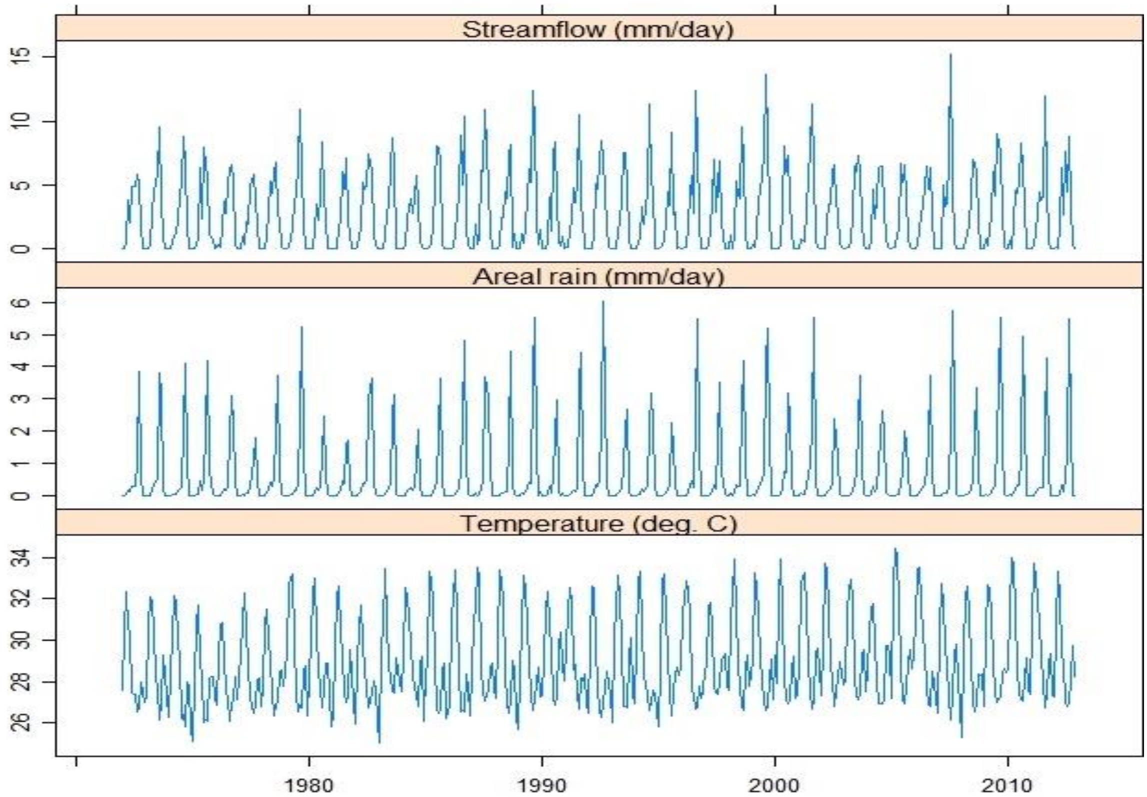
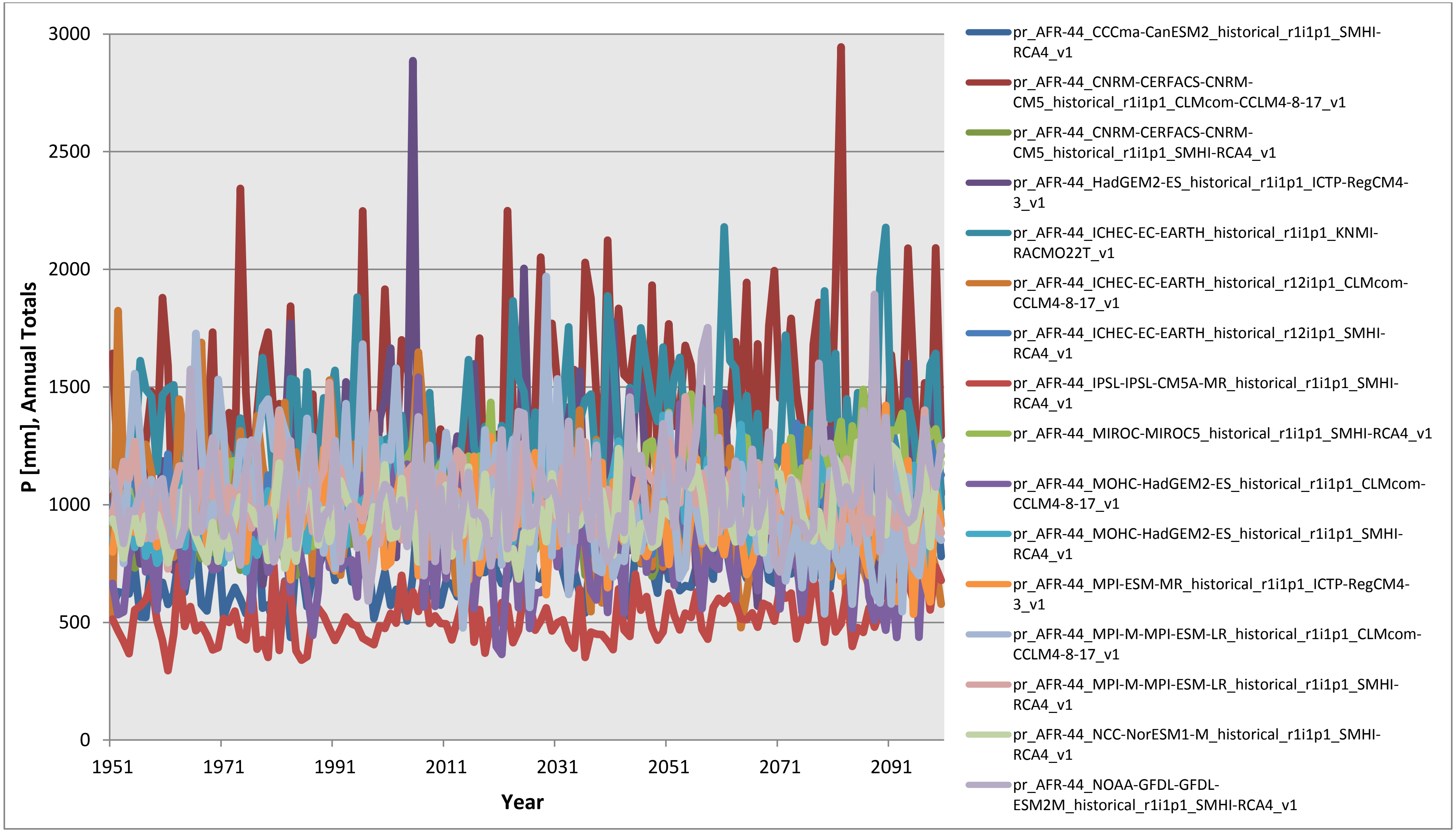


Figure 4.8: *Catchment areal monthly mean rainfall, monthly mean estimated streamflow in millimetres per day and monthly mean temperature for the Vea Catchment*

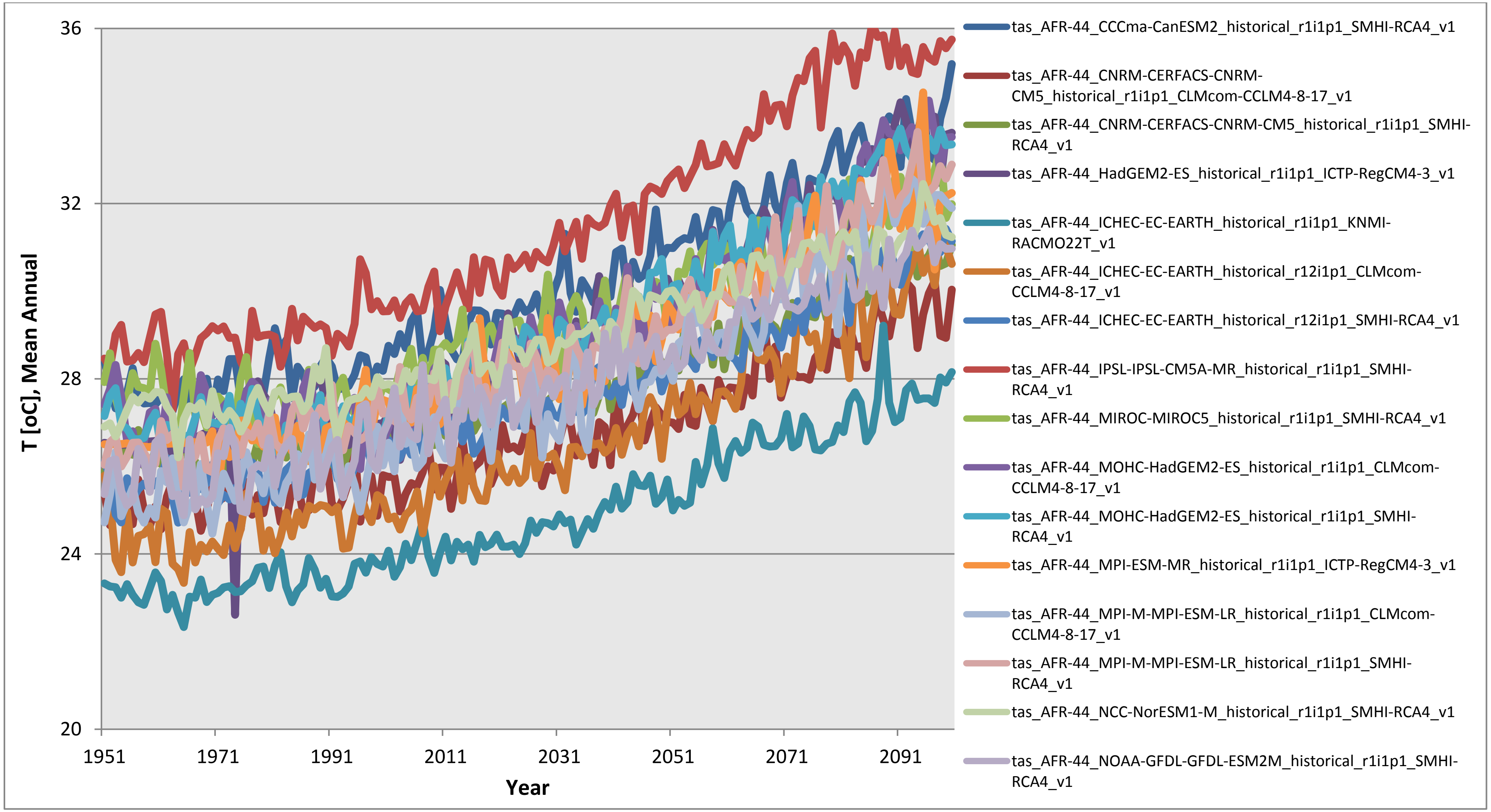
4.5 Raw (uncorrected) RCMs simulations

There were varied differences between the 16 RCMs simulated data. While the variations between some RCMs data could be regarded as marginal, variations between others, particularly the extremes were considerably large. For example, while the variation between the RCM simulated rainfall series by CNRM-CERFACS_SMHI-RCA4 and HadGEM2-ES_ICTP-RegCM4 as well as variation between those of MOHC-HadGEM2-ES_CLMcom-CCLM4 and MPI-ESM-MR_ICTP-RegCM4 are relatively marginal, the variation between the two extreme climate conditions (i.e. highest and lowest) of CNRM-CERFACS_CLMcom-CCLM4 and IPSL-IPSL-CM5A_SMHI-RCA4 are considerably large (see Fig. 4.9a). Similarly, the variation between the RCM simulated temperature data by MOHC-HadGEM2-ES_CLMcom-CCLM4 and MOHC-HadGEM2-ES_SMHI-RCA4 as well as variation between those of MPI-M-MPI-ESM-LR_SMHI-RCA4 and NCC-NorESM1-M_SMHI-RCA4 are relatively marginal, compared with the variation between the two high and low extreme climate conditions of IPSL-IPSL-CM5A_SMHI-RCA4 and ICHEC-EC-EARTH_KNMI-RACMO22T (see Fig. 4.9b). The biases associated with each of the RCMs simulations could therefore vary significantly in a similar pattern, necessitating bias correction of each of RCMs data.



3000
2500
2000
1500
1000
500
0
P [mm], Annual Totals
1951
1971
1991
2011
2031
2051
2071
2091
Year
pr_AFR-44_CCCma-CanESM2_historical_r1i1p1_SMHI-RCA4_v1
pr_AFR-44_CNRM-CERFACS-CNRM-CM5_historical_r1i1p1_CLMcom-CCLM4-8-17_v1
pr_AFR-44_CNRM-CERFACS-CNRM-CM5_historical_r1i1p1_SMHI-RCA4_v1
pr_AFR-44_HadGEM2-ES_historical_r1i1p1_ICTP-RegCM4-3_v1
pr_AFR-44_ICHEC-EC-EARTH_historical_r1i1p1_KNMI-RACMO22T_v1
pr_AFR-44_ICHEC-EC-EARTH_historical_r12i1p1_CLMcom-CCLM4-8-17_v1
pr_AFR-44_ICHEC-EC-EARTH_historical_r12i1p1_SMHI-RCA4_v1
pr_AFR-44_IPSL-IPSL-CM5A-MR_historical_r1i1p1_SMHI-RCA4_v1
pr_AFR-44_MIROC-MIROC5_historical_r1i1p1_SMHI-RCA4_v1
pr_AFR-44_MOHC-HadGEM2-ES_historical_r1i1p1_CLMcom-CCLM4-8-17_v1
pr_AFR-44_MOHC-HadGEM2-ES_historical_r1i1p1_SMHI-RCA4_v1
pr_AFR-44_MPI-ESM-MR_historical_r1i1p1_ICTP-RegCM4-3_v1
pr_AFR-44_MPI-M-MPI-ESM-LR_historical_r1i1p1_CLMcom-CCLM4-8-17_v1
pr_AFR-44_MPI-M-MPI-ESM-LR_historical_r1i1p1_SMHI-RCA4_v1
pr_AFR-44_NCC-NorESM1-M_historical_r1i1p1_SMHI-RCA4_v1
pr_AFR-44_NOAA-GFDL-GFDL-ESM2M_historical_r1i1p1_SMHI-RCA4_v1

(a)

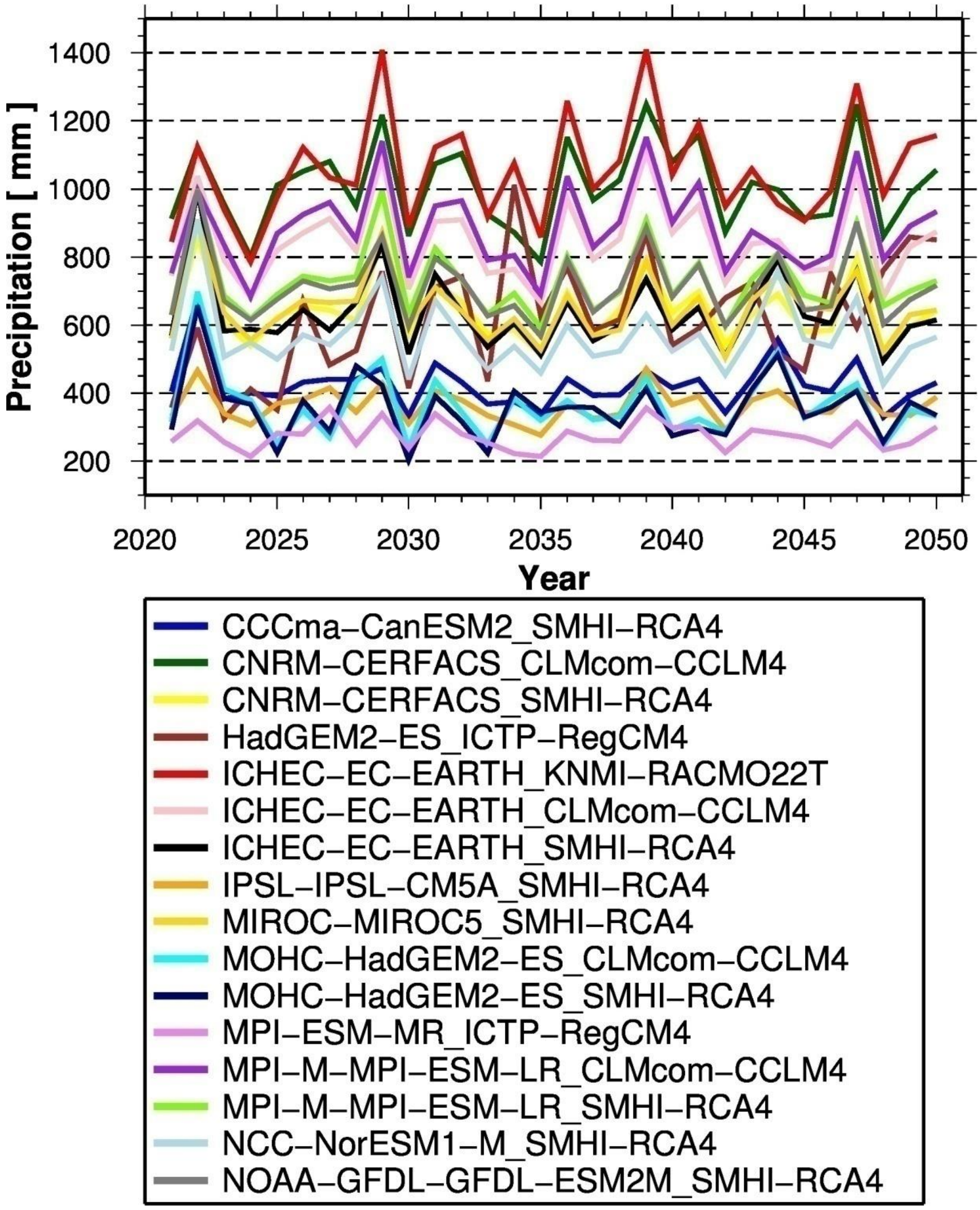


(b)

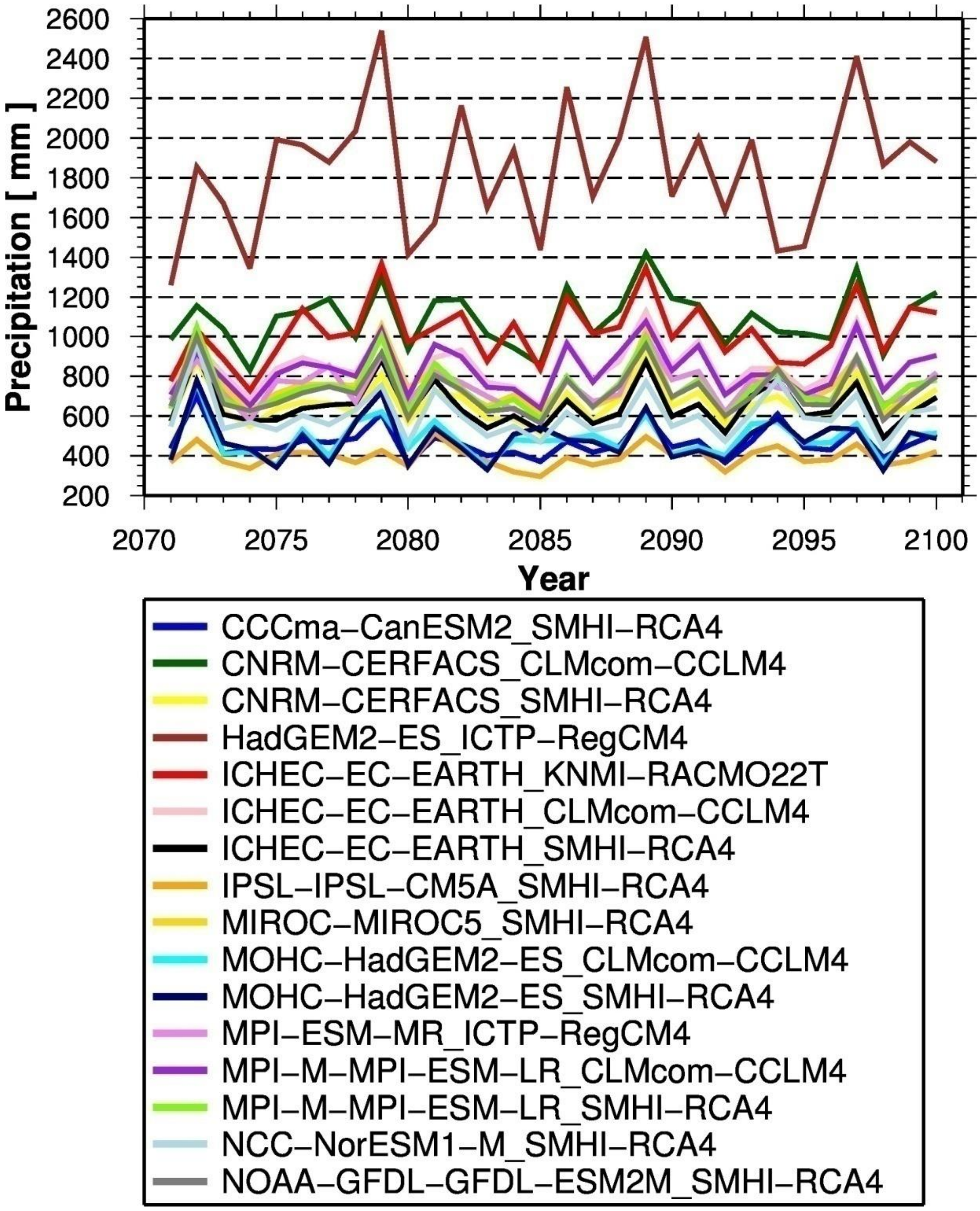
Figure 4.9: *The raw (uncorrected) RCMs-simulated rainfall (a) and temperature (b) of both the control run (1951-2005) and scenario RCP8.5 (2006-2100) for the Vea catchment*

4.6 Bias (delta-change) correction of rainfall and temperature

The results of the bias-corrected RCMs-simulated rainfall and temperature are as presented in figures 4.12 and 4.13 respectively. The figures 4.12(a) and 4.12(b) illustrate the time series of annual total rainfall of the climate conditions in the two time slices under consideration, 2021-2050 and 2071-2100 respectively. Similarly, the figures 4.13(a) and 4.13(b) also illustrate the time series of annual mean temperature of the climate conditions in the two time slices, 2021-2050 and 2071-2100 respectively. Considerable varied differences between the 16 RCMs simulated data still persist despite the bias corrections. However, variances between each pair of RCMs simulations are now different from what exist in the uncorrected RCMs data (Fig. 4.9). For instance, the simulated rainfall series by IPSL-IPSL-CM5A_SMHI-RCA4, MOHC-HadGEM2-ES_CLMcom-CCLM4 and MOHC-HadGEM2-ES_SMHI-RCA4 for the period 2021-2050 are very similar with relatively marginal variances between them. The same similarity could be seen between rainfall time series simulated by ICHEC-EC-EARTH_SMHI-RCA4 and MIROC-MIROC5_SMHI-RCA4 for the same period (Fig. 4.10a). On the other hand, it is the simulated rainfall series by MIROC-MIROC5_SMHI-RCA4, MPI-ESM-MR_ICTP-RegCM4 and MPI-M-MPI-ESM-LR_SMHI-RCA4 for the period 2071-2100 that are similar with relatively marginal variance. Also similarities exist between rainfall time series simulate by ICHEC-EC-EARTH_SMHI-RCA4 and CNRM-CERFACS_SMHI-RCA4 as well as between MOHC-HadGEM2-ES_CLMcom-CCLM4 and MOHC-HadGEM2-ES_SMHI-RCA4 for the same period of 2071-2100. The extreme climate conditions (i.e. highest and lowest) in the two time slices are also different. For the near future (2021-2050), the extreme climate conditions of highest and lowest rainfall time series were simulations by ICHEC-EC-EARTH_KNMI-RACMO22T and MPI-ESM-MR_ICTP-RegCM4 respectively, while for the distance future (2071-2100), the highest and lowest rainfall time series were derived by HadGEM2-ES_ICTP-RegCM4 and IPSL-IPSL-CM5A_SMHI-RCA4 RCMs respectively (Fig. 4.10b).


1400
1200
1000
800
600
400
200
Precipitation [mm]
2020
2025
2030
2035
2040
2045
2050
Year
CCCma-CanESM2_SMHI-RCA4
CNRM-CERFACS_CLMcom-CCLM4
CNRM-CERFACS_SMHI-RCA4
HadGEM2-ES_ICTP-RegCM4
ICHEC-EC-EARTH_KNMI-RACMO22T
ICHEC-EC-EARTH_CLMcom-CCLM4
ICHEC-EC-EARTH_SMHI-RCA4
IPSL-IPSL-CM5A_SMHI-RCA4
MIROC-MIROC5_SMHI-RCA4
MOHC-HadGEM2-ES_CLMcom-CCLM4
MOHC-HadGEM2-ES_SMHI-RCA4
MPI-ESM-MR_ICTP-RegCM4
MPI-M-MPI-ESM-LR_CLMcom-CCLM4
MPI-M-MPI-ESM-LR_SMHI-RCA4
NCC-NorESM1-M_SMHI-RCA4
NOAA-GFDL-GFDL-ESM2M_SMHI-RCA4

(a)

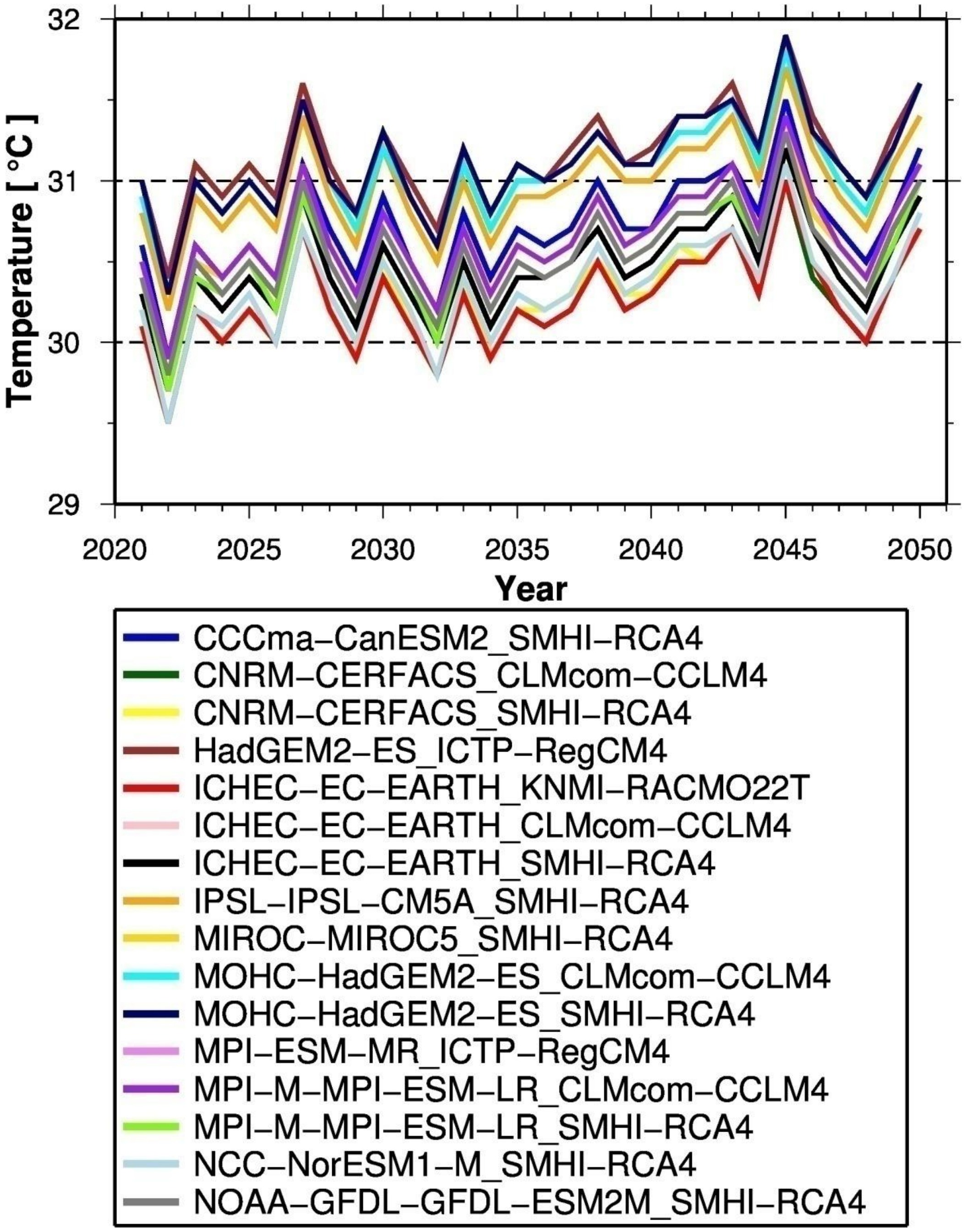


(b)

Figure 4.10: *The bias corrected RCMs-simulated rainfall of the scenario RCP8.5 for the Vea catchment. The (a) depicts the rainfall time series of each of the corrected 16 RCMs data of the climate conditions for 2021-2050, while (b) illustrates the rainfall time series of each of the corrected 16 RCMs data of the climate conditions for 2071-2100.*

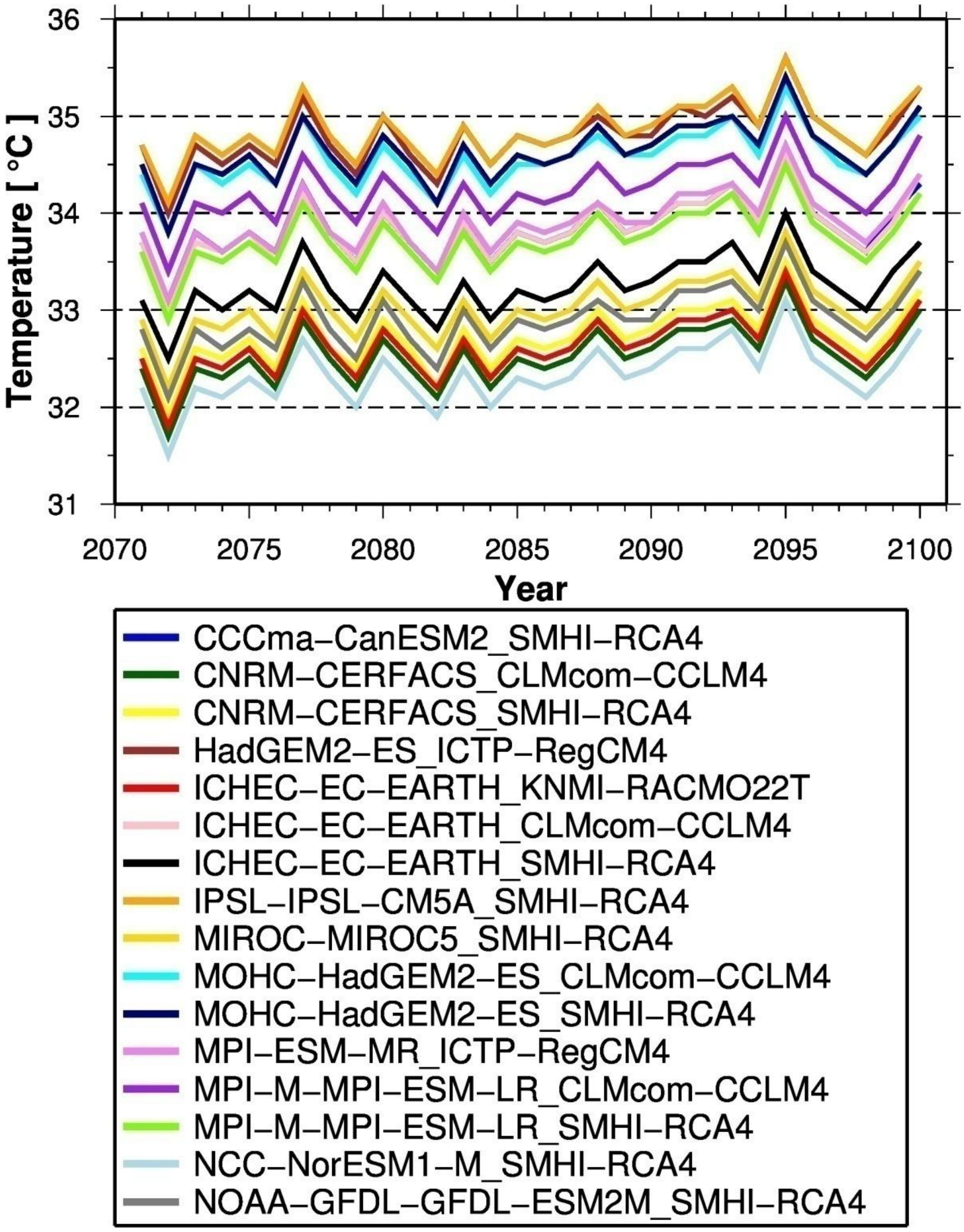
With regards to temperature, the extreme climate conditions of highest and lowest time series for the near future (2021-2050) were simulations by HadGEM2-ES_ICTP-RegCM4 and NCC-NorESM1-M_SMHI-RCA4 respectively (Fig. 4.11a), while for the distance future (2071-2100) the highest and lowest temperature time series were derived by IPSL-IPSL-CM5A_SMHI-RCA4 and NCC-NorESM1-M_SMHI-RCA4 respectively (Fig. 4.11b).

Notably, in both future time slices, the lowest temperature time series were derived by the same model, NCC-NorESM1-M_SMHI-RCA4. Four different sets of bias-corrected RCMs simulated temperature data for the period 2021-2050 are distinctively similar. These include simulations by ICHEC-EC-EARTH_CLMcom-CCLM4, ICHEC-EC-EARTH_SMHI-RCA4, MPI-ESM-MR_ICTP-RegCM4, MPI-M-MPI-ESM-LR_SMHI-RCA4 and NOAA-GFDL-GFDL-ESM2M_SMHI-RCA4 as one set, CNRM-CERFACS_CLMcom-CCLM4, CNRM-CERFACS_SMHI-RCA4, ICHEC-EC-EARTH_KNMI-RACMO22T and NCC-NorESM1-M_SMHI-RCA4 as another. Other sets include simulations by MPI-M-MPI-ESM-LR_CLMcom-CCLM4, MIROC-MIROC5_SMHI-RCA4 and CCCma-CanESM2_SMHI-RCA4, as well as a set of simulations by MOHC-HadGEM2-ES_SMHI-RCA4, MOHC-HadGEM2-ES_CLMcom-CCLM4, IPSL-IPSL-CM5A_SMHI-RCA4 and HadGEM2-ES_ICTP-RegCM4. Variations between temperature times series in each of these sets of RCMs simulations are relatively marginal compared with variations between simulations in different sets (Fig. 4.11a). The bias-corrected RCMs simulated temperature times series for the distance future (2071-2100) are rather more diverse with fewer similarities. The simulated temperature times series of all the 16 RCMs for the two future time slices (2021-2050 & 2071-2100) show increasing trend, indicating the certainty about temperature rise in the catchment (Fig. 4.11a & Fig. 4.11b).



32
31
30
29
Temperature [°C]
2020
2025
2030
2035
2040
2045
2050
Year
CCCma−CanESM2_SMHI−RCA4
CNRM−CERFACS_CLMcom−CCLM4
CNRM−CERFACS_SMHI−RCA4
HadGEM2−ES_ICTP−RegCM4
ICHEC−EC−EARTH_KNMI−RACMO22T
ICHEC−EC−EARTH_CLMcom−CCLM4
ICHEC−EC−EARTH_SMHI−RCA4
IPSL−IPSL−CM5A_SMHI−RCA4
MIROC−MIROC5_SMHI−RCA4
MOHC−HadGEM2−ES_CLMcom−CCLM4
MOHC−HadGEM2−ES_SMHI−RCA4
MPI−ESM−MR_ICTP−RegCM4
MPI−M−MPI−ESM−LR_CLMcom−CCLM4
MPI−M−MPI−ESM−LR_SMHI−RCA4
NCC−NorESM1−M_SMHI−RCA4
NOAA−GFDL−GFDL−ESM2M_SMHI−RCA4

(a)



(b)

Figure 4.11: *The bias corrected RCMs-simulated temperature of the scenario RCP8.5 for the Vea catchment. The (a) depicts the temperature time series of each of the corrected 16 RCMs data of the climate conditions for 2021-2050, while (b) illustrates the temperature time series of each of the corrected 16 RCMs data of the climate conditions for 2071-2100.*

4.7 Evapotranspiration

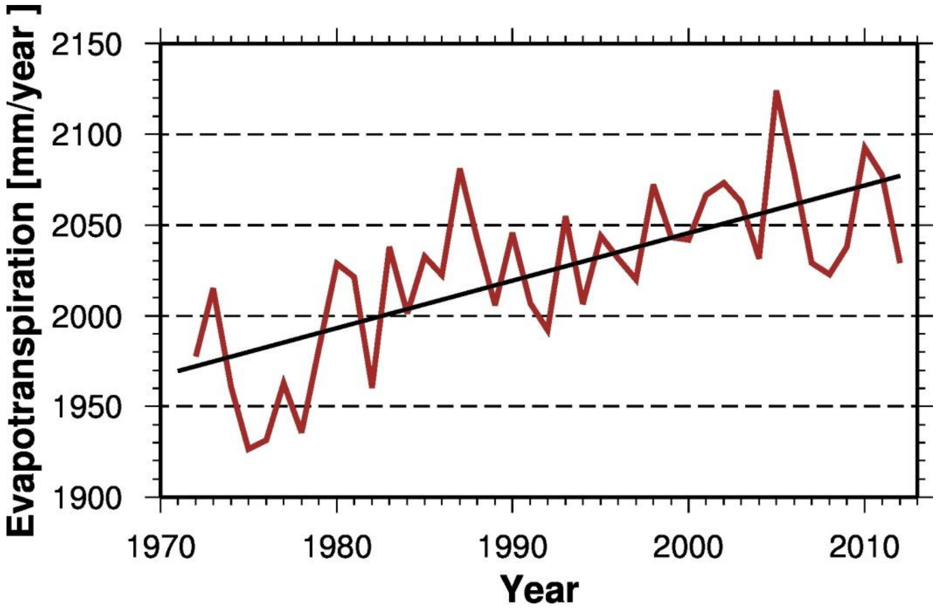


Figure 4.12: *Annual evapotranspiration trend in the catchment*

There is a clear evidence of positive and persistent increasing trend in evapotranspiration (ET) in the study area as illustrated by figure 4.12. No statistical testing of the data was required since ET is based on temperature which was tested accordingly. The maximum and minimum of the monthly long-term averages for the study period were 244 mm and 132 mm and occur in April and August respectively while the maximum and minimum of the annual totals were 2124 mm and 1926 mm and occur in 2005 and 1975 respectively. The balance between annual rainfall and ET remains negatively high in the catchment – often considerably higher than the annual total rainfall (Fig. 4.13).

The situation will most likely persist far into the future as both the average and extreme RCMs-simulated conditions show a continuous increasing trend in ET across the entire 21st century (Fig. 4.14 a & b). Figure 4.14 (a) indicates that between now and the year 2021, annual ET will most likely rise by about an average of 150 mm and by about an average of 200 mm between now and the year 2050. Similarly, figure 4.14 (b) depicts that an annual ET will increase by about an average of 400 mm and 500 mm between now and the years 2071 and 2100 respectively.

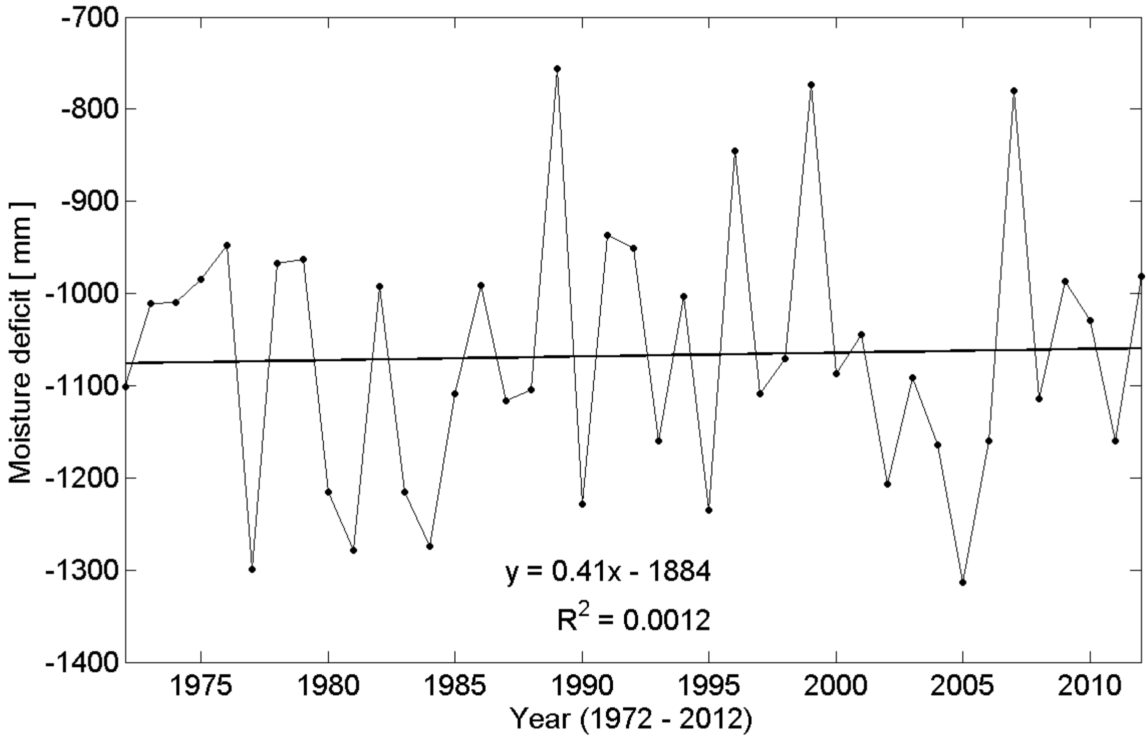


Figure 4.13: *The balance between rainfall and evapotranspiration (annual moisture deficit) in the catchment*

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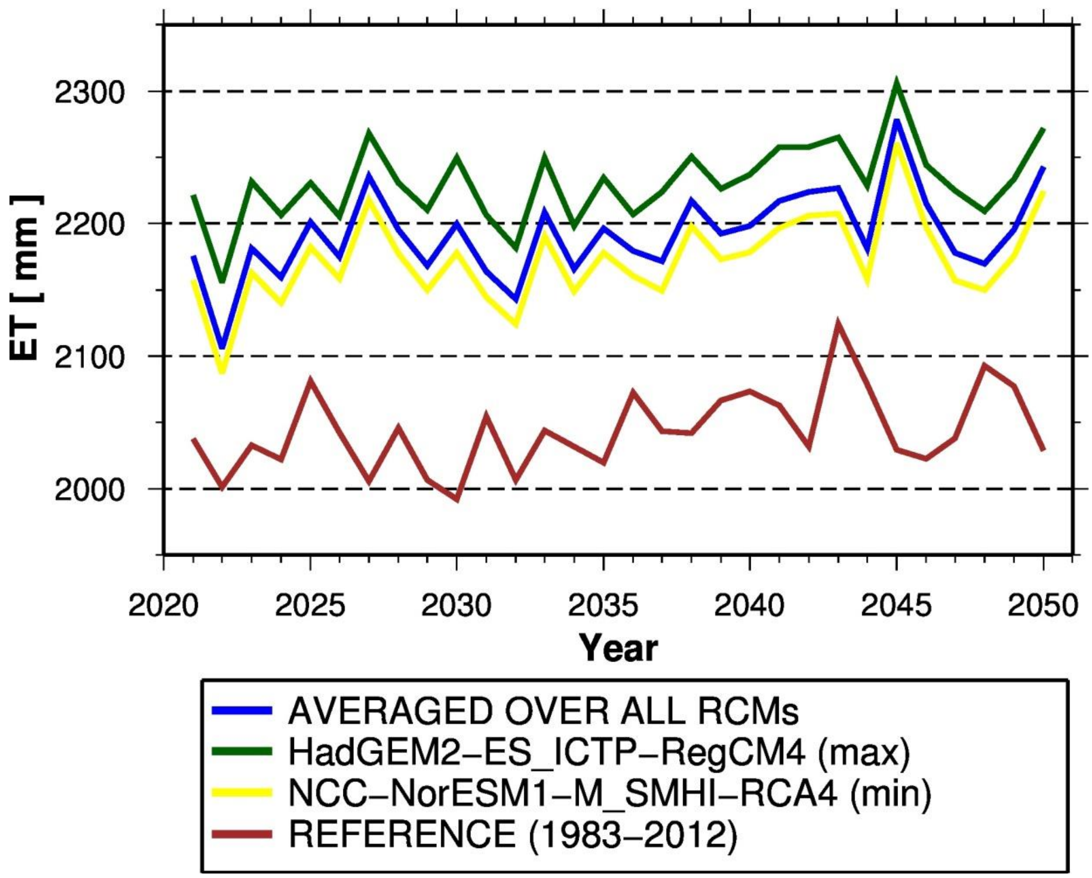
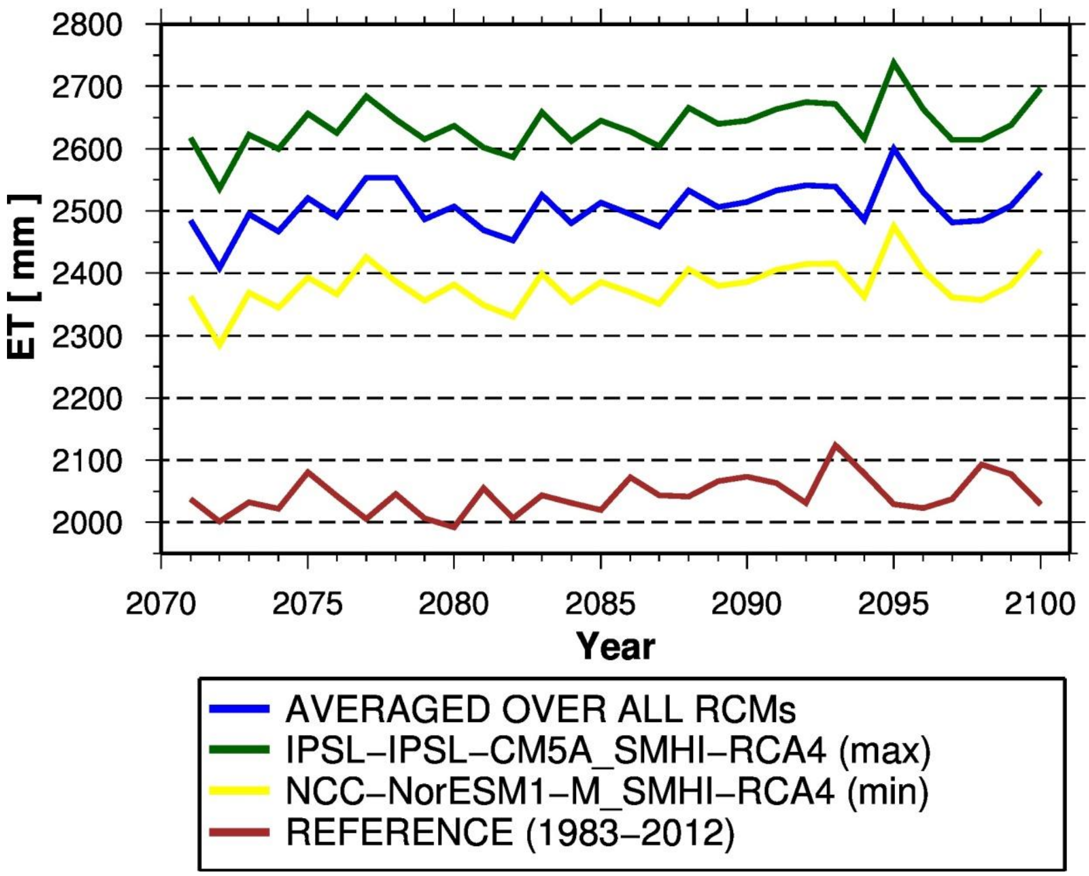


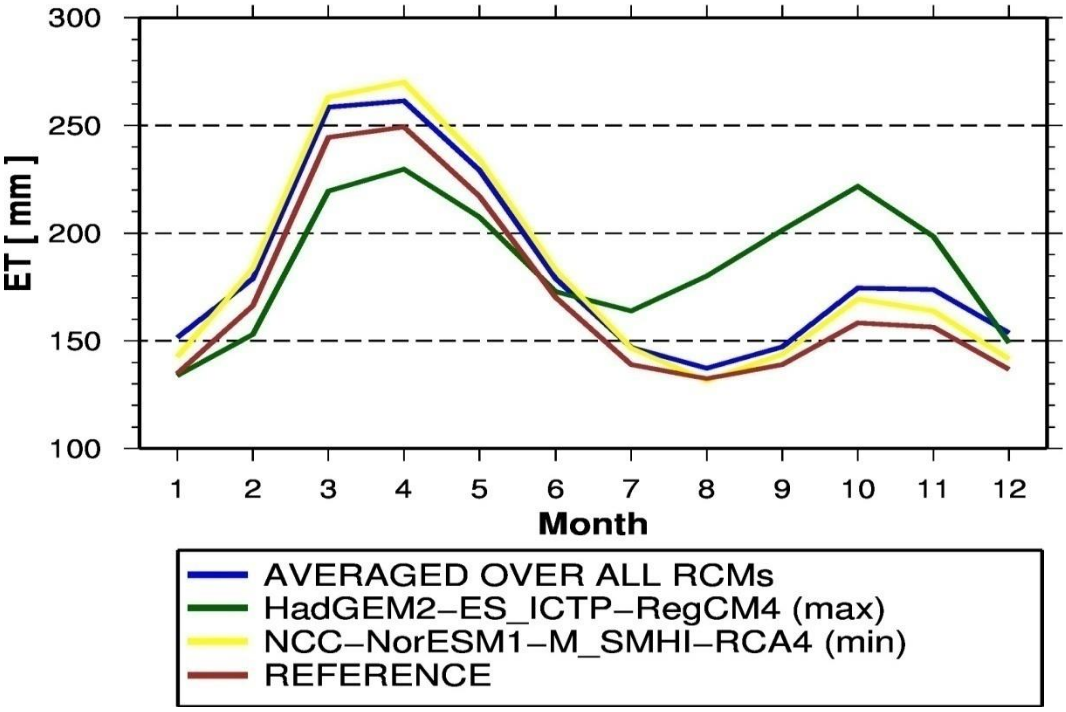
(a)



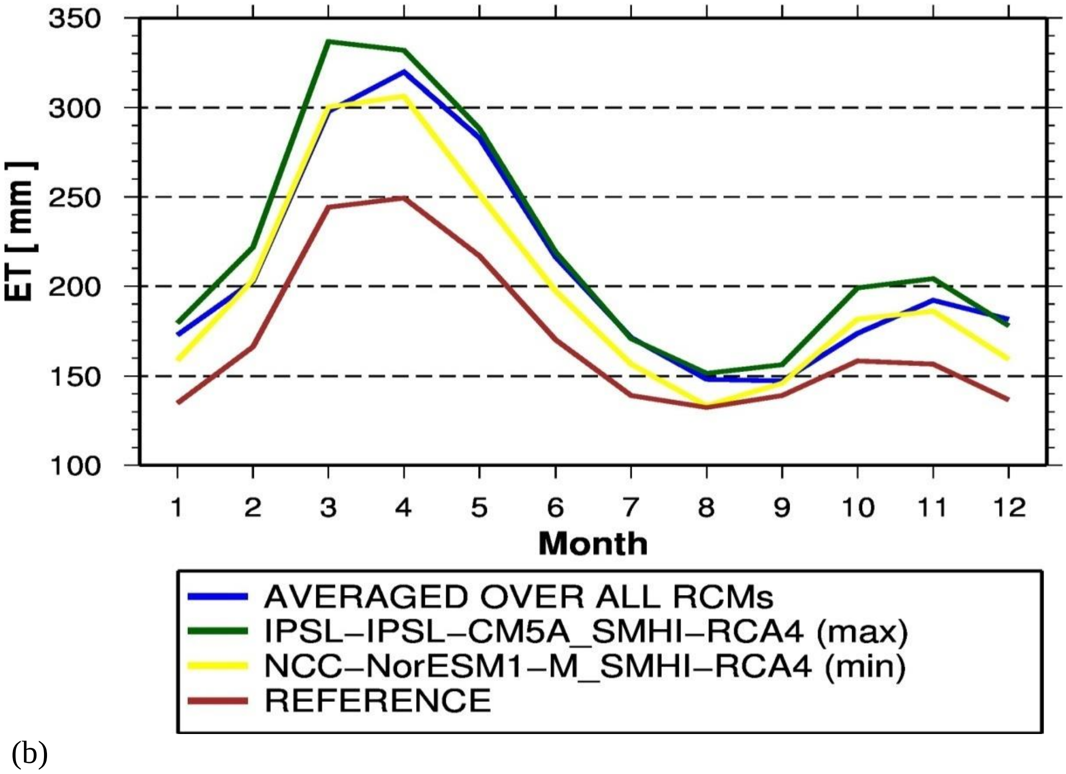
(b)

Figure 4.14: *Annual evapotranspiration of the two simulated extreme future temperature time series (the highest and the lowest) and of temperature averaged over the 16 RCMs-simulated future climate conditions compared with the annual evapotranspiration of reference temperature (1983-2012). The (a) presents the annual evapotranspiration of each of the four temperature time series for the near future (2021-2050), while (b) presents the annual evapotranspiration of each of the four temperatures time series for the near future (2071-2100).*

The comparison of 30-year long-term monthly average ET estimated from the RCMs-simulated climate conditions with that of the reference condition, also indicates considerable increases in monthly average ET across all months in a year in both the near future (Fig. 4.15a) and the distance future (Fig. 4.15b) periods.



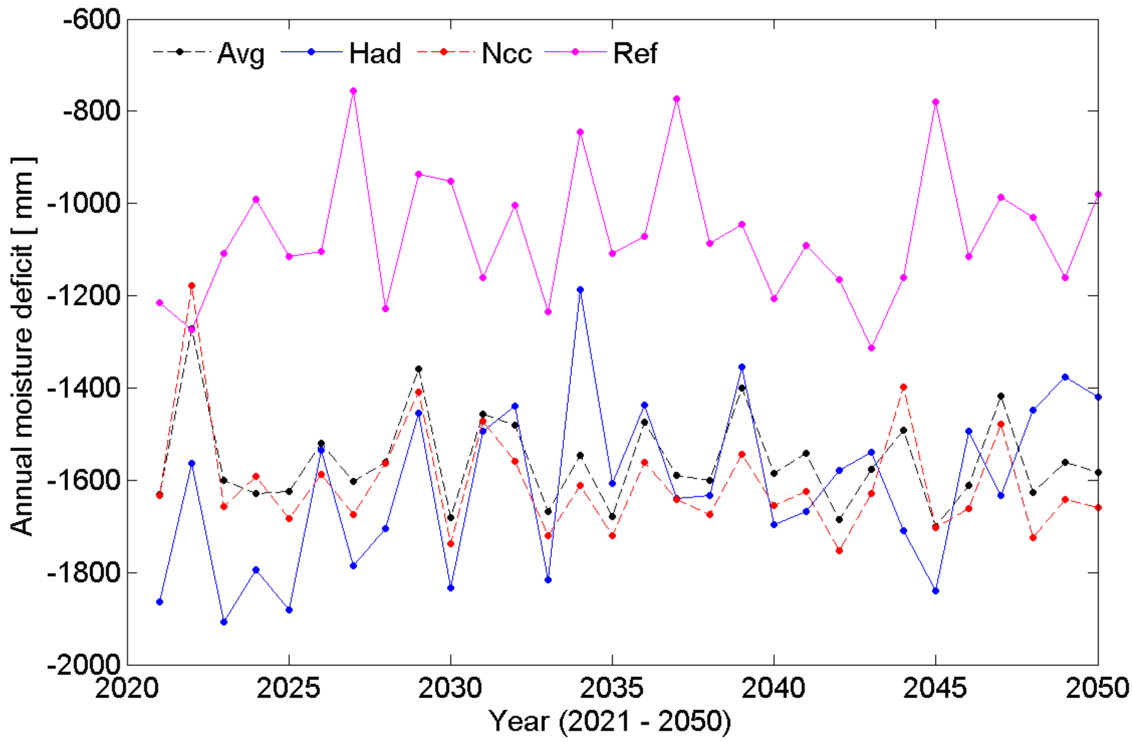
(a)



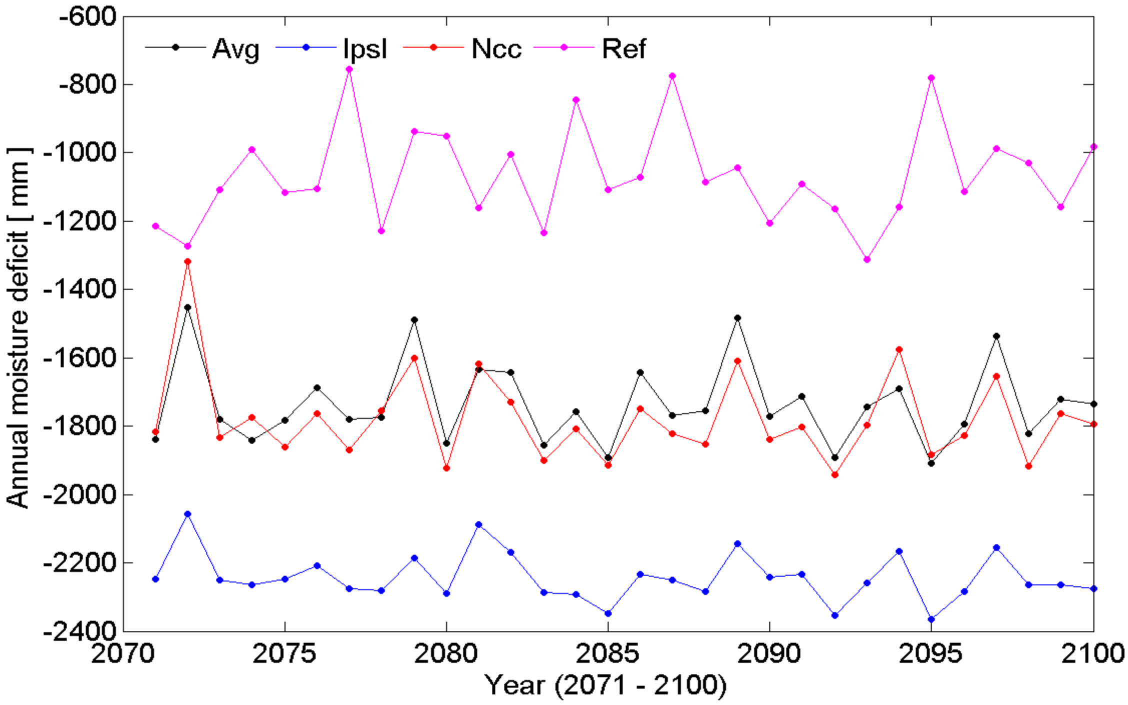
(b)

Figure 4.15: *The 30-year long-term monthly average evapotranspiration of two simulated extreme future temperature time series and of temperature averaged over the 16 RCMs-simulated future climate conditions compared with that of reference temperature (1983-2012). The (a) presents the monthly average evapotranspiration of each of the four temperature time series for the near future (2021-2050), while (b) presents the monthly average evapotranspiration of each of the four temperatures time series for the near future (2071-2100).*

The annual moisture deficit will increase much higher in the catchment considering the various RCMs-simulated climate conditions of the future. Figure 4.16 (a) and (b) depict that the annual moisture deficit could rise as high as more than twice the annual total rainfall. Figure 4.16(b) indicates that the situation could be severer in the distance future (2071-2100), especially if the climate conditions evolve as predicted by the extreme RCMs-simulated conditions (blue in Fig. 4.16b). In the near future period of 2021-2050, the annual moisture deficit derived from all the three RCMs-simulated conditions under review (red, blue and black in Fig. 4.16a) shows a convergence at an average of about 1600 mm. For the distance future (2071-2100), the annual moisture deficit derived from two of the three RCMs-simulated conditions under review (red and black in Fig. 4.16b) shows a convergence at an average of about 1750 mm, while the extreme RCMs-simulated condition (blue in Fig. 4.16b) within the period indicates higher average annual moisture deficit of about 2300 mm. These point to indications that between now and the year 2021, annual moisture deficit will most likely rise by about an average of 500 mm and by about an average of 650 mm between now and the year 2071 (Fig. 4.16a & b).



(a)

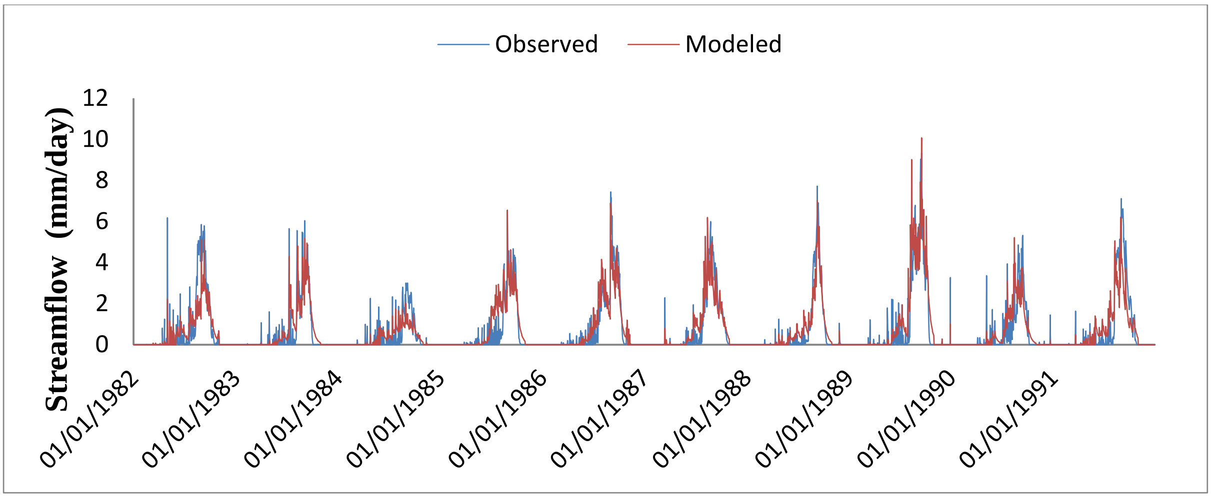


(b)

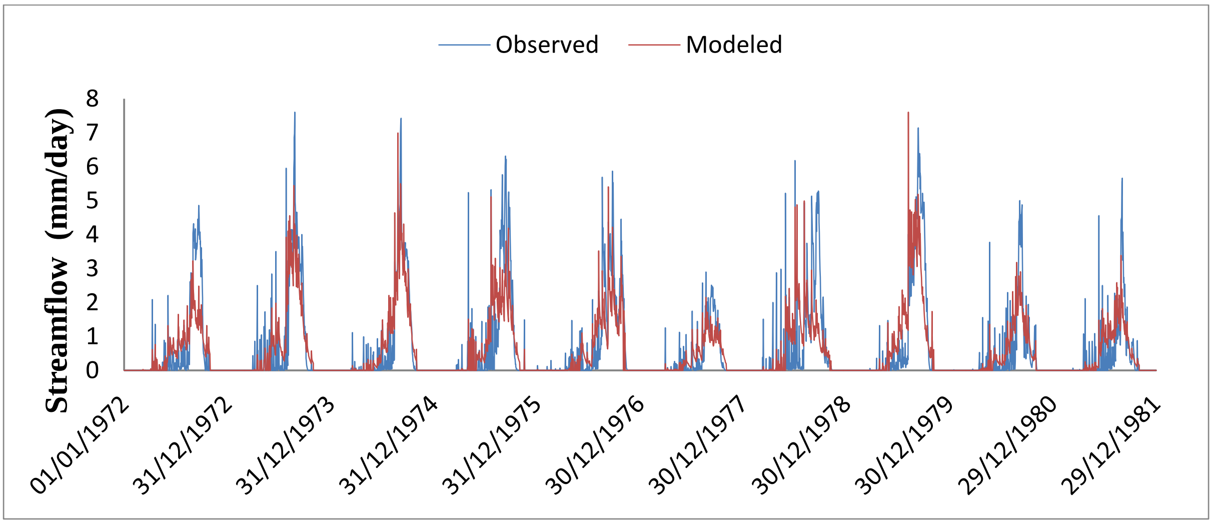
Figure 4.16: *The annual moisture deficit associated with the two simulated extreme future temperature time series and temperature averaged over the 16 RCMs-simulated future climate conditions compared with the reference period (1983-2012). The (a) presents the annual moisture deficit associated with each of the four temperature time series for the near future (2021-2050), while (b) presents the annual moisture deficit associated with each of the four temperatures time series for the near future (2071-2100).*

4.8 Model calibration and validation

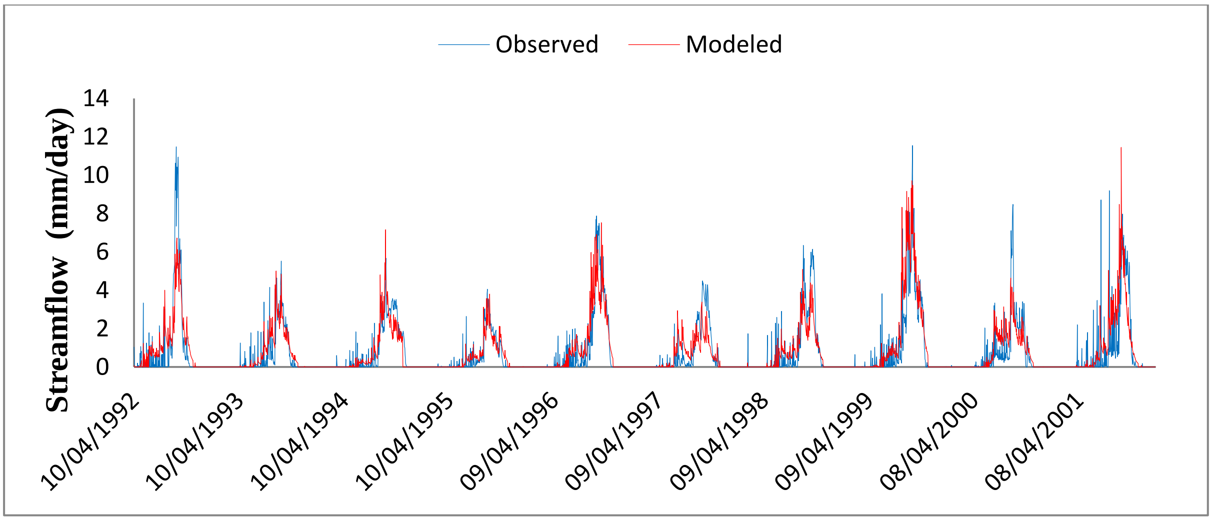
Results from both the calibration and validation of the IHACRES CWI model for the catchment are presented in figure 4.17 below. The figures 4.17a, 4.17b and 4.17c show the calibration period 1982-1991 and the validation periods of 1972-1981 and 1992-2001 respectively.



(a)



(b)



(c)

Figure 4.17: *Calibration period (a) and validation periods (b) and (c) from IHACRES CWI model showing observed and modelled time series.*

4.9 Model performance assessment

The summary of results of the performance assessment obtained from the calibration and validation of the IHACRES CWI rainfall-runoff model is as presented in Table 4.1. The summary gives the statistical performance evaluations defined by the four statistical methods used in this study as described in chapter 3 (subsection 3.3.8.3). This included results of performance assessment based on verification using data for the entire study period under review (1972-2012). The results of all the four performance assessment methods showed that the calibrated model reproduced the observed flows quite well and the overall model performance at the catchment was deemed satisfactory when compared with assessment standards. The results of both *r.squared* and *r.sq.sqrt* methods are relatively more satisfactory and show similarity in the performance of the model during the calibration and first validation periods as well as during the final verification with entire period 1972-2012. This was a proof of how well the fitted model was likely to predict future streamflows with input data from RCMs simulations. Figure 4.18 presents a plot of performance statistics over time in regular 2 year blocks from three of the statistical methods for simulation (verification) over the entire data period (1972-2012), showing also the runoff coefficient and observed streamflow data. Similarity between the results of both *r.squared* and *r.sq.sqrt* is further shown clearly from figure 4.18, particularly in the trend, as in between 1972-1979, 1982-1987 and 1994-2012.

The runoff coefficient is shown to be lowest between 1980-1981, with other relatively low values between 1984-1985 and 2004-2005. The highest runoff coefficient is shown to have occurred between 1998 and 1999 and in the last year of the period under review, 2012. The highly responsive regime of the upper part of the study catchment of area 143.94 km^2 which drains to feed Vea Irrigation Dam reservoir is shown by the high runoff coefficient in most of the year with an average of 0.2588 found for the calibration period.

The performance of the model during the verification with the entire data set of the study period as illustrated in Table 4.1 and figure 4.18 showed that the IHACRES CWI model was well fitted and satisfactorily captured the streamflows in the catchment. The fitted model was then used to estimate future streamflow for the catchment using the bias corrected rainfall and temperature time series of the RCMs simulations as shown in the next subsection. The calibrated parameter values of the IHACRES model depict the rainfall-runoff dynamic response characteristics of the catchment as shown in Table 4.2.

Table 4.1: *Performance statistics for entire study period (1972-2012)*

PERIOD	STATISTICAL METHOD			
	rel.bias	r.squared	r.sq.sqrt	r.sq.log
Calibration (1982-1991)	0.05	0.79	0.78	0.65
1st Validation (1972-1981)	-0.02	0.68	0.67	0.53
2nd Validation (1992-2001)	0.04	0.81	0.75	0.61
Verification (1972-2012)	0.00	0.75	0.74	0.62

Table 4.2: *The rainfall-runoff dynamic response characteristics of the catchment*

Calibrated Parameters					
Non-linear module			Routing module		
τ_w [days]	f [1/°C]	*1/c* [mm]	τ_q[days]	τ_s [days]	v_s [unitless]
4.3	1.892	176	0.6	25	0.13

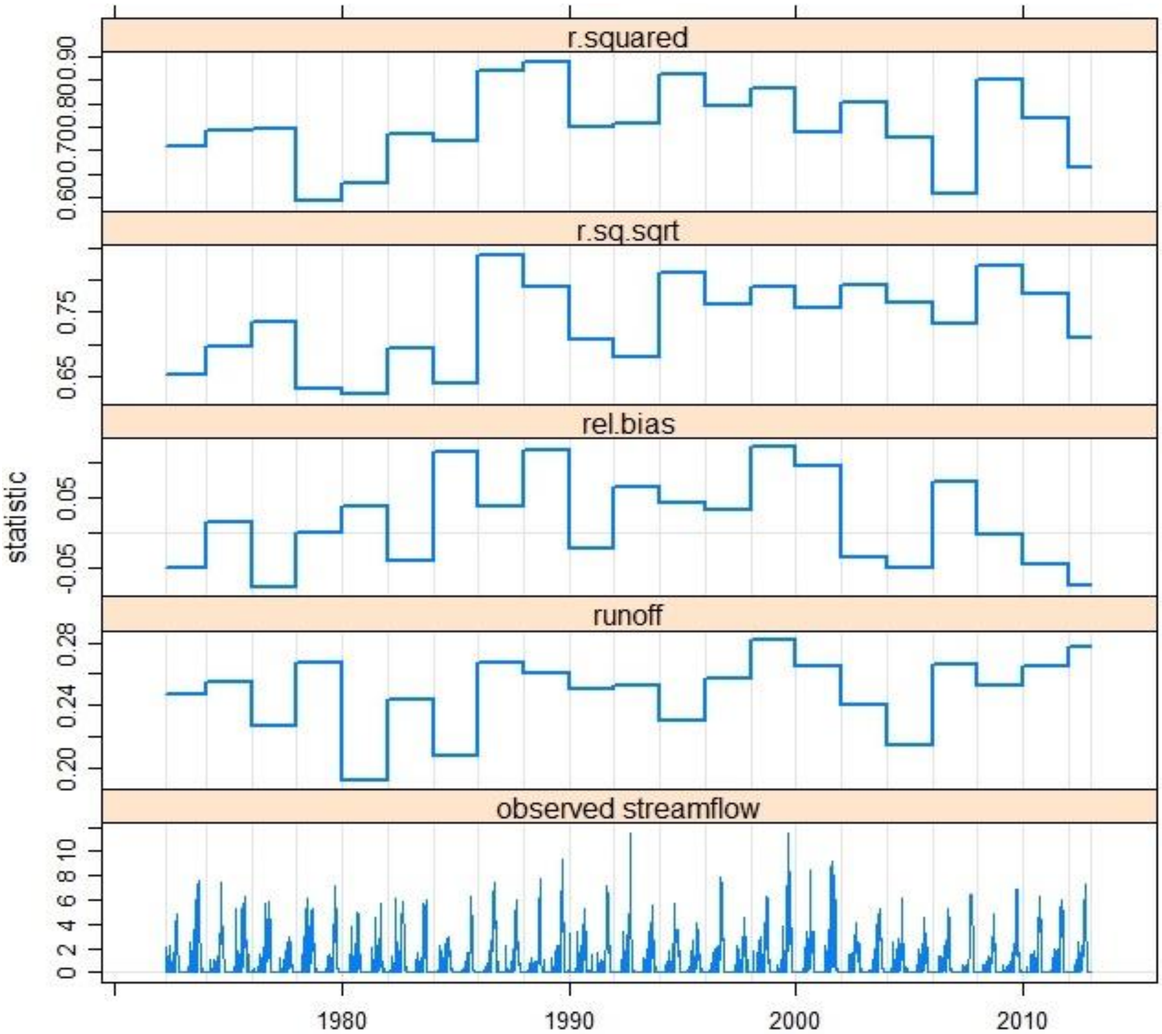
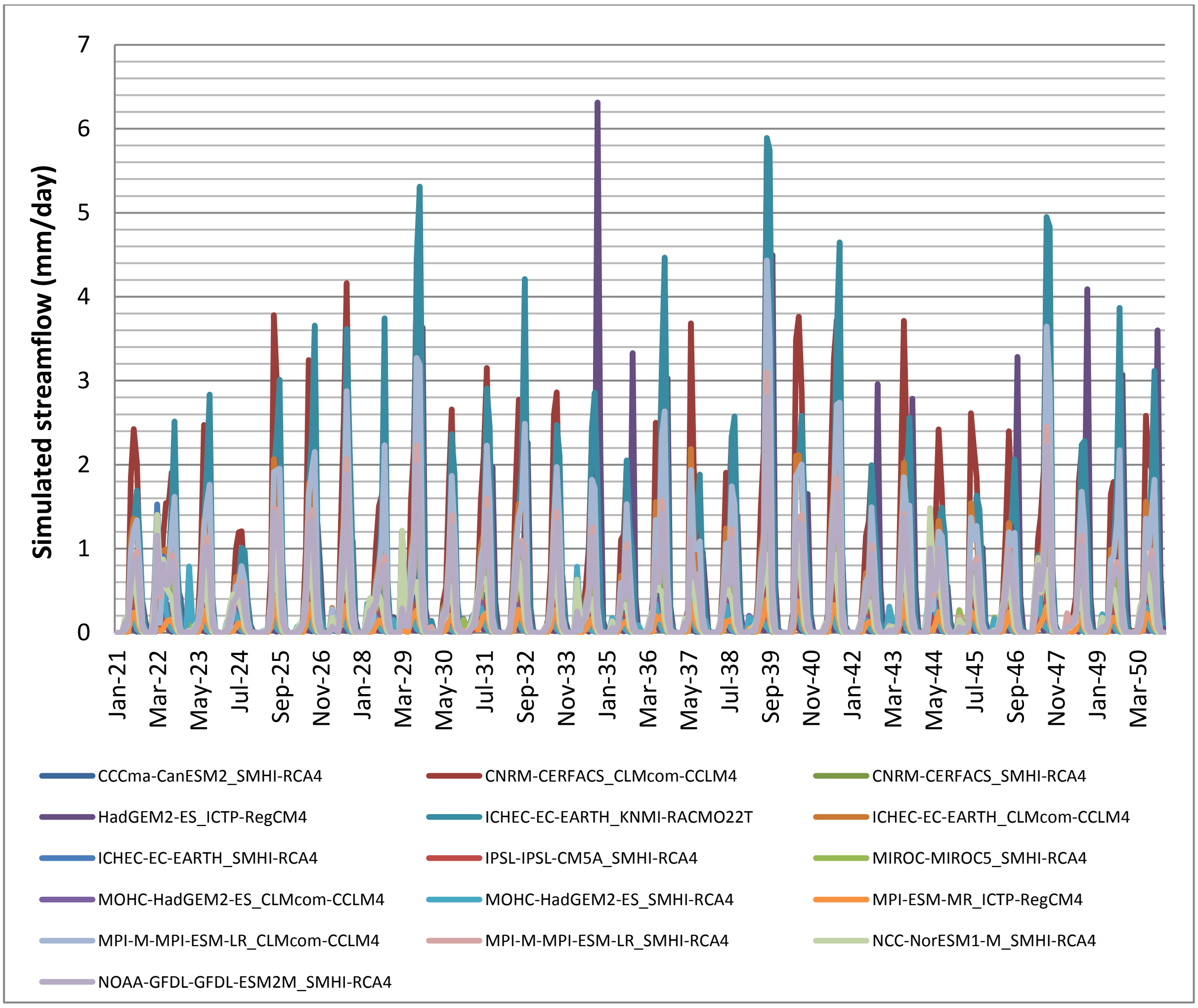


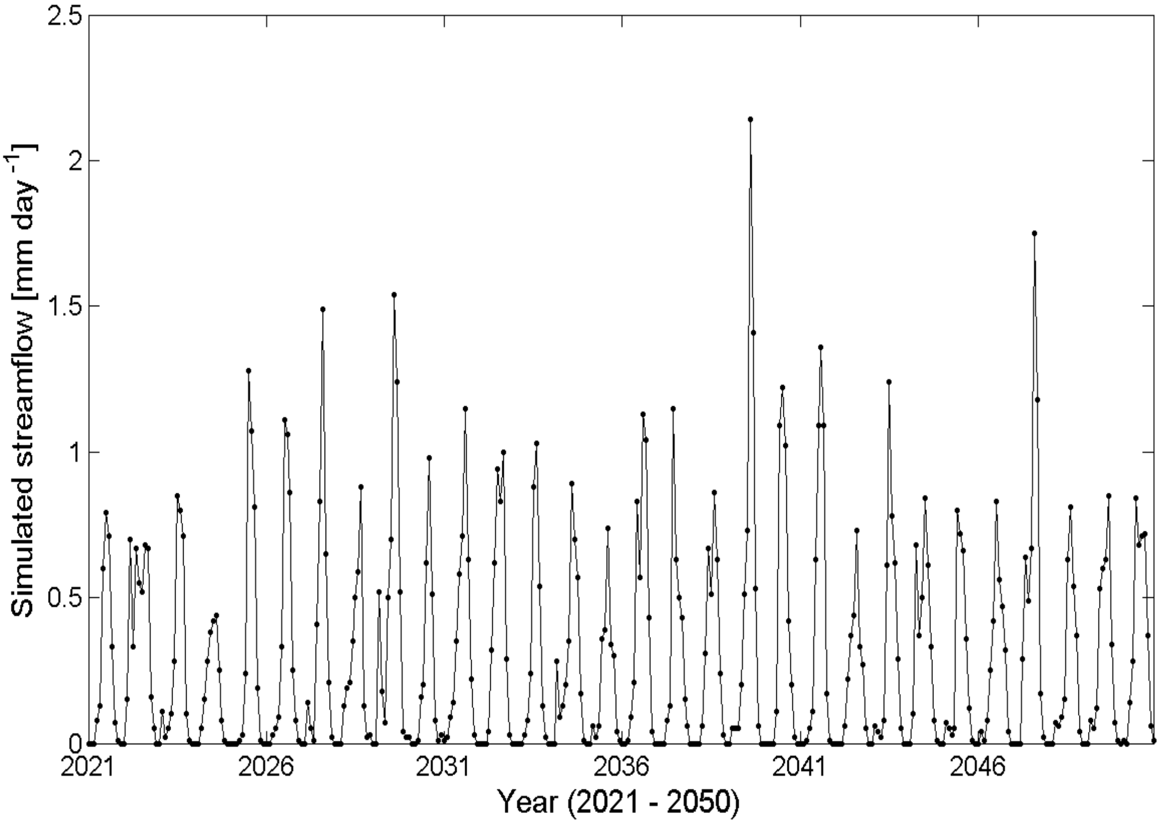
Figure 4.18: *Fit statistics calculated in simulation over the entire study period (1972-2012).*

4.10 Future streamflow prediction with climate simulations

The results of the future streamflows simulated by the calibrated IHACRES CWI model using bias-corrected 16 different RCMs simulations of rainfall and temperature time series of future climate conditions are presented in figures 4.19 (a & b) and 4.20 (a & b). The figure 4.19 (a & b) presents monthly mean streamflow time series derived from the simulated near future (2021-2050) climate conditions of the Vea catchment, while figure 4.20 (a & b) depicts monthly mean streamflow time series predicted with the simulated distance future (2071-2100) climate conditions of the catchment. The figures 4.19(a) and 4.20(a) show the monthly means of the streamflows simulated with each of the bias-corrected 16 RCMs data, while 4.19(b) and 4.20(b) illustrates the monthly mean streamflow averaged over all the bias-corrected 16 RCMs data.

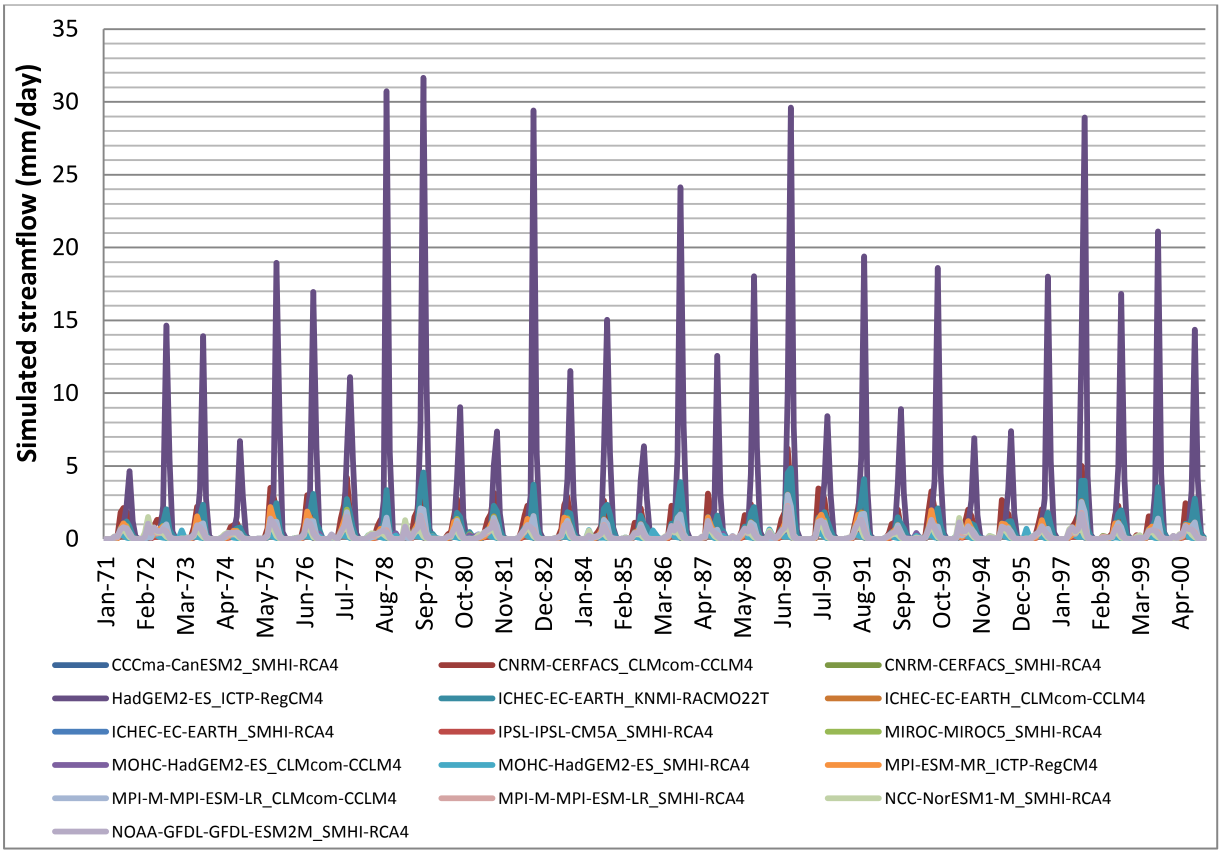


(a)

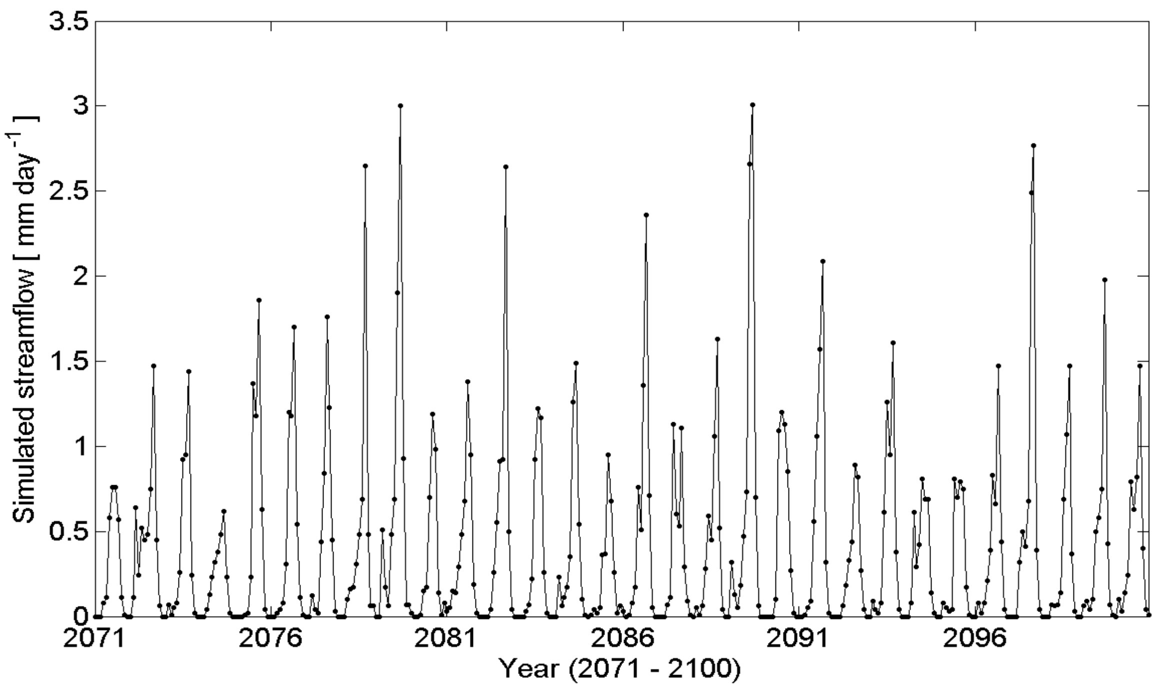


(b)

Figure 4.19: *The monthly mean streamflow for the Vea catchment for the near future climate conditions (2021–2050) simulated from rainfall and temperature time series of all the bias-corrected 16 different RCMs simulations. The (a) presents the monthly mean streamflows of each of the corrected 16 RCMs data, while (b) presents the monthly mean streamflow averaged over all the corrected 16 RCMs data.*



(a)



(b)

Figure 4.20: *The monthly mean streamflow for the Vea catchment for the distance future climate conditions (2071–2100) simulated from rainfall and temperature time series of all the bias-corrected 16 different RCMs simulations. The (a) presents the monthly mean streamflows of each of the corrected 16 RCMs data, while (b) presents the monthly mean streamflow averaged over all the corrected 16 RCMs data.*

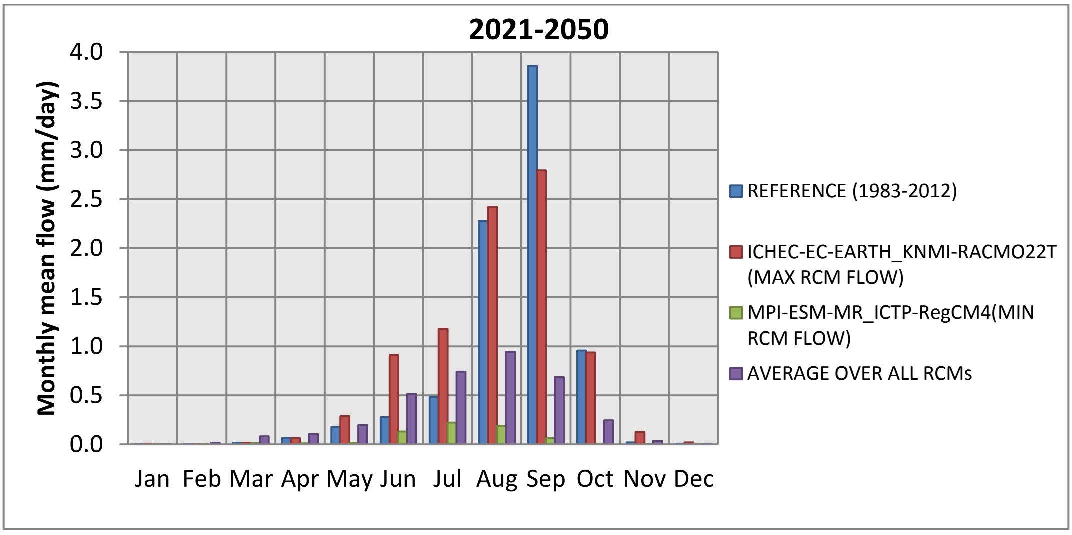
While the figures 4.19(b) and 4.20(b) are quite similar in the scale of streamflow, figures 4.19(a) and 4.20(a) are much different. This is mainly due to a large increasing change in the streamflow time series derived from the simulated conditions by the HadGEM2-ES_ICTP-RegCM4 RCM between the two future time slices (2021–2050 & 2071–2100). The average streamflow time series derived from each of the 16 RCMs simulations decreased between the two time slices, except for 5 RCMs simulations that experienced increased changes with the largest of up to 692.25% increase showed by the simulation of the HadGEM2-ES_ICTP-RegCM4 model. This resulted in the large difference between the scales in figures 4.19(a) and 4.20(a). The streamflows derived from simulations of other 4 RCMs namely, MIROC-MIROC5_SMHI-RCA4, MOHC-HadGEM2-ES_CLMcom-CCLM4, MOHC-HadGEM2-ES_SMHI-RCA4 and MPI-ESM-MR_ICTP-RegCM4, also showed increases between the two time slices (2021–2050 & 2071–2100), but at relatively smaller levels of 17.9%, 6.5%, 23.0% and 416.4% respectively. These increases have led to the overall increase in the scale of the monthly mean streamflow averaged over all the streamflow time series derived from the 16 RCMs simulations as shown in figure 4.20(b).

For both future time slices, the extreme conditions of highest and lowest streamflows were of most interest in the current study. The two extreme conditions of highest and lowest streamflows in the near future (2021-2050) were driven by climate conditions simulated by the ICHEC-EC-EARTH_KNMI-RACMO22T and MPI-ESM-MR_ICTP-RegCM4 RCMs respectively (Fig. 4.19a). These were different for the distance future (2071-2100) where the highest and lowest streamflows were rather driven by climate conditions of simulation by the HadGEM2-ES_ICTP-RegCM4 and IPSL-IPSL-CM5A-MR_SMHI-RCA4 RCMs respectively (Fig. 4.20a). The streamflows of the two extreme conditions for each of the two future time slices (2021-2050 & 2071-2100) were used as inputs for the Water Evaluation and Planning (WEAP) model to examine the water stress situation in the catchment as illustrated in the next section.

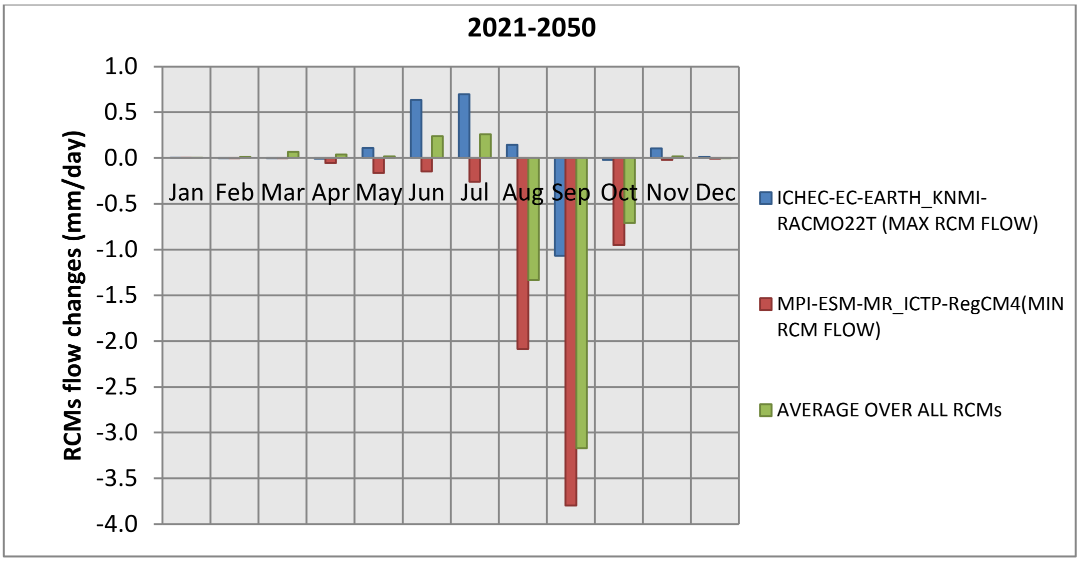
4.11 Impacts of RCMs-simulated climate conditions on catchment streamflow

Three different streamflow time series derived from the RCMs-simulated climate conditions in each of the two future time slices (2021-2050 & 2071-2100) were of interest in this study and were compared with reference streamflow time series of 1983-2012 to assess variations due to changes in climate conditions. These three simulated future streamflow time series were the two extreme streamflow time series (the highest and the lowest) and streamflow averaged over all the 16 RCMs-simulated climate conditions. The long-term (30 years) monthly averages of each of these three streamflow time series were computed and compared with the long-term monthly averages of the reference streamflow time series for assessment of changes in monthly streamflow time series resulting from changes in climate conditions between the current situation and the situation in each of the future time slices. The variations between the long-term monthly averages of each of the three simulated future streamflow time series and the long-term monthly averages of the reference streamflow were determined for comparison. The results are as illustrated in figures 4.19 and 4.20.

The variability between the lowest of the RCMs-derived future streamflows (green in Fig. 4.21a & red in Fig. 4.21b) and the reference flow showed considerably the largest decreased change across almost all months in the future period of 2021-2050. This is followed by a considerable decreased change between the future flow averaged over all the 16 RCMs-simulated climate conditions (purple in Fig. 4.21a & green in Fig. 4.21b) and the reference flow, particularly in the peak period of August to October. There was, however, an increased change between the highest of the RCMs-derived future streamflows (red in Fig. 4.21a & blue in Fig. 4.21b) and the reference flow in the pre-peak period of May to August and in November, except significant decrease in the peak month of September and slightly in October.



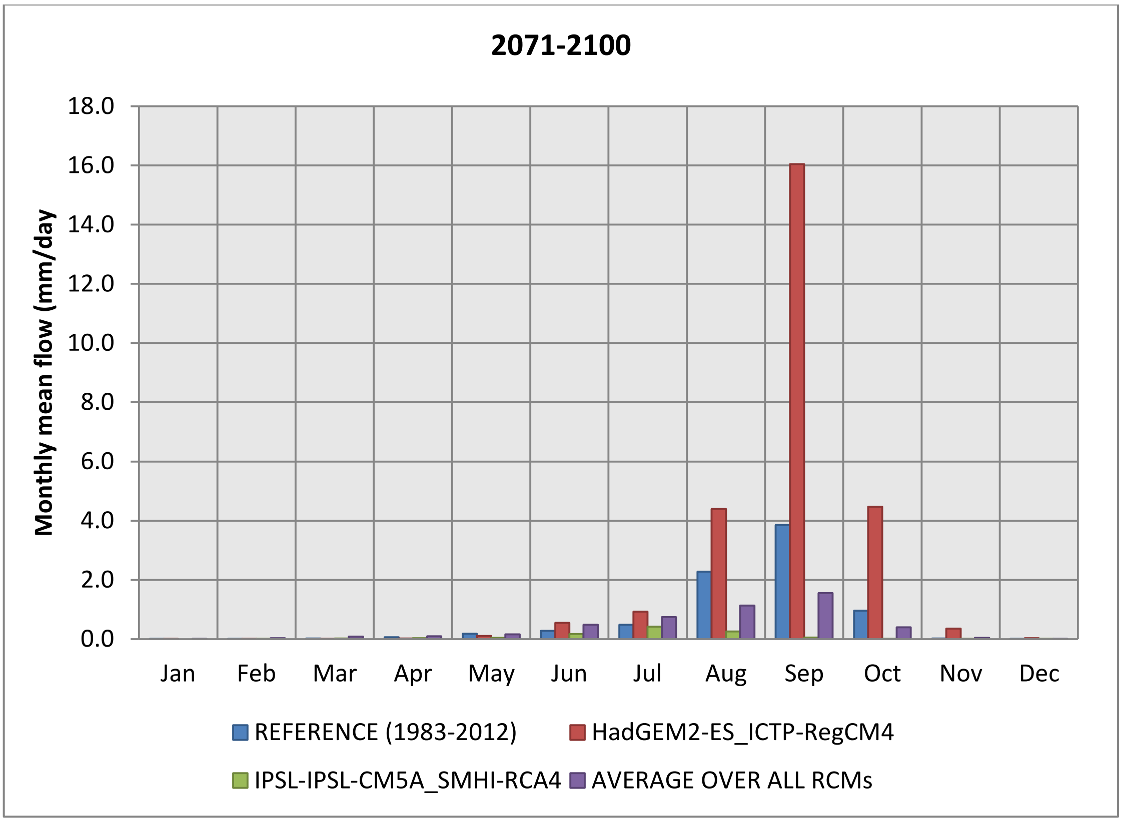
(a)



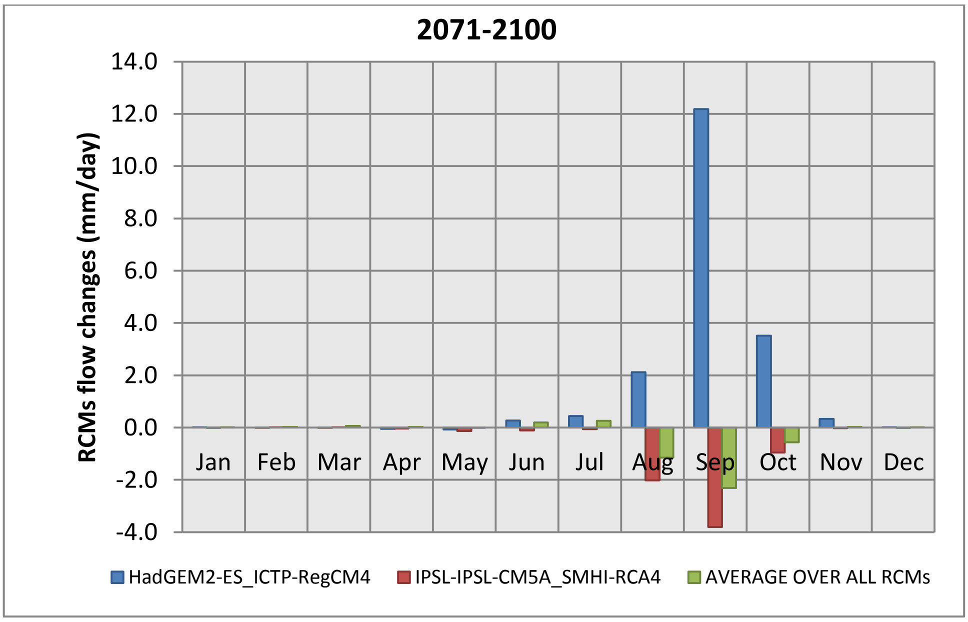
(b)

Figure 4.21: *The monthly mean of each of the two simulated extreme future streamflow time series and monthly mean of streamflow averaged over the 16 RCMs-simulated future climate conditions (2021-2050) compared with monthly mean of reference streamflow (1983-2012). The (a) presents the monthly mean of each of the four streamflows time series, while (b) presents the anomalies between the monthly mean of the reference streamflow and the monthly mean of each of the three selected future streamflow time series.*

In contrast with simulated streamflow regime in the near future period (2021-2050), the situation in the far distance future (2071-2100) indicates a considerable increased change between the highest of the RCMs-derived future streamflows (red in Fig. 4.22a & blue in Fig. 4.22b) and the reference flow across all months in a year. The increased anomaly is particularly large in the peak period of August to October. The lowest of the RCMs-derived future streamflows (green in Fig. 4.22a & red in Fig. 4.22b) and the future flow averaged over the 16 RCMs-simulated climate conditions (purple in Fig. 4.22a & green in Fig. 4.22b) have, however, both indicated considerable decreased in streamflow in the peak period of August to October in comparison with the reference streamflow with the latter showing slight increases in June, July and November in the future period of 2071-2100.



(a)



(b)

Figure 4.22: *The monthly mean of each of the two simulated extreme future streamflow time series and monthly mean of streamflow averaged over the 16 RCMs-simulated future climate conditions (2071-2100) compared with monthly mean of reference streamflow (1983-2012). The (a) presents the monthly mean of each of the four streamflows time series, while (b) presents the anomalies between the monthly mean of the reference streamflow and the monthly mean of each of the three selected future streamflow time series.*

4.12 Discussions

The findings of the current study on temperature and rainfall trends are similar to findings by Ofori-Sarpong, (2001) for Navrongo from 1961-1998. Using the mean annual meteorological data, he reported a steady rise in temperature over the period. The occurrence of the lowest temperature in December and January is as a result of the dry and cold harmattan winds which characterises the period between late November and early February. The steady rise in temperature could have serious adverse effects on agriculture in the study area as a result of a proven sudden drop in net crop growth and yield when temperatures exceed the optimal for biological processes (Ofori-Sarpong 2001; Bhatti & Khan 2012). Soil moisture for crops need will be affected by temperature increases, irrespective of any change in rainfall (Bhatti & Khan, 2012). The greatest impacts of CC in the study area may stem from associated temperature-driven evapotranspiration increases and agricultural drought resulting from constant soil moisture deficits. The steady rise in evapotranspiration in the area may have accounted for the farmers' perceived decreasing trend in rainfall amount and droughts. Obeng (2014) observed that increases in evapotranspiration rate adversely affect crop production in the study area since grain crops (millet, sorghum, rice and maize) with shallow roots that obtain their moisture requirement from top soil remain the major crops grown in the area.

According to Ofori-Sarpong (2001), drought is defined as any period during which rainfall falls below the long-term mean. Over the 41 year period (1972-2012), the long term mean annual rainfall for the study area was 957 mm. Using this as a basis for analysis, the period under review was divided into two periods, 1972-1988 (relatively dry period) and then 1989-2012 (relatively wet period). In the first period, 10 out of 17 years recorded annual total rainfall amounts below the computed mean of 957 mm. In the second the results was no different as 11 of the 24 years had rainfall totals below the mean. This means 21 out of 41 years in the period of consideration 1972-2012 and 15 out of the past 30-year period 1983-2012 were drought years (Fig. 4.2). One may conclude that given any particular period of years in the study area, drought years are either more than half or at least half the number of years within the period, thus the area could be regarded as a drought endemic area as observed by some previous studies in the region (e.g. Ofori-Sarpong 2001). The observed rainfall anomalies for individual months within the growing/cropping period, (May-October) (Fig. 4.3) indicate a general fluctuating trend in intra-seasonal rainfall distribution since 1972 with the largest anomalies occurring in August and September as similarly observed by other previous studies (Nicholson *et al.* 2000; Kemausuor *et al.* 2011).

The absence of break-points and trends in the time series of all rainfall datasets indicate that the average annual rainfall amount and average number of annual rainfall events (days) as well as the average monthly rainfall amount within the growing/cropping period have not significantly changed in the catchment over the study period (1972-2012). Nonetheless, the annual average number of 69 rainy days found for the catchment over the 41-year period under review fell short of the required average of 75 rainy days between April and November to achieve a good harvest in the Region as observed by Yaro (2004). Only 9 out of the 41 years recorded the number of annual rainfall events greater than or equal to the expected average of 75 rainy days. The implication is that agriculture production could have been affected over the remaining 32 years of this study.

Remarkably, the occurrences of minimum rainfall amount and minimum rainy days of the peak month (August) in different years of 1986 and 1997 respectively, is an indication of varied nature of rainfall duration and intensity in the area.

The observed occurrence of peak streamflow in September in the catchment as from the estimated flux does not necessarily mean that it is the peak month of rainfall in the area. As a characteristic of semi-arid areas, much proportion of rains in the previous months of onset of wet season went into soil infiltration until field capacity was reached when much runoff is generated, as was observed earlier (Ofosu, 2011).

The results of the bias correction showed considerable changes between the corrected and uncorrected time series of each of RCMs simulated variables (rainfall and temperature). The indication is that if the biases were not corrected, it could have significantly affected the prediction of future streamflow and evapotranspiration as well as the overall outcome of the assessment of CC impacts on water resources of the study area. This points to a strong consistency with earlier studies that observed that uncorrected RCM simulated data were often a great source of uncertainty in the application of such data (Teutschbein & Seibert 2012). Despite the bias correction, the RCMs simulations of rainfall for the near future showed wide variations among all the models. This is an indication of uncertainty regarding rainfall simulation for the period (2021-2050). On the other hand, an increasing trend in temperature across both future time slices depicted by all the 16 RCMs simulations is an indication of certainty about the effects of global warming in the area across the 21st century conforming to the IPCC (2007b) report.

By exploring the two extreme RCMs simulated climate conditions and average over all the 16 RCMs, this study demonstrates that average monthly streamflows will considerably decreased in the catchment across the 21st century if climate conditions during the period turn up as simulated by any of these RCMs. This implies that water availability in the catchment could be affected negatively.

4.13 Summary and conclusions

This chapter examined the current status and future evolution of water components in the study catchment. The current trend of both temperature and rainfall were analysed as well as the current and future trend of evapotranspiration examined. The catchment flux estimation was also carried out and future streamflow predicted for assessing of water stress conditions in the subsequent chapter. The following conclusions are drawn based on the above mentioned undertakings:

- Temperature is on a steady rise in the study area and the ripple effect has been the steady rise in evapotranspiration. The rising trend in the temperature-driven evapotranspiration was observed to persist throughout the entire 21st century which could adversely affect agriculture production in the area.

- There was no evidence of trends and changes in variability in all the fourteen different rainfall time series derived from the primary daily dataset for analysis of different aspects of the observed rainfall data. However, annual rainfall amounts have been generally lower than the long-term average indicating that the study area is characterised by frequent droughts and high soil moisture deficits.

- The estimated runoff time series for the catchment was fairly good and representative of the historical streamflow of the catchment as it showed a good relationship and fairly consistent change with the catchment areal rainfall time series for all the years in the study period.

- IHACRES hydrological model was calibrated and validated successfully by a combination of an in-built semi-automatic optimisation method within the hydromad package and sensitivity analysis. The performance assessment obtained from four different statistical methods showed that the parameters were successfully optimized and verification with entire dataset showed that the model reproduced the observed streamflow satisfactorily and depicted the rainfall-runoff dynamic response characteristics of the catchment quite well.

- The bias correction showed relative improvement of certainty among all the 16 RCMs simulations, particularly temperature for both future time slices and rainfall for the distance future (2071-2100). However, there were still wider variations among the bias-corrected RCMs simulations of rainfalls for the near future (2021-2050) showing uncertainty among the models.

- There was evidence of expected decreased streamflows in both future time slices. A decreased in monthly streamflows for the near future (2021-2050) was observed from comparison made between the reference streamflow and the three simulated future streamflow time series derived from the two extreme time series (the highest and the lowest) of the RCMs simulations and streamflow averaged over all the 16 RCMs-simulated climate conditions. The situation is the same for the distance future (2071-2100) except for the highest of the streamflow time series derived from the RCMs simulations by HadGEM2-ES_ICTP-RegCM4 model which showed an increase in the monthly streamflow over the reference period.

CHAPTER 5: PERCEPTION AND SCENARIO BUILDING FOR THE FUTURE

5.1 Introduction

This chapter presents the findings of the analysis of perception on climate change (CC) and adaptation from the households and institutional interviews as well as focus group discussions. These include results of analysis of perceptions on changes in long-term temperature and rainfall as well as vulnerability levels of livelihoods, adaptation practices and future adaptation plans, external adaptation supports and barriers to adaptations. This chapter also includes results of analysis of perceptions on land use and land cover changes and the derived scenarios on possible future irrigation and water demands/uses trends.

5.2 Farmers' perceptions about climate variables (temperature and rainfall)

Most farmers (89.5%) interviewed perceived that temperature has increased over the past 30 years in the VEA Catchment (Fig. 5.1).

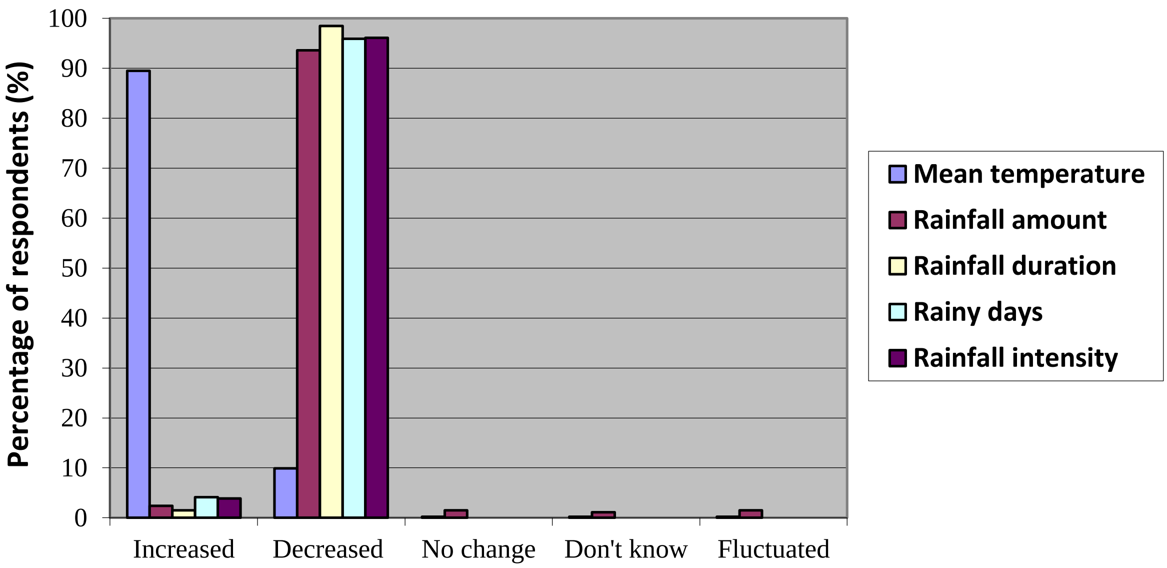


Figure 5.1: *Perceptions of changes in temperature & rainfall (amount, duration, intensity & rainy days) over the past 30 years*

With regards to rainfall, the majority of farmers believe that it decreased over the years in all measures regarding amount of rainfall, duration, intensity and number of rainfall events (Fig. 5.1).

The farmers perceived various degrees of changes in climate (Fig. 5.2) and the effects (Fig. 5.3) based on their exposure levels, resilience and adaptive capacities. To some respondents as shown in figure 5.3, the effect of the changes has been severer compared to others. Some, but few (1.9%) of the farmers however did not see any significant impacts of the changes.

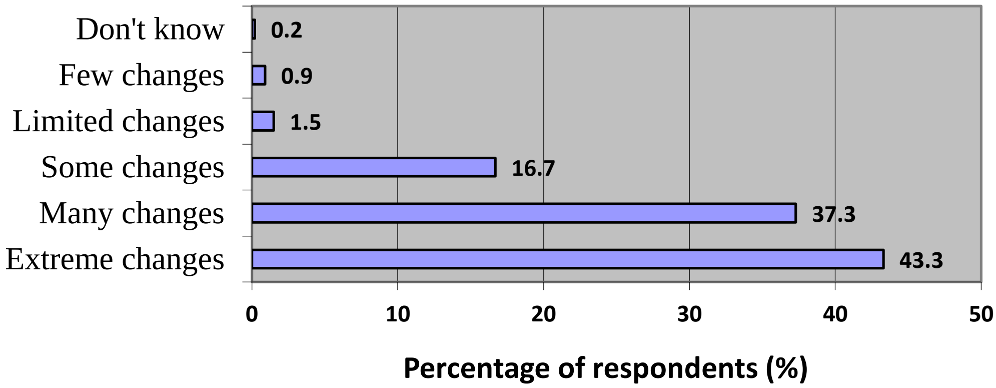


Figure 5.2: *Farmers' perception/view of extent of changes in climate variables over the past 30 years*

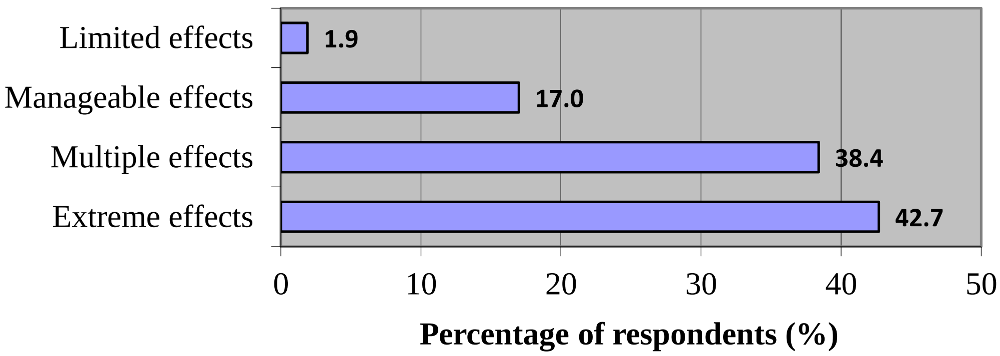


Figure 5.3: *Farmers' view of extent of negative impacts of changes in climate variables over the past 30 years*

The majority of farmers (97%) perceived that they are extremely vulnerable to changes of onset of planting season, poor rainfall amount and distribution during the cropping season and also intermittent drought situations that sometimes occur during crop growth stage. According to the farmers the outlined conditions have the potential to affect the growth of the crops, their maturity and consequently could lead to reduced yields and food insecurity. Over 80% of respondents also observed that their livelihoods face serious risk due to the increasing temperature and sporadic floods that occur in the area.

5.3 Farmers' observed opportunities (positive impacts) of changes in climate

We were interested in finding out if the farmers see any opportunities in climate variability/change. The majority of the respondents believed periodic increased runoff if harvested properly could be used to facilitate dry season farming (Fig. 5.4). It was obvious to them that increased runoff could be channelled into dams to help irrigation and promote fishing as alternative livelihood source. From the analysis in figure 5.4, the positive effects aside fishing and increased irrigation potential, was the hypothetical increase in groundwater reserves. Even though this could not be verified scientifically or quantitatively, further queries showed that their assumptions were based on the yields of hand dug wells and boreholes in the neighbourhoods. Thus, it was the view of the majority that they could manage the adverse effects of CC through irrigation farming and fishing given that necessary means are at hand.

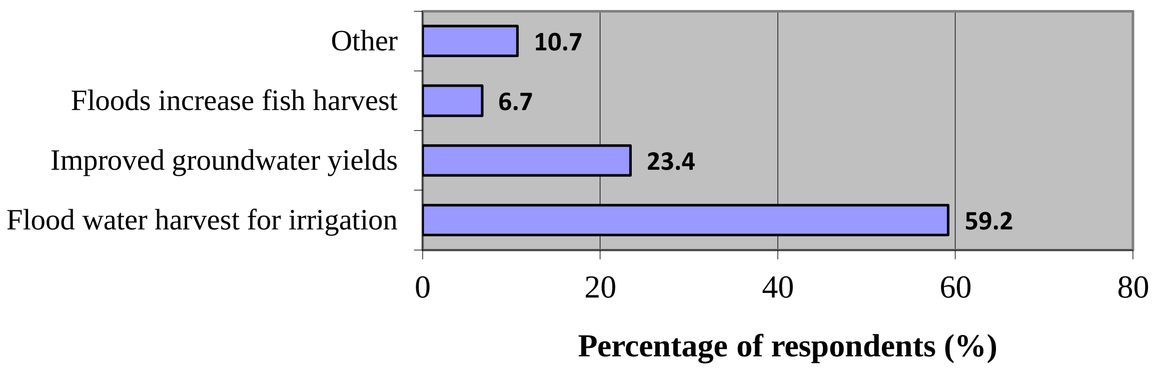


Figure 5.4: *Farmers' observed positive impacts of changes in climate variables over the past 30 years*

A cumulative 88.8% of respondents mentioned the practice of irrigation farming as the adaptive strategy to fully benefit from the changes while 0.7% and 10.5% mentioned fish farming and other activities respectively as the way forward in the light of the impacts of the changes in climate (Fig. 5.5).

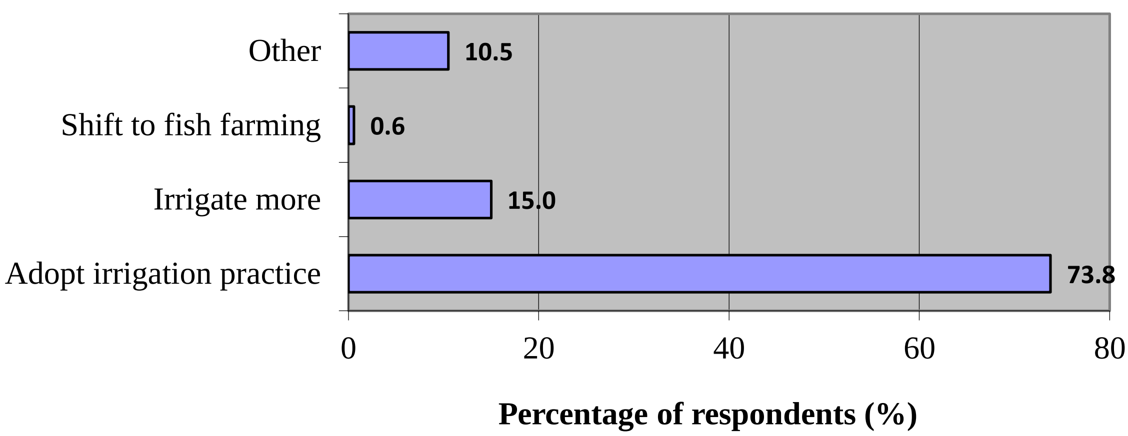


Figure 5.5: *Farmers' future plans of capitalizing on positive impacts of changes in climate*

5.4 Perceptions of causes of changes in climate variables/climate change

The causes of CC as perceived by farmers was due to human activities such as overexploitation and indiscriminate felling of trees for firewood, charcoal and rafters, bush fires and overgrazing (54%). Other (21%) farmers perceived that CC was a result of wrath of ancestral gods for destroyed fetish shrines, disregard for traditions and taboos. According to 13.5% of the respondents, CC was a result of fury of God on current generation due to sinful behaviours, while 11.5% indicated that they had no idea what might be the cause. It was obvious that the perceived causes of CC will, to a great extent, influence farmers' adjustment practices as adaptation measures.

5.5 Farmers' adjustment to climate change over the last 10 years in terms of farming methods

Almost all the respondents (99.6%) indicated that they have made adjustments to their farming methods in response to CC and variability over the last 10 years. Several adaptation measures were observed to have been taken by farmers in response to changes in both rainfall and temperature as shown in figure 5.6.

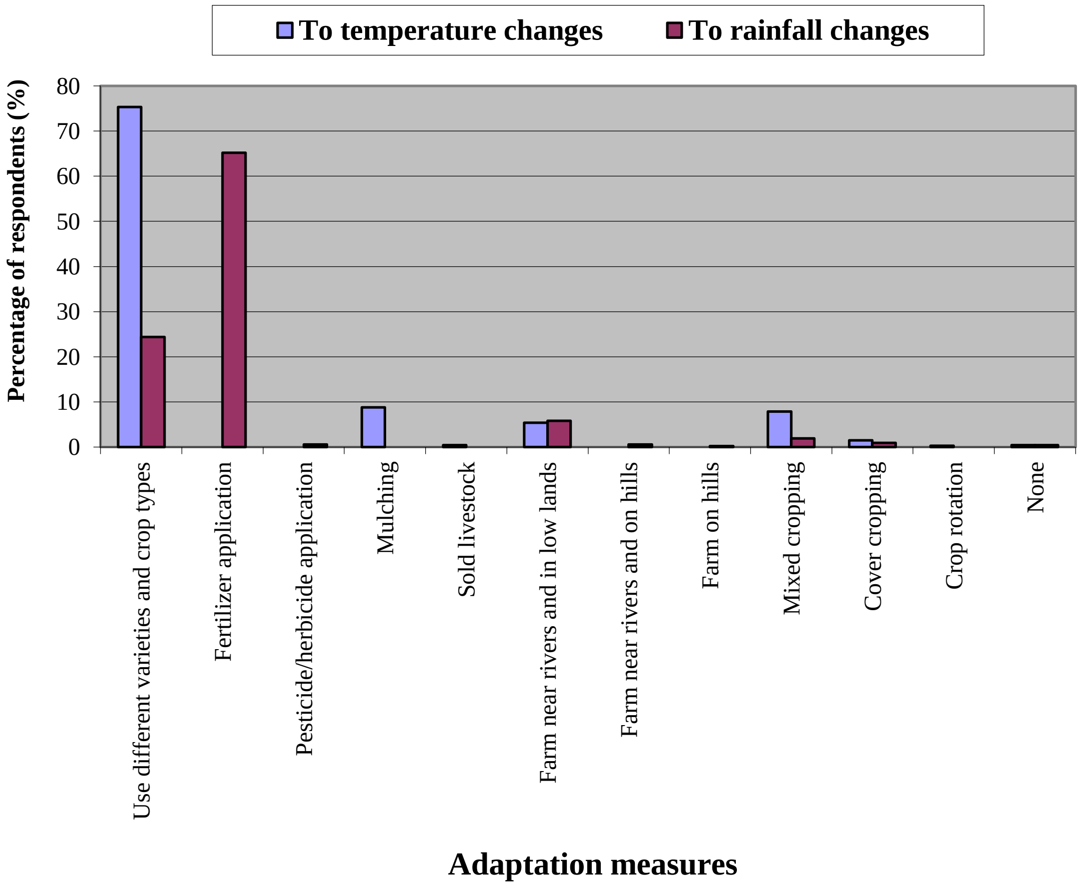


Figure 5.6: *Adjustments to long-term shifts in rainfall and temperature by farmers*

Farmers saw off farm jobs as alternative, but remained committed to improve farming as their heritage. They therefore enumerated a number of practices being adopted over the last 10 years to make farming reliable and sustainable amidst the changing climate. Among the adjustment practices that farmers named were adoption of improved crop varieties that are drought resistant and high yielding, and mulching which they noted helps to maintain soil moisture and maintain the minimal soil conditions to sustain production due to high temperatures in the area.

Regarding the improvement of the soil, most farmers relied on the use of fertilizers to promote early growth of crops and also to offset the effects of the long term shifts in rainfall (variability and quantum). The problem noted with this strategy is that with limited rainfall amounts and without irrigation crops burn up due to the effect of the fertilizer. It was also noted that farmers' adaptation measures were location dependent. Those in the valleys tended to farm along the hill to avoid periodic flooding while those located in the hilly areas had decided to draw their farms closer down-slope to avoid drier conditions up hill. Other agronomic practices such as cover cropping, mix cropping and the use of herbicides and pesticides were patronised as ways of adapting to CC effects. Further queries confirmed that the farmers believe the changes in the climatic conditions have led to the incidence of more difficult-to-control weeds unfamiliar to them as well as the incidence of pests and diseases. This is what has necessitated the application of the unorthodox method of weed and pest controls.

Among the farmers who have engaged in the application of pesticides, fertilizers and herbicides, almost 66% apply them yearly, 17.8% apply them biannually, and 4.3% apply them once every two years while 12% use them tentatively as and when the situation in the particular time demands so (Fig. 5.7). The reasons given by farmers who do not employ these adaptation methods include perceived dangers on users' health associated with the application of these chemicals to their crops. Other potential reasons why the 10% of the respondents do not use the chemicals include illiteracy and poverty which increase their distance to the chemicals socially and economically.

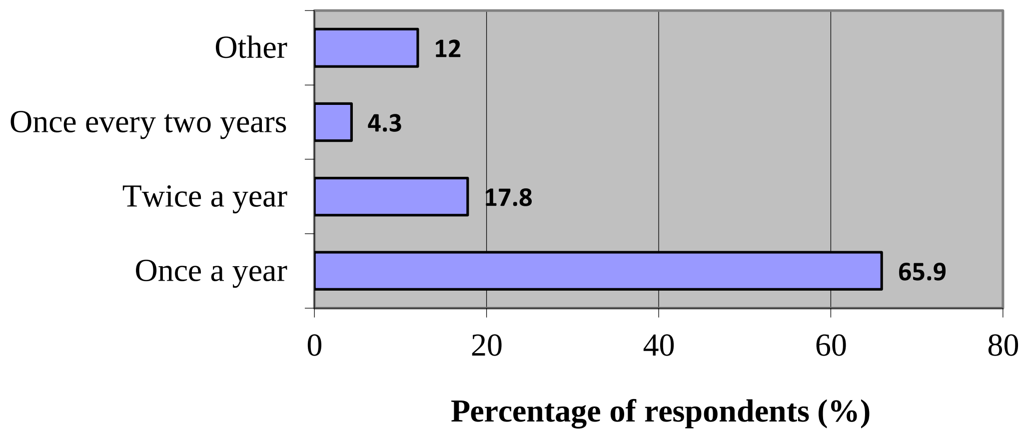


Figure 5.7: *Farmers' frequency of fertilizer and pesticide/herbicide application*

5.6 Famers' perception of vulnerability and risk levels of their livelihood to incidences of changes in climate variables

Seasonal variations in rainfall patterns and amount and temperatures affect farm operations and therefore yields. Negative effects of these changes pose vulnerability and/or risk challenges to livelihoods of farmers and entire population at large. Information gathered indicates that each farmer perceives the incidence of his/her vulnerability or risk at different levels. While vulnerability here refers to exposure level of livelihoods to effects of changes in climate variables, risk refers to the level of fear associated with the purported effects or the probability of occurrence of the effects considering that livelihoods are vulnerable.

5.6.1 Perception level of vulnerability to negative effects of changes in climate variables

Majority of farmers (97%) perceived that they are extremely vulnerable to frequent occurrences of changes of time of start of planting season (changed timing of rains), poor rainfall amount (decreased rainfall) and distribution during entire cropping season and also intermittent drought situations that sometimes occur during crop growth stage. According to them the conditions above have the potential to affect the growth of the crops, their maturity and consequently could lead to reduced yields and food insecurity. Besides, over 80% of respondents also mentioned increases in temperature with abrupt changes in growing/planting season and periodic floods that occur in the area as risks. Details on perception of vulnerability levels of the farmers are as presented in figure 5.8(a) below.

5.6.2 Perceptions of risk levels of livelihoods to negative effects of changes in climate variables

Assessment of perception levels indicates also that majority of farmers (over 94%) were *"very certain"* that increased temperature, decreased rainfall amount, drought and changed timing of rains pose serious threats to their livelihoods and food security (See Fig. 5.8). About 88% of them had *"near certain"* opinion that their livelihoods and food security were at risk of periodic floods owing to negative effects of CC. About 89.5% of respondents expressed their farms and food securities are *"very likely"* at risk of adverse effects of CC, including climate variability and extremes events, particularly the abrupt change in season and changes in growing season. Figure 5.8(b) also presents a detail picture of various levels of risk perceived to be associated with various manifestations of CC.

5.6.3 Respondents' perceptions of the severity of adverse effects of climate change

Nineteen (19) possible adverse effects of CC were put out to respondents during the questionnaire survey for them to assess their severity. Over 85% of farmers perceived that the impacts of *"changed timing of rains"* and *"increased frequency of drought"* on their farms/livelihoods were *"disastrous (extremely severe")*. Other impacts or adverse effects of CC such as *"reduced cropping season"*, *"poverty and food shortages"*, *"lack of adequate potable water"*, *"rising cost of farming/fishing"*, *"climate-induced-rural-urban migration", "siltation of water bodies" and "disappearance of vegetation cover"* were perceived to be *"very severe"* and militating against their livelihoods and food security. Between 67 – 90% of the respondents were of this opinion (Fig. 5.9).

Adverse effects of CC such as *"abrupt changes in crop growing season", "post-harvest losses in crops", "prevalence of crop/livestock diseases", "pest infestation", "soil erosion", and "high mortality in livestock"* were considered by between 83 - 91% of farmers to be *"severe"* on their farms/livelihoods.

Severity of adverse effects produced through *"frequent floods"* was considered to be *"significant"* by 83% of farmers, while severity of the adverse effects produced through extinction of some crops/crop varieties was perceived to be *"somewhat significant"* by also 83% of farmers and that of *"destruction of farm roads and homes"* through extreme storms and floods was regarded by 88% of the respondents to be an impact that is *"irrelevant"* to their food security (Fig. 5.9). For adverse effects such as *"extinction of fishes and aquatic* *life"*, almost all farmers said they have no idea of its adverse effects and severity on their livelihoods.

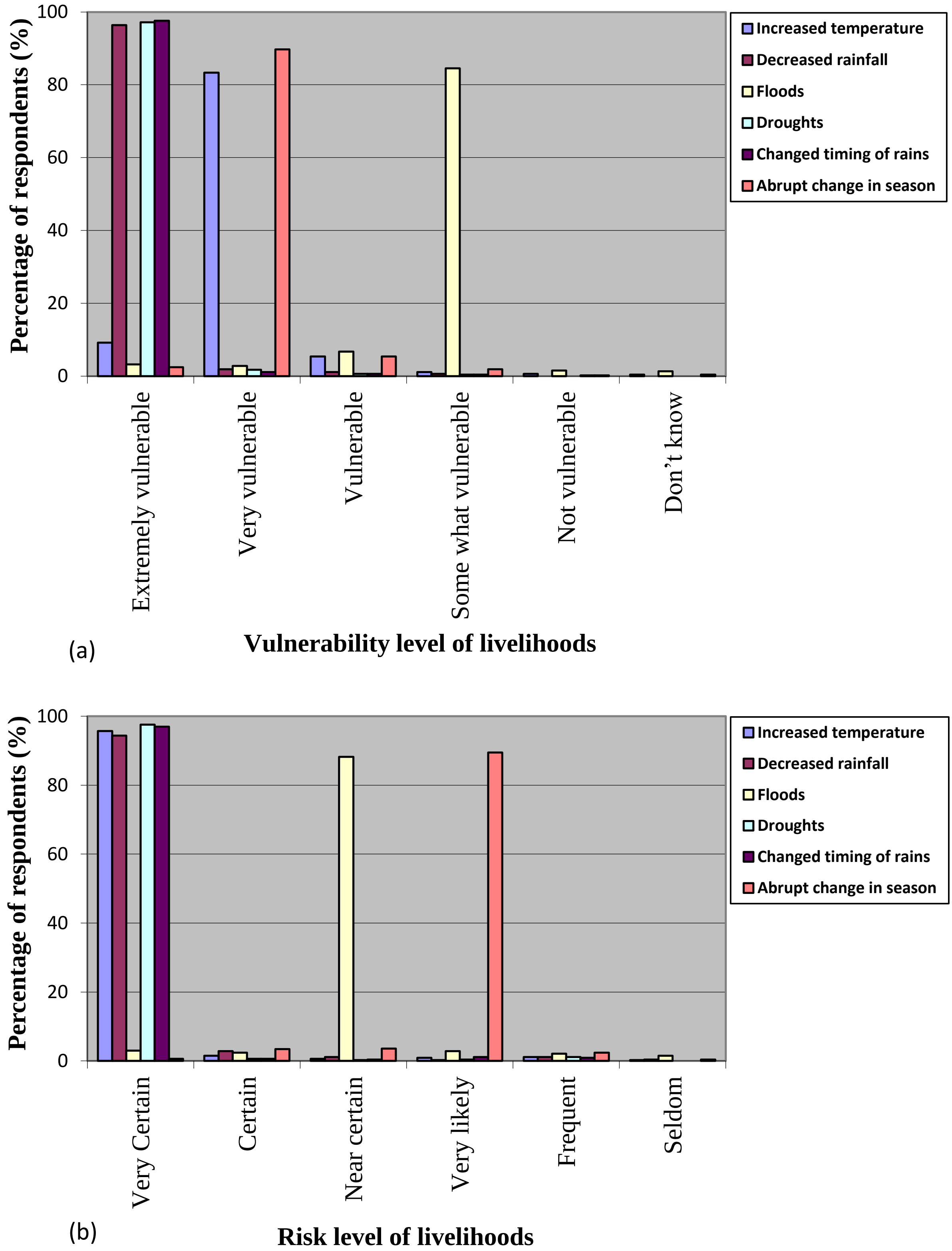


Figure 5.8: *Farmers' perception of the vulnerability (a) and risk (b) levels of farm activities/livelihood to the incidences of climate variable change*

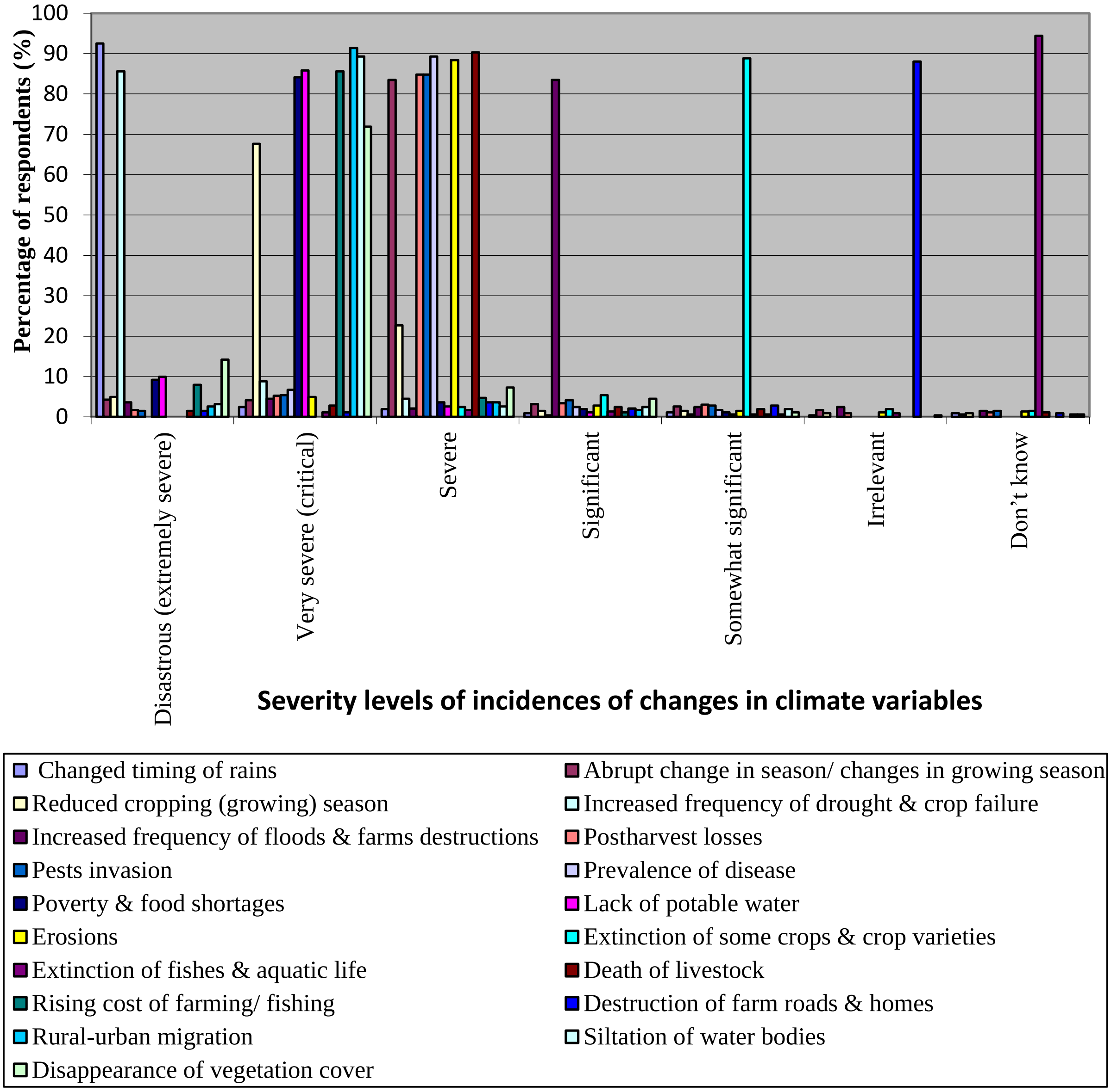


Figure 5.9: *Farmers' perception of the severity of negative impacts of changes in climate variables*

5.7 Farmers' external support for adaptation

A large percentage of the farmers depend on external support for their adaptation to the adverse effects of climatic change. The forms of support received included finance and material inputs at subsidised costs. Others were extension services and communal labour as summed in Table 5.1. Some of the external supports received by farmers were free while others were not. The sort of support free of charge included extension services delivered by MOFA as well as government subsidy portion of fertilizer costs started in the year 2008. Communal labour provided by farmers themselves to each other is normally not paid for but farmers to whom the support is being rendered, provided meals and drink for the workers**.**

Farmers who receive financial and material supports do not receive it free; as they have to pay back and definitely because of the interest they have to pay on such support.

Table 5.1: *Type, length of time of existence & frequency of external adaptation support*

Type, length of existence & frequency of external support	Response	Percent (%)
Form of adaptation support received by respondent	Financial support	2.6
	Material support	8.2
	Extension services	44.5
	Subsidized farm inputs	30.4
	Communal services	14.3
Length of existence of external adaptation support	1-5 years	57.3
	6-10 years	34.0
	11-15 years	5.6
	16-20 years	1.9
	Other	1.2
Frequency of external adaptation support	Once a year	86.6
	Twice a year	6.3
	Once every two years	0.7
	Once every three years	0.5
	Other	5.9

The different forms of assistance to farmers for adaptation practices have been in existence for varied lengths of time. Some of the beneficiary farmers noted that their support elements have been in existence for a period of between 1-5 years (Table 5.1). Notable ones are the government block farm and input subsidy programmes implemented since 2008. Other farmers said some support systems have been in existence for a period of between 6-10 years and this is with particular reference to financial assistance in the form of loans/credits from some financial institutions and NGOs. Others have been in existence for much longer time as shown in Table 5.1.

One key consideration on support received by farmers was its frequency. It was realised that while some were received once or twice a year, for others it was twice every two or more years. For instance, MOFA extension services, government input subsidy, block farm programmes and communal labour services received by majority were relatively frequent. Those support services received once/twice every two or three years included cash/input loans from credit facilities and NGOs and this benefited a privileged few, an indication that credit and input accessibility remains a huge unmet need for CC adaptation. Other beneficiaries (farmers) said the support they receive have not been regular but rather in an ad hoc manner, particularly during extreme events. The varied sources from which the support was received ranged from government and its decentralised agencies to NGOs. Government agencies provide adaptation support like extension services and input subsidy, while Agricultural research stations contribute improved crop varieties. Community's portion of the support is in the form of communal labour, while NGOs provide some, but limited extension services and input/cash loans. Some few credit facilities were also acknowledged to have offered some, but limited cash/input loans.

To majority of the beneficiary farmers the external supports given them have been helpful except for a few (Table 5.2). This was attested to by almost all the respondents. They acknowledged benefiting from the support in the following ways; increased crop and animal yields, reduced post-harvest losses, improvement in household food security among others as indicated by Table 5.2.

Table 5.2: *Farmers' perceptions about the benefits of the external adaptation support*

Benefits of the external adaptation support	Response	Percentage (%)
Is the external adaptation support given the respondent beneficial?	Yes	99.1
	No	0.9
Benefits of the external adaptation support to respondent	I got capital to expand my farm	1.7
	Reduced postharvest lost	16.3
	Improved yield	58.0
	Reduced hunger	19.1
	Took another wife	1.9
	Purchase additional farm machinery	2.8
	Other	0.2

Extension services and technological information are often delivered to the farmers through various channels. Such information includes weather (rainfall, Temperature and wind) and technical information/assistance. Majority of these information are expected to reach farmers through MOFA extension officers during farmer home and farm visits which unfortunately have not been regular. The analysis indicated few farmers received such information from MOFA extension staff regularly. According to the analysis most of the farmers on the other hand, were not reached regularly or at all by these MOFA extension staff and hence had no access to such extension services. This deprived group believed that successive governments have not acquitted their responsibilities for them in dependability. They observed that more MOFA extension workers were required as well as equipping them with required tools including mobility.

Radio broadcast has been the dominant source of information to the farmers. All local FM radio stations via the local languages provide farmers with technical information regarding farming and CC. A few others also depended on neighbouring farmers, community leaders as well as the television broadcast. According to Table 5.3, there were others who still could not be reached for information.

Table 5.3: *Farmers' sources of climatic information*

Farmers sources of climatic information	Response	Percentage (%)
Extension officers' regular provision of information on expected rainfall and temperature	Yes	34.5
	No	65.5
Other sources of information and technical assistance to respondent beside official extension workers	Television	0.2
	Radio	62.3
	Neighbouring farmer	23.5
	Community leaders	2.0
	Relatives	2.0
	None	9.4
	Others	0.7

5.8 The most needed adaptation interventions

The first services/investments, facilities and resources identified by farmers as their most urgent needs for adaption to the adverse effects of CC are as presented in Table 5.4. Each respondent held different view as to the most urgent need or intervention required for adaptation and whose duty it is to provide the resource. The provision of irrigation facilities was of major priority to most farmers of which majority assigned the responsibility of its provision to central government. Other facilities identified by the rest of the farmers, in decreasing order of views about which has precedent over the other in terms of urgent need are captured in Table 5.4. Overall, majority of respondents in each case assigned the responsibility of provision of these services to central government.

Table 5.4: *Farmers' most needed services/investments/developments for adaptation*

	Whose responsibility					
Perceived most needed intervention	**Central government**	**Local government**	**Local community**	**Private sector**	**Total**	**Percentage (%)**
Irrigation development	177	23	1	8	209	44.8
Climatic information/ extension services	30	6	0	2	38	8.2
Credit facilities	98	11	0	16	125	26.8
Health services	43	8	0	0	51	10.9
Agric mechanization/Subsidize farm inputs	12	13	0	0	25	5.4
Electricity	6	0	0	0	6	1.3
Potable water	1	7	0	0	8	1.7
Improved crops seeds/ economic trees	1	0	0	0	1	0.3
Vocational/basket weaving centers (Jobs)	2	0	0	0	2	0.4
Dug out (water for animals)	1	0	0	0	1	0.2
Total	**371**	**68**	**1**	**26**	**466**	**100**

There was seemingly poor interest in the acquisition of vocational skills as illustrated in Table 5.4. Most of the farmers did not see off-farm-jobs as an alternative option in the worsening of the prospects in farming. The various reasons given include lack of money for acquisition of such jobs and inadequate information. The other fundamental reasons span across lack of basic skills, non-availability of such jobs, and strong attachment to farming and so on. However, a few farmers indicated that they were already in some form of off farm jobs (Table 5.5).

All the famers interviewed had never also endeavoured to insure their investments for various reasons. The major reasons given were lack of money or credit facility and inadequate information, showing indications of the effects of poverty and inaccessibility of information.

Table 5.5: *Farmer's reasons for not adapting some measures*

Reason for not adapting some measures	Response	Percentage (%)
Reason for not buying insurance	Lack of money/credit facility	48.5
	Lack of information/ unaware	42.7
	Not applicable here (not available)	0.4
	Don't need it/not interested	7.5
	Don't have trust	0.4
	Other	0.4
Reason for not finding off-farm job	Lack of money/credit facility	23.4
	Lack of information/ never thought of it	27.6
	Lack of relevant skill/qualification	6.0
	I am already into off-farm job	3.6
	Planning to do so	0.9
	No available off-farm jobs	21.8
	Because of family/marriage/socio-cultural reasons	0.7
	Farming is better/prefer farming	12.5
	Other	3.5

5.9 Perceptions on levels of severity of barriers to climate change adaptation measures and suggestions for improvement

In this study we formulated a set of possible barriers to CC adaptation measures and asked for farmers' opinions on them, regarding the level of severity of each barrier and possible solutions to remove or reduce the barrier. Options of severity levels proposed for respondents to choose appropriately for each adaptation barrier were: extremely severe, very severe, severe, significant, somewhat significant and irrelevant. The analysis as per the table below (Table 5.6) highlights the farmers' observed severity level of each adaptation barrier and provides the suggested solutions that the farmers think are needed. In this analysis, only the highest score for severity level and suggested solution for each barrier is highlighted. Inadequate capital (97.9%) and lack of access to credit (98.5%) were considered to be extremely severe. Other issues such as, lack of education (95.9%), lack of access to information (96.8%), physical characteristics of the land (94.6%), infertile soil (98.1%) and inaccessibility of water for dry season irrigation (96.8%) were considered very severe and priority issues to tackle in adapting to the adverse effects of CC for increased household food security. The lack of extension services (93.3%) and adaptation sustainability issues (95.1%)

were generally viewed as severe in terms of severity level ranking. While old age (95.7%), topography of land (91.8%) and inadequate labour (94.4%) were also considered significant, other issues such as societal norms/values (96.6%), land tenure issues (90.3%) and length of time required to see results of adaptation measures (96.4%) were viewed to be of less important and regarded as irrelevant (Refer to Table 5.6 below for details)

Table 5.6: *Respondent's suggestions on how barriers to adaptation could be solved*

EXPECTED BARRIER	SEVERITY ON ADAPTATION AS CONSIDERED BY FARMERS		SUGGESTED SOLUTION BY FARMERS	
	Severity Level	**Score (%)**	**Solution**	**Score (%)**
Lack of education	Very severe	95.9	Periodic education on CC and new farming techniques	62.9
No access to information	Very severe	96.8	Increase accessibility to climatic information	70.0
Inadequate extension services	Severe	93.3	Recruit more Agric. Ext. agents (AEAs)	88.8
Incompatibility with social norms and values	Irrelevant	96.6	Education/Sensitization	97.9
Inadequate capital	Extremely severe	97.9	Make credit easily accessible	56.2
Lack of access to credit	Extremely severe	98.5	Make credit easily accessible	88.4
Sustainability challenges	Severe	95.1	Improve access to credit & mutual trust between providers& beneficiaries	97
Length of time required to see results too long	Irrelevant	96.4	Provision of credit facilities and easy access to credit/loan	94.6
Old age	Significant	95.7	Improved mechanized agriculture and input credit	61.8
Land tenure issues	Irrelevant	90.3	Review of land tenure system	94.6
Topography of the land	Significant	91.8	Education on crop suitability and farming techniques	95.9
Physical characteristics of the land	Very severe	94.6	Education and implementation of soil/land conservation techniques	96.8
Infertile soils	Very severe	98.1	Provision of fertilizers on subsidy basis	56.9
Inadequate labour availability	Significant	94.4	Improved mechanized agric. /provision of implements/equipment on loans to farmers	78.8
Lack of access to water for irrigation	Very severe	96.8	Government increase investment in irrigation development	80.3

On suggestions as to how these barriers to adaptation could be trounced, poor or no education was identified as a bane and in that respect the farmers (23.4%) called for the establishment of more but affordable schools to be complemented by non-formal education (11.6%). Majority (62.9%) of the respondents, however, believe that the best form of education needed is a periodic public/community based education/sensitisation on the issues of CC and new farming practices/techniques. This was observed to be crucial in addressing adaptation problems related to illiteracy. Increased accessibility to climatic information (70.0%) by responsible state agencies like Ghana Meteorological Agency and recruitment of more Agriculture Extension Agents (AEAs) (88.8%) were also noted as key solutions to information deficiency and inadequate extension services respectively.

Provision of credit facilities for easy accessibility to credit/loan coupled with improvements of mechanized agriculture through provision of implements and equipment on loans to farmers were identified as the major elements of lasting solutions to issues of inadequate capital, credits inaccessibility, adaptation sustainability challenges, inadequate labour availability and old age (Table 5.6). Even though majority (96%) of the farmers thinks that the issue of length of time required to see results of any adaptation measure does not matter and irrelevant, these famers (95%) believe that such rare barriers would not occur if there is adequate provision of credit facilities and easy accessibility to credits. The call for provision of credit facilities and easy accessibility to credit/loan was central in all proposed solutions by farmers.

Most of the farmers (97%), however, cautioned that unless there is mutual trust between providers and beneficiaries in the provision of credits/loans and material support, it becomes a disincentive rather than an incentive or adaptive intervention. They emphasized this, saying it was part of past lessons and experiences in which some individuals and organizations offered them credits/loans on agreed conditions only for these providers to change the conditions of the credits/loans on payment, obviously to extort them resulting in disputes and scuffles. This, farmers noted has scared most of them from accepting credits/loans and material supports from providers, even though they are often in dying need of these supports. They therefore called on government and corporate organizations to provide reliable credit facilities and flash out exploiters to ensure sanity and re-enkindle their trust in accepting credits/loans.

Education on crop suitability and farming techniques (95.9%); implementation of soil/land conservation techniques (96.8%) as well as continuation of the already implemented programme on fertilizer subsidy (56.9%) were also identified as solutions to barriers associated with topography of the land, physical characteristics of the land and infertile soils respectively.

Other issues regarded as no anticipating barriers such as incompatibility of adaptation measure with social norms and values as well as land tenure issues were observed as rare issues which could be reduced by education/sensitization (97.9%) and review of land tenure system (94.6%) respectively. Irrigation was identified as paramount and a critical CC adaptation strategy for the area which is endowed with irrigation potential. Majority (80.3%) of these farmers, however, acknowledged that irrigation requires significant investment and capital, thus called on government to increase investment in irrigation development in the area to solve the acute problem of inaccessibility of water for irrigation. This confirms the earlier popular endorsement of irrigation as the first most needed services/investments/ developments for adaptation as in Table 5.4 above.

5.10 Perception of changes in vegetation cover

Majority of farmers observed that there have been decreases in both vegetation type and cover over the last 30 years in the area (Fig. 5.10 & Fig. 5.11). This is consistent with the results of the analysis of land use satellite data for the area as discussed in chapter 7. Clearly, the species that are replacing the lost ones are said to be poorer in value, size and productivity in the view of respondents. Nonetheless, some, but a few respondents indicated that there have been increases in both vegetative type and cover. Indeed one cannot begrudge their perception considering the fact that the multiplication of grass species in the rainy season in particular give the impression that the vegetative type and cover have improved over the original life forms.

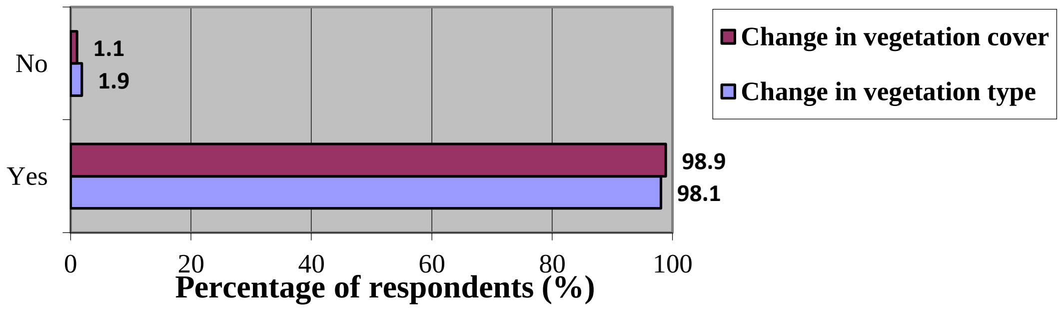


Figure 5.10: *Farmers' observations of change in vegetation cover & type over the last 30 years*

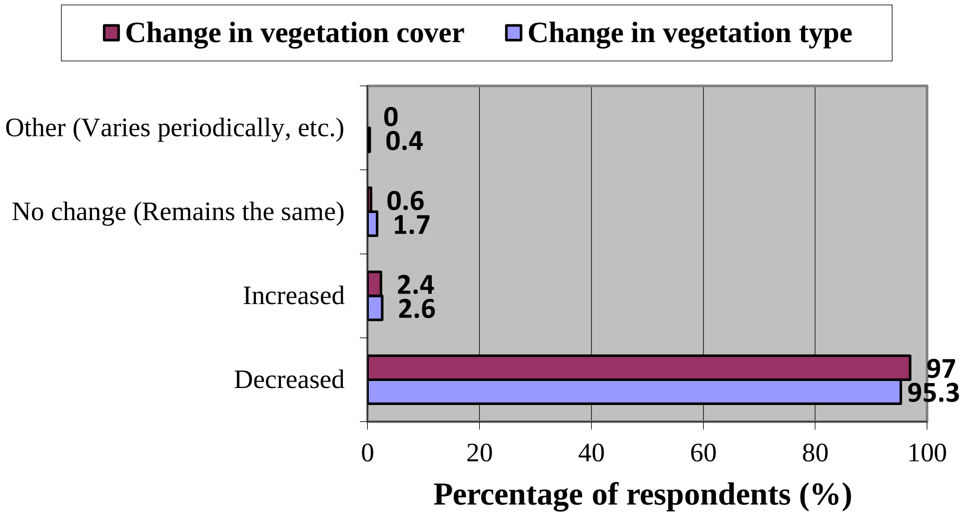


Figure 5.11: *Farmers' observed kind of changes in vegetation cover & type over the last 30 years*

5.11 Focus group discussions

5.11.1 Recognition of climate change

In all the interviews, respondents agreed that there are changes in the environment in terms of dryness arising from irregular and inadequate rainfall. The changes realized included increased number of hot days in the past three decades. Others specifically said the level of temperature had also gone up but acknowledged occasional fluctuations. The respondents' view on rainfall was almost unanimous as they agreed that it had reduced over the years not only in quantum but also its reliability and heaviness of intensities. This, they were able to measure by the observation of the constantly changing planting times in different years as well as the extinction of some crop species which they attributed to the changed rainfall patterns. These observations are consistent with the results of the analysed household questionnaires (HHQs) that showed perception of increased temperature, decreased rainfall (amount, intensity, duration and rainy days) as well as decreased vegetation cover and type.

5.11.2 Perceived causes of climate change

Except for a respondent in Boko-Tindongo who could not tell what was changing the conditions of the environment, all the other respondents in the focus group discussions and the interviews largely acknowledged that environmental abuses via various human interventions were the causes of the changes. The following were mentioned: cutting down of trees, poor harvesting habits, overgrazing, defilement of the gods and the activities of Christianity which has led to reduced respect and commitment of the people to the gods. Some respondents attributed the change to bush burning. On the part of nature, respondents were of the view that persistent increases in temperature with dwindling rainfall are contributing factors to the environmental changes being experienced. This believe in the duality of the causation of the changes reflect the view that natural and human forces work in a synergy to effect the changes in the environment. However, in these instances, human factors were the most emphasized. These views were similar to those gathered by the household questionnaires (HHQs).

5.11.3 Effects of climate change

The farmers in the focus group discussions have enumerated the perceived or real consequences of CC to include the obvious delay in cropping seasons and a kind of cyclical changes in rainfall pattern. This has resulted in the steady environmental desiccation and its accompanying loss of biodiversity. There is persistent crop failure and annual food shortages especially before the start of the cropping season. The consequence of the above situation is the increase in poverty and the inability to cater for their family's needs especially in the payment of school fees. The discussants also hinted that the incidence of certain strange diseases hitherto unknown to them is as a result of the CC particularly temperature. Examples of these diseases they said was cerebro-spinal meningitis diseases and some skin disorders that they could not name. Animals are also lost through increased mortality as well as the missing of some due to the longer distances covered during free range grazing.

"*It is interesting to note that most migrants often start their migratory attitudes during such harsh conditions of drought and crop failure*" a comment by a 59 year old farmer at Zaare Asigribisi community. Never the less, the participant identifies the prolonged lifespan of their mud houses as a result of drought as a blessing.

5.11.4 Strategies to counter climate change

In the midst of the changes, the discussants noted that they have adopted the following measures to counter the adverse effects. Shift to livestock rearing and fishing in some communities which have reservoirs to contain the flood waters and coincidentally have good pastures around the said dams and reservoirs. Some communities are however seriously constrained in this regard basically because of the lack of water. In some cases their animals die due to lack of feed (pastures) and water.

In terms of crop cultivation, the use of fertilizers has become the order of the day for them to sustain yields and to avoid stunted growth of the crops. In this dire circumstance, others have resorted to urban migration and engagement in non-farming livelihood enterprises e.g. basketry is done for pleasure and domestic purposes.

5.11.5 Suggested measures to counter the effects

From experience, a large scale irrigation scheme according to the farmers is very good but it mostly benefits those farmers in the scheme areas and the close peripheries. Since this is the case, they suggest assistance to engage in community and household irrigation schemes through high yielding boreholes within smaller cluster areas. According to them household irrigation schemes will not only increase accessibility of water to many farmers but will greatly reduce the cost of adaptation to CC because they will not require to pay extra for land. However, the constructions of new dams and reservoirs and rehabilitation of the existing Vea irrigation dam will still be appropriate specifically for improving on fishing alongside mainstream agriculture. Fish and fish-farming, in the view of participants has the capacity to reduce hunger and improve on farmers' incomes. Participants suggested that planting trees will control erosion and will eventually help improve soil fertility.

"The exigencies of the environmental change due to climate change with worsening soil infertility and persistent drying means we have to cultivate more new lands while using fertilizers" this is the view of a 54 year old participant from Gowrie. This is in line with the theory of agricultural intensification and intensification as a means of securing food security in arid and semi-arid areas. To ensure this, participants called for availability of loan facilities and good access to improved crop species.

The participants called on the government to create land reserves purposely for agricultural intensification and for those who engage in dry season farming, they asked for assistance in accessing market for perishable produce especially tomatoes. The participants in all the focus group discussions held, particularly called on the government in collaboration with Ministry of Food & Agriculture (MOFA), Crop Research Institute (CRI) of the Council for Scientific and Industrial Research (CSIR) and other Crop Scientists to intervene by developing and introducing high quality and high yielding crops, specifically tomato, for them to be able to compete favourably with their counterparts from Burkina Faso for market. According to the farmers, their counterparts from Burkina Faso have since several years invaded the local Ghanaian tomato market with their relatively attractive variety and fruity tomato compared with the variety grown in the study area. This, the participants, noted has compelled them to abandon tomato cultivation and that has severely affected their livelihoods. Participants observed that if no appropriate interventions are made, they will be compelled to completely shift to rice irrigated farming that could amplify and exacerbate the water demand challenges on the catchment area. These observations were also particularly made by most of the respondents during the household questionnaire administration.

The participants further called for introduction of other crops that are drought-resilient and with low crop water requirement (CWR) as measure to overcome the challenges of dwindling water resources availability and water storage as well as frequent droughts in the study catchment.

5.11.6 Perceived challenges

Poverty is claimed as the worse impediment to the farmers in their effort to adapt to CC. According to the respondents, the ability to properly and effectively respond to the changes requires that one should be able to afford good seeds and chemicals for pest and weed control. They equally need adequate information on the proper approach to the challenges. In this wise, the unavailability of the capacities and extension services constitute a new dimension of poverty which affect their resilience. Dual effects of flooding and drought are both a bane as well as a potential blessing. Drought is certainly not good for farmers but the good thing is that after each drought, comes a heavy flood as has been the experience over the years. However, the inability to harvest the flood waters for irrigation purposes has become a bane to the prospects of farming in the midst of worsening CC effects. Consequently, according to the narration of the participants in the focus group discussions, inadequacy of irrigation facilities impedes both livestock and crop farming in the study area in spite of all efforts to strategize to offset the effects of CC. Responses from the questionnaire administration and institutional interviews also point to this.

5.11.7 Responsibility for the suggested measures

Majority of the participants placed the responsibility for the provision of the facilities and services to help adapt to the CC effects at the bosom of central government and the agricultural extension services. This probably suggest that the farmers are not adequately benefiting from the decentralization process through the district assemblies or possibly the district assemblies have not shown enough commitment to the course of production at the local level. The virtual absence of collaboration between the local government and the people, make the people still heavily dependent on the central government for several interventions including assistance to adapt to CC.

5.11.8 Expected benefits if measures are carried out

The expectation of the farmers in terms of provision of the needed facilities and assistance include the following; an increase productivity in all sectors of farming especially in the production of the cereals which are the staples and motivation for the youth to engage in agriculture and stay back in the community instead of migrating to the south in search for greener pastures. This, they said will indirectly also affect food availability and income to care for their children. The other side of increased production comes through the reduction of post-harvest losses.

5.12 Institutional interviews

In the quest to further understand the possible future CC adaptation dynamics and options for building modelling scenarios, the research interviewed eight key stakeholder institutions on CC, its impacts on the populace and their activities, adaptation measures currently being implemented and how best CC adaptation can be financed. The selected institutions which included Irrigation Company of Upper Region (ICOUR), Ghana Irrigation Development Authority (GIDA), Ministry of Food & Agriculture (MOFA), Ghana Water Company Limited (GWCL), Community Water and Sanitation Agency (CWSA), Water Resources Commission (WRC), Hydrological Service Department (HSD) and Environmental Protection Agency (EPA) were chosen based on the critical role they play in the catchment area. The following section of the study presents analyses of the responses obtain during the interview with these institutions.

5.12.1 The reality of climate change and variability - Institutions points of view

The incidence of CC and variability appears to have been evidently noticed by all the institutions interviewed because all the eight institutions responded to have noticed long term changes in mean temperature and rainfall in the past 30 years. Despite the consensus on the change in the climatic conditions, the research however observed a mild variance between responses from these institutions on the cause of these changes. Some institution indicated that changes in climatic conditions was due to human activities such as depletion of vegetation cover, bad agricultural practices and environmental pollution, while others attributed the changes to natural global warming without acknowledging the role of Man.

Questions were also to ascertain the level of awareness of the public and farmers as observed by the institution during the course of the routine activities and responses showed that five out of eight institutions interviewed agreed that there is adequate awareness among farmers and the general public on climatic changes. The remaining institutions however believed the awareness on climate conditions was not much because, though, most people have observed changes in climate conditions; they are not able to tell the causes of these changes.

5.12.2 Impact of climate change and variability – Institutions points of view

An interview of the institutions also revealed that the changes in climate conditions have clear impacts on water resources and lives/livelihoods within the catchment area. The major observed impacts on water resources are the quantitative reduction of available water volume as well as pollution of the water bodies. These, they observed are as a result of siltation of reservoirs and loss of water through evaporation due to high temperatures particularly during the dry season. These impacts have further constrained lives and livelihoods within the catchment due to the dependence of the populace on water resources to engage in farming which is their primary occupation. Among the impacts on livelihoods enumerated by the institutions are reduced farmlands due to lack of water for irrigation, floods, droughts and delayed start of season culminating into poor crop yield with its attendant challenges such as food insecurity, nutritional challenges, low household income and poverty.

The impacts are also extended to the institutions and their activities as all institutions acknowledged to have experienced the impact of these changes or expect to be affected by them in the future. For example MOFA and EPA have an extra burden of sensitization and education with their limited staff as a result of these changes while ICOUR is currently experiencing reduction in the amount of levies collected due to low crop yield. The GWCL on the other hand is yet to feel the impact of the changes in climatic conditions; though, the institution has noted shortfalls of water for their operation is certain in the future if nothing is done about the current trend. Besides the above, MOFA believes that these impacts also offers them a leverage not only to demand but also make adequate use of some government policies such as input subsidies, improved seeds varieties and technologies. Future risk of changes in temperature and rainfall in the next 30 years were observed to include desertification, extinction of crop and animal species, famine and prevalence of diseases, while the institutions could hardly identify any positive impacts of the changing climate in the next 30 years except the development of new crop and animal species and modern technologies to adopt to the adverse effects of CC.

5.12.3 Climate change adaptation measure implemented by key institutions within Vea catchment

In the midst of the challenges of CC, these institutions in collaboration with government and the private sector have identified and planned to implement some adaptation measures and, key among these measures mentioned are expansion of irrigation facilities and improvement of irrigation efficiency from 50% to 70%, rehabilitation of existing and building of new water supply infrastructure, sensitisation of communities to use improved mud stove and gas fuel. For instance, the GWCL noted that on foreseeing serious future constraints on water availability and supply in the area, it has, in collaboration with Ministry of Water Resources, Works and Housing (MWRWH) laid down plans for extension of its water supply system to source water from a bigger dam reservoir at Tono for supply of water to the cities of Bolgatanga, Navrongo and their surroundings, while the existing supply system which currently serves Bolgatanga and Bongo would be rehabilitated and dedicated to serve only Bongo and its surroundings. This planned measures were noted to be borne out of the observation that the raw water source for the existing system, the Vea irrigation reservoir, was now feared being exploited to its limit in the near future due to impacts of CC.

Other adaptations measures identified and implemented are the introduction of new farming methods and technologies, drought resilient animal and crop species and engaging in forestation projects to restore the lost vegetation cover. These adaptation measures have varied benefits to each of the institutions. The MOFA, for example, acknowledges that these measures have not only provided opportunities for unused expertise to be practically demonstrated but also enable them acquire new expertise to address current development trends within the sector. In the case of ICOUR, the planned expansion and usage of irrigation facilities as well as government ongoing rehabilitation of Pwalugu Tomato Factory in the area to provide tomato market will enable the institution raise some funds from levies for maintenance of the facilities and sustenance of the company. This planned irrigation expansion was said to include rehabilitation of dilapidated irrigation infrastructure (e.g. broken down canals) resulting in water loss and dredging of the reservoir. The research however showed that for all these measure to be efficient there is the need to address constraints such as illiteracy rate among farmers to enable them abandon outmoded agricultural/irrigation practices and accept improved ones introduced. Other constraints to adaptation include competing land use demands and unavailability of markets for farm produce. The information obtained from the interview showed a clear need for these adaptation measures to be properly synergised to comprehensively reduce the vulnerability of the society.

5.12.4 Financing climate change adaptation within the Vea catchment

Adaptation to CC cost money and as a result the study inquired on how CC adaptation is being financed since this is critical. Three main categories of organisations were mentioned by the institutions as the major financiers of the adaptation within their setup. These are government (through the Ghana social opportunities projects), agriculture related NGOs and financial institutions. The forms of support normally received included services, credit facilities, land preparation machinery, arranging markets and inputs. Through the support institutions have been able to facilitate field activities, increase productivity and organised trainings and demonstrations for farmers. Though these have, to some extent, helped in adapting to the adverse effects of CC and positioned famers to be able to effectively adapt in the future, the institutions agreed to the need for more organised and comprehensive support programmes that will help in overhauling the whole irrigation infrastructural network, introduce reliable and dependable land preparation machinery, provide ready markets for farm produce and distribute tree seedlings to farmers among others.

Clearly, the incidence of CC and its adverse effects have been observed by key stakeholder institutions within the Vea Catchment and both institutions and individual farmers have started experiencing the burden of this change on their organisation and activities. Though several attempts are currently being made to adapt to these changes, there is the need for synergies and programming of all these efforts to better results.

5.13 Discussion

The perception of farmers that temperature had increased over the past three decades in the study area corresponds with the analysis of observed temperature as discussed in chapter 4 of this study and relate to perception of farmers in some parts of Ghana and other parts of Africa as observed by Maddison (2007); Yesuf *et al.* (2008); Kemausuor *et al.* (2011); Nyanga *et al.* (2011); Fosu-Mensah *et al.* (2012); Juana *et al. (*2013) and Kalungu *et al. (*2013).

The farmers' perception on rainfall is, however, inconsistent with the results from the analysis of observed rainfall data within the period as there were no trends and no break points in rainfall time series as well as there were no observed changes in variability over the study period. Blench (2006) found a similar case where there was disparity between public opinion on annual rainfall amount and variability and the results of analysed observed rainfall data in the Upper East Region (UER). In that study, it was that there were inter-annual fluctuations with fairly stable levels of annual rainfall amount across the Region (UER), while farmers held the belief that there was a declining trend in annual rainfall amount coupled with unreliable distribution. This is partly due to variation in scientific measurement of rainfall trends and drought with emphasis on meteorological drought while farmers consider agronomic droughts as explained by (Slegers 2008). According to Ovuka & Lindqvist (2000), scientists often analyse climate data at different timescales rather than those that are important for farmers and crop growth. This is a reason to expect variations in farmers' perception and observed data as found by this study.

Regarding the perception of farmers on causes of CC, fury of God was mentioned as a cause. Indeed, the respondents from their rural background and strong attachment to tradition and beliefs could not blame CC on any empirical interaction rather than a reaction of the supernatural. Earlier studies by Gyampoh *et. al*. (2008) and Nyanga *et al.* (2011) elsewhere in Ghana and Zambia respectively reported similar findings where respondents had attributed CC to supernatural causes. This belief and the inability of a few farmers to see any significant impacts of the changes in the climate could be attributed to the high illiteracy rate in the area that inhibits farmers' ability to keep records of their farming activities and to carry out evaluations and cost analysis of their activities. Obviously, the deviation from the common agreement on the adversity of CC impacts could be attributable to the fact that some farmers are still not able to assess the causal linkages between their activities and the quality of the environment.

The farmers practices both anticipatory and reactive adaptation strategies similar to what Burke and Lobell (2010) referred to as ex ante and ex post adaptive measures. Largely, their adaptive practices were location-specific and tied to anticipated moisture dynamics comprising of on and off-farm adaptations. However, their commitment is tilted more to improving on the age-old farming practices. This commitment of the farmers to on-farm activities is partially due to their scepticism against the off-farm alternatives which they have no insurance or safety nets in case of failure as acknowledged by Hoddinott & Kinsey (2001) and Maccini & Yang (2009). In the valleys, famers relocated their farms to uplands for fear of possible floods while those in the uplands relocated closer to the river valleys to avoid excessive dryness in the event of drought. Kemausuor *et al.* (2011) observed that such emerging practices of relocating farms closer to rivers coupled with the use of chemical fertilizers and pesticides will lead to pollution and affect aquatic lives and ecology of rivers and the long-term impact on water availability for domestic use.

The external CC adaptation support received by farmers varied in terms of frequency of access and content of support such as extension services, material inputs or financial support with the financial support being the least and favoured only a privileged few. Nevertheless, previous studies have shown that access to credit is influential in adapting to CC through access to inputs for reducing vulnerability (Butt *et al*. 2006; Antwi-Agyei *et al*. 2012; Fosu-Mensah *et al*. 2012).

Most of the technical information necessary for effective farmer adaptation comes either too late or in some cases not at all. Yet that is the sole responsibility of the MOFA extension officers whose duties are to reach all farmers with such technical assistants including weather forecast and rainfall pattern each year. This has resulted in many farmers lacking reliable climate adaptation information particularly onset and cessation of rainfall, thus one of the major challenges confronting farmers in CC adaptation as also observed by other recent studies (Antwi-Agyei *et al*. 2012). This is also consistent with findings by Antwi-Agyei *et al*. (2012) that indicated that irrigation facilities were crucial for climate-sensitive (rain-fed) agriculture dependent famers in the area, as means of reducing their vulnerability to CC. Thus further studies on feasibility of more irrigation schemes establishment in the area and sustainability of such schemes are required.

5.14 Summary and conclusion

The analysis points out that, farmers are generally aware of CC, although in a very subjective term as their understanding of it is directly linked to the outcome of their daily livelihood activities. Even though most of the farmers could not explain what CC is, they could give a description of it based on their assessment of increases in temperature, change in rainfall amount, intensity, duration, number of events and the timing of rainfall. Their observations about changes in climate and climate variability were generally consistent with analysed observed temperature data, but differ from results of analysed observed rainfall as discussed in chapter 4. Farmers perceived decreasing trend in rainfall could be influenced by the temperature-driven evapotranspiration increase. In spite of farmers' knowledge of CC, its effects and alternative livelihood chances, they could not pursue a coping strategy because of poverty, inaccessibility to loan facilities, lack of irrigation facilities, and so on. With limited governmental interventions, the farmers are almost without any capacity to avert the environmental threat.

Modern agricultural extension systems comprise of four major actors/stakeholders: public agencies, private service providers, producer organizations (POs), and non-governmental organizations (NGOs) (Neuchâtel Group, 1999). This study, however, revealed that only two of these actors operate in the study area, namely the MOFA-extension-service (public agency) and NGOs. This creates a major shortfall of information and technology dissemination, farmers' access to organisations such as farm input suppliers, food purchasers, trade unions, cooperatives, and so on. To address these adaptation shortfalls and other challenges, both farmers and stakeholder institutions have identified and outlined some adaptation measures to be taken as means of adjusting to the adverse effects of the changing climate. These planned measures include expansion of irrigation facilities, extension and restructuring of domestic water supply infrastructure as well as farmers intent to resort to only rice irrigation cultivation due to invasion of the local tomato market by their counterparts from Burkina Faso. Most other farmers who previously practiced only rain-fed agriculture have now also planned to go into irrigation as the only option. These planned adaptation measures could have consequential impacts on the water resources in the catchment and therefore raise several scenarios for assessing these impacts. The scenarios include answering the following questions. What will be the catchment water resources availability situation in the future if:

- ✓ The irrigation continues to expand at the current rate of 1.1%/a or even higher with business as usual (current % proportion of each crop).
- ✓ The potential irrigable area (1400 ha) is developed with business as usual.
- ✓ Only rice is used for total developed irrigable area (850 ha).
- ✓ Only rice is used for total potential irrigable area (1400 ha).
- ✓ Only tomato is used for total developed irrigable area (850 ha).
- ✓ Only tomato is used for total potential irrigable area (1400 ha).
- ✓ Vea irrigation reservoir serves domestic water supply to only Bongo District (Bongo and its environs).

The following recommendations are therefore proposed.

- There is the need for MOFA to facilitate the formation of a modern agricultural extension system consisting of all four actors and ensure smooth coordination among the organisations. This will get farmers participate in decision making process; improve their knowledge base by easy transfer of ideas/information. The creation of linkages or partnerships between farmers and private actors should be the prime focus to facilitate farmers' access to a range of services such as farm inputs, loan facilities, product marketing, and so on.
- Government and its executing institutions should embark on alternative irrigation systems such as household and community cluster irrigation schemes in order to avert possible famine due to cumulative effects of annual crop yield reductions resulting from a temperature-driven evapotranspiration increase, constant soil moisture deficits and agricultural drought
- Government should, as a matter of urgency, salvage the collapse of Vea irrigation scheme through reconstruction of broken down canals, dredging of the reservoir and revamping of Irrigation Company of Upper East Region (ICOUR) which manages the scheme.
- In the meantime, MOFA and its allied public agricultural advisory research institutions like the Council for Scientific and Industrial Research (CSIR) and NGOs currently rendering advisory and other supports to farmers, should provide services tailored towards developing the capacities of smallholder farmers to properly adapt to demands of CC. Such services should include credit facilities (minor loans), new improved seeds, developing and introducing of high quality and high yielding crops, specifically tomato and other drought resistant crops with low crop water requirement (CWR), and so on.
- MOFA extension service should be upgraded in terms of personnel and mobility to better access farms. Farmers would greatly benefit from extension personnel trained on CC and adaptation strategies.

CHAPTER 6: IMPACTS OF FUTURE CLIMATE CHANGE ON WATER RESOURCES AND FUTURE WATER PLANNING WITH WEAP

6.1 Introduction

This chapter presents the findings of the analysis and assessment of the impact of future climate change (CC) on water resources and water allocations in the study area. These include results of the analysis to assess the future situation of water availability for irrigation, domestic supply and livestock watering in the study area. The chapter is organized using three main sub-headings, namely: (1) results of scenarios analysis, (2) discussion and (3) summary and conclusion.

6.2 Results of scenarios analysis

Remarkably, all simulated results as presented in this sub-section are based on the highest climate emission scenario, Representative Concentration Pathway (RCP 8.5), from which all the 16 RCMs simulations used in predicting future streamflows were obtained as discussed in chapter 3 and chapter 4. For each of the two future time slices under review, the near future (2021-2050) and the distance future (2071-2100), WEAP results of four streamflow time series (scenarios) are compared in the context of eight different "what-if" scenarios of likely future development options in the catchment as discussed in chapter 3 and chapter 5. These four streamflow time series which were used as inputs into the WEAP model are: the reference streamflow (1983-2012), the two extreme streamflow time series (the highest and the lowest) derived from the 16 RCMs simulations for the period and the streamflow time series averaged over the 16 RCMs simulations. As discussed in chapter 3 (sub-section 3.3.13), these four streamflow time series are herein referred to as: "reference", "wet", "dry" and "average" scenarios, respectively, for the purpose of convenience. That is, the reference scenario represents a future with rainfall and streamflow as has been over the reference period (1983-2012); the wet scenario represents a future with the highest rainfall and streamflow among all the 16 RCMs simulations used in this study; the dry scenario represents a future with the lowest rainfall and streamflow among all the 16 RCMs simulations; and the average scenario represents a future with rainfall and streamflow as averaged over all the 16 RCMs simulations.

It should be noted that for each of the two periods, 2021-2050 and 2071-2100, the two RCM models from which the highest (wet) and the lowest (dry) streamflow time series were derived, are different. That is, for the near future (2021-2050), the wet scenario was derived or predicted from the ICHEC-EC RCM model simulated climate conditions, while the dry scenario was derived from MPI-ESM model simulated climate conditions. On the other hand, the wet and dry scenarios for the distance future (2071-2100), were derived from the simulated climate conditions by HadGEM2-ES and IPSL-IPSL-CM5A RCM models respectively.

6.2.1 The situation in the future if irrigation continues to expand at the current rate of 1.1%/a under business as usual (BAU) (current % proportion of each crop)

6.2.1.1 Annual unmet demands

From the records made available by the Irrigation Company of Upper Region (ICOUR) which manages the irrigation project at the study area, irrigation growth rate in the area had varied over the past years but in recent years the average annual irrigation growth rate is 1.1% with irrigation efficiency of 50%. The crops grown were mainly rice (70.2% of annual cropped area), tomato (15.7% of annual cropped area), onion (9.2% of annual cropped area) and pepper (4.9% of annual cropped area). In assessing the availability of water in the catchment by a "what-if" scenario where the current growth rate and percentage areas by crops project into the future, the results obtained from WEAP were as illustrated in figures 6.1 and 6.2 for the period 2021-2050 and figures 6.3 and 6.4 for the period 2071-2100.

It is observed from figure 6.1 that with the reference and the wet (ICHEC-EC model) scenarios, WEAP estimates that water availability in the catchment will be sufficient for all demands throughout the entire period (2021-2050). This is similar to WEAP results for the average scenario, except in the first year of the period (2021) where the latter scenario (green in Fig. 6.1) showed annual unmet demand of about 0.6 x 10^6 m^3. However, WEAP results for the dry scenario (MPI-ESM model) indicates considerable levels of annual unmet water demands across the period 2021-2050 (red in Fig. 6.1). With the current irrigation efficiency of 50%, the average annual unmet demand and the total sum of unmet demands were 1.3 x 10^6 and 40.3 x 10^6 m^3 respectively for the period 2021-2050 based on the dry scenario (green in Fig. 6.1). However, if there is an improvement in irrigation efficiency from 50% to 70%, as targeted by ICOUR, the average annual unmet demand and the total sum of unmet demands will reduce to 1.1 x 10^6 and 32.9 x 10^6 m^3 respectively for the period (Fig. 6.2). This gives percentage reduction in both average annual unmet demand and the total sum of unmet demands of about 18%.

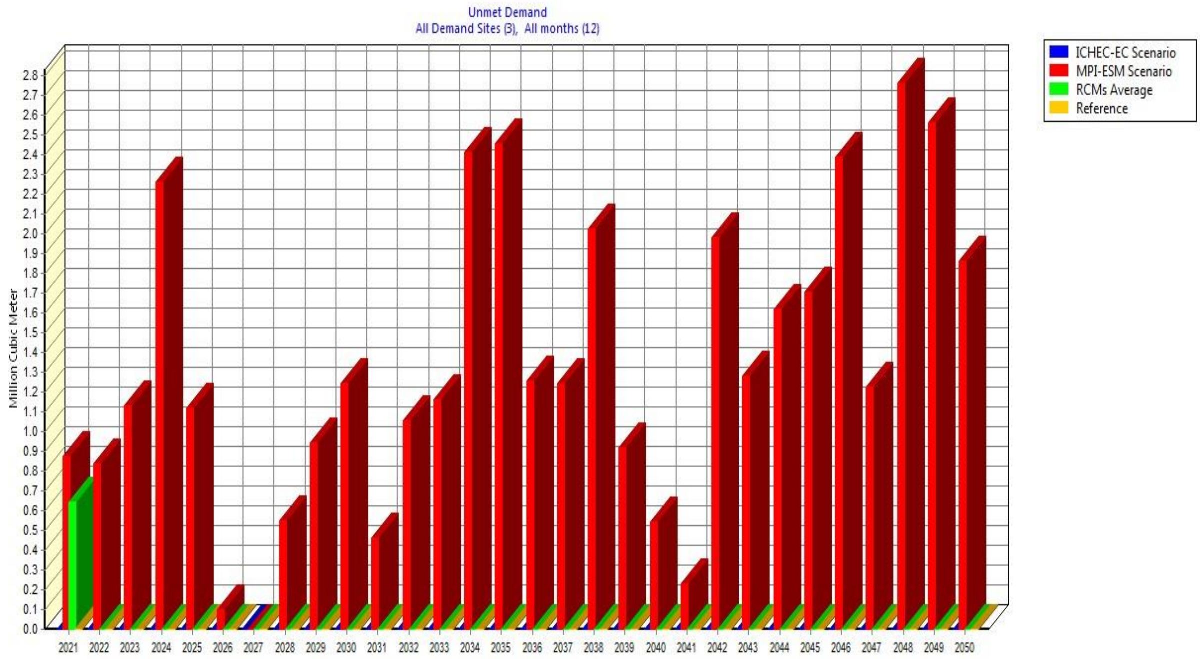


Figure 6.1: *The water availability situation in the period 2021-2050 if irrigation continues to expand at the current rate of 1.1% with business as usual (current proportions of crops & efficiency of 50%)*

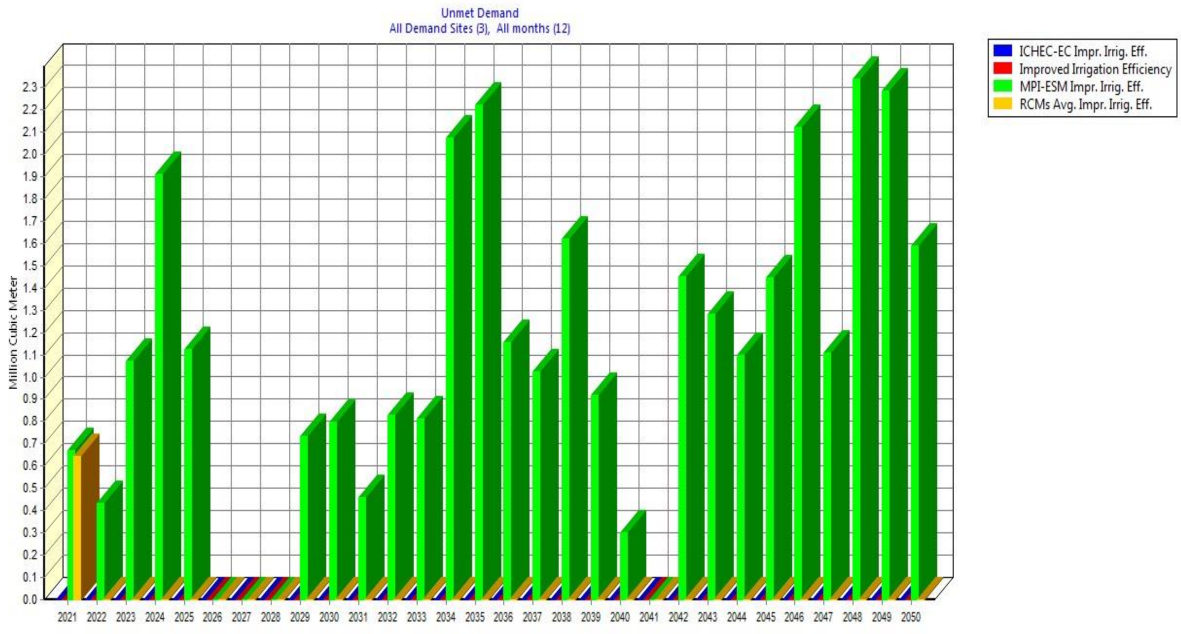


Figure 6.2: *The water availability situation in the period 2021-2050 if irrigation continues to expand at the current rate of 1.1% with improved efficiency from 50% to 70%*

With the same scenario of irrigation rate at 1.1%, WEAP results for the distance future (2071-2100) was similar to results for the near future (2021-2050) in terms of trend, but differ with regards to magnitude of unmet demands. Figures 6.3 and 6.4 depict that water availability in the catchment will be sufficient for all demands over the period 2071-2100 based on the reference and the wet (HadGEM2-ESmodel) scenarios. Like in the near future (2021-2050), WEAP results of the average scenario, show sufficient water availability for all demands across the period 2071-2100, except in the first year of the period (2071) where the latter scenario (green in Fig. 6.3) showed annual unmet demand of 1.0 x 10^6 m^3.

The WEAP results based on the dry scenario (IPSL-IPSL-CM5A model), however, indicate considerable annual unmet water demands across the period 2071-2100. With the current irrigation efficiency of 50%, the average annual unmet demand and the total sum of unmet demands were 1.8 x 10^6 and 55.41 x 10^6 m^3 respectively for the period 2071-2100 (red in Fig. 6.3). With improvement in irrigation efficiency from 50% to 70%, however, the average annual unmet demand and the total sum of unmet demands are reduced to about 1.6 x 10^6 and 49.3 x 10^6 m^3 respectively for the period 2071-2100 (Fig. 6.4). This gives percentage reduction in both average annual unmet demand and the total sum of unmet demands of about 16%.

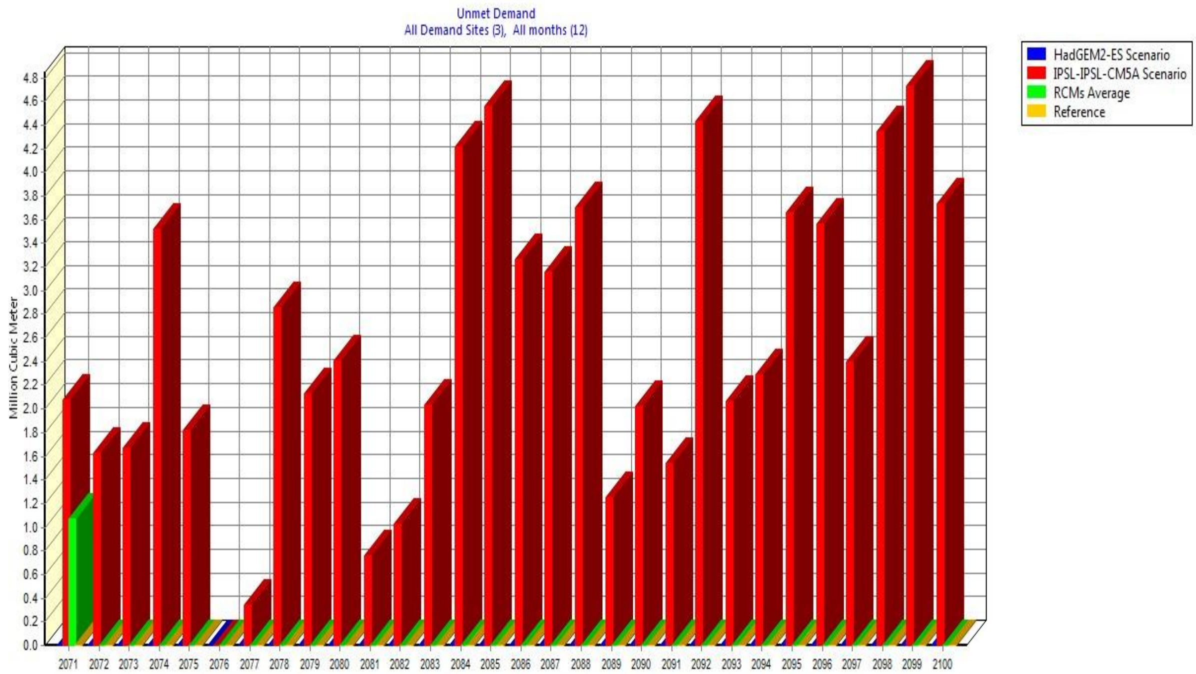


Figure 6.3: *The water availability situation in the period 2071-2100 if irrigation continues to expand at the current rate of 1.1% with business as usual (current proportions of crops & efficiency of 50%)*

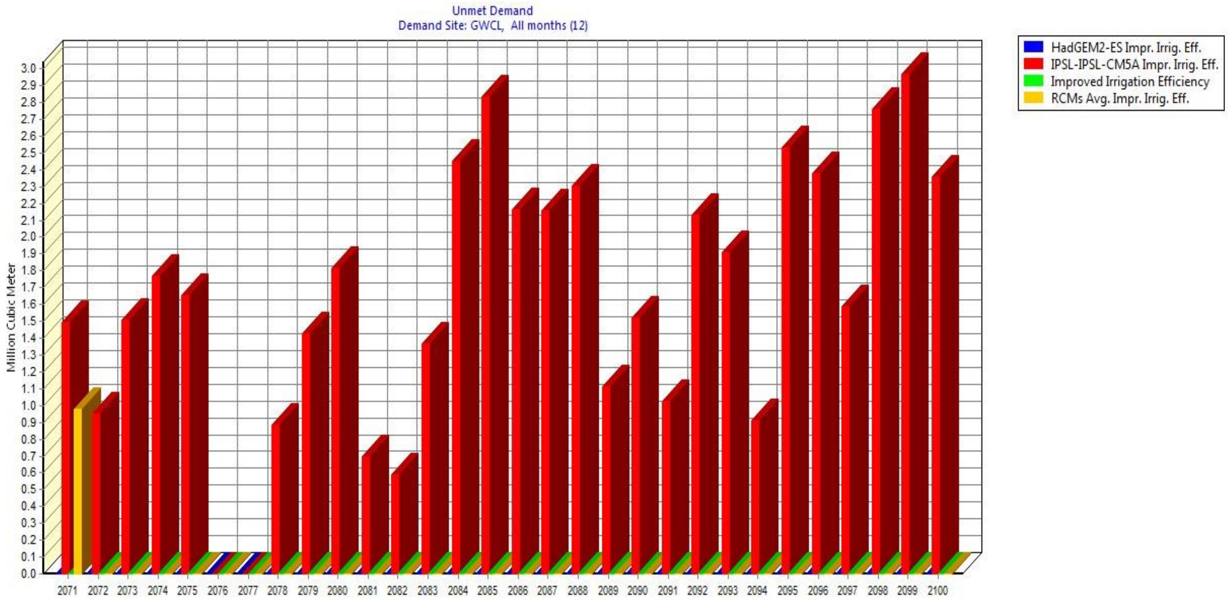


Figure 6.4: *The water availability situation in the period 2071-2100 if irrigation continues to expand at the current rate of 1.1% with improved efficiency from 50% to 70%*

6.2.1.2 Domestic water supply coverage

In terms of domestic water supply by the Ghana Water Company Limited (GWCL), Table 6.1 shows the results of monthly average percentage coverage for the reference scenario of current streamflow in comparison with the three RCMs-derived streamflow scenarios under review: the wet, dry and average scenarios derived from the 16 RCMs simulated conditions for the period, 2021-2050. From the table, it is shown that under both the average and the dry scenarios, there would be shortfall in domestic water supply coverage during the near future period (2021-2050). The most severe situation would be under the dry scenario (MPI-ESM model).

Table 6.1: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if irrigation continues to expand at the current rate of 1.1% and irrigation efficiency of 50%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	33.7	28.4	30.3	26.5	34.4	96.1	100	100	100	92.2	70.6	51.2
Average scenario	96.7	96.7	96.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.2 depicts that if there is improvement in irrigation efficiency from the current 50% to 70%, there would be relative increase in domestic water supply coverage in the period as shown by the dry scenario (MPI-ESM model).

Table 6.2: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if irrigation continues to expand at the current rate of 1.1% under improved irrigation efficiency from 50% to 70%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	52.1	37.3	35.9	31.3	38.6	96.1	100	100	100	95.7	76.3	62.7
Average scenario	98.3	98.1	99.7	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.3 indicates that under the current irrigation efficiency of 50%, there would be shortfall in domestic water supply coverage during the distance future period (2071-2100) based on both the average and the dry scenarios. The severer situation would be felt if conditions turn up as predicted by IPSL-IPSL-CM5A model from which the dry scenario was derived.

Table 6.3: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if irrigation continues to expand at the current rate of 1.1% and irrigation efficiency of 50%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	23.3	15.7	23.6	36.1	47.4	95.2	100	100	99.3	83.4	57.3	37.4
Average scenario	96.7	96.7	96.7	99.8	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.4 shows that if there is improvement in irrigation efficiency from the current 50% to 70%, there would be corresponding increase in domestic water supply coverage in the period 2071-2100 as shown by the dry scenario (IPSL-IPSL-CM5A model).

Table 6.4: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if irrigation continues to expand at the current rate of 1.1% under improved irrigation efficiency from 50% to 70%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	34.6	29.6	29.2	37.5	50.5	95.2	100	100	99.8	88.2	65.3	43.9
Average scenario	98.7	98.5	98.3	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

6.2.2 The situation in the future if irrigation expands at a rate of 2.3%/a under BAU

6.2.2.1 Annual unmet demands

If the infrastructure of the irrigation project is revamped based on laid done policies and plans by the government, then it should be possible to achieve the annual growth rate of 2.3% as was previously and now, the target of the project management. In that case, figures 6.5 and 6.6 depict the situation of how water availability in the catchment will evolve in the near future (2021-2050), while figures 6.7 and 6.8 present the situation in the distance future (2071-2100). Under this scenario of irrigation rate at 2.3%, it is only the results of the dry scenario predicted from the RCMs simulated conditions that indicate annual unmet demands across both future time slices with much higher annual unmet demands in the distance future (2071-2100). For the near future (2021-2050), the average annual unmet water demand and the total sum of unmet demands are found as 1.8 x 10^6 and 53.7 x 10^6 m^3 respectively under the current irrigation efficiency of 50% (Fig. 6.5). These will, however, reduce to about 1.5 x 10^6 and 43.6 x 10^6 m^3 respectively if irrigation efficiency is improved from 50% to 70% (Fig. 6.6), given a reduction of about 18% in both values.

On the other hand, the average annual unmet demand and the total sum of unmet demands are found to be 2.5 x 10^6 and 74.8 x 10^6 m^3 respectively for the distance future (2071-2100), based on the irrigation efficiency of 50% (Fig. 6.7). These, however, will similarly reduce to about 2.4 x 10^6 and 70.7 x 10^6 m^3 respectively on improvement of irrigation efficiency from 50% to 70% (Fig. 6.8), representing a reduction of about 5% in both figures.

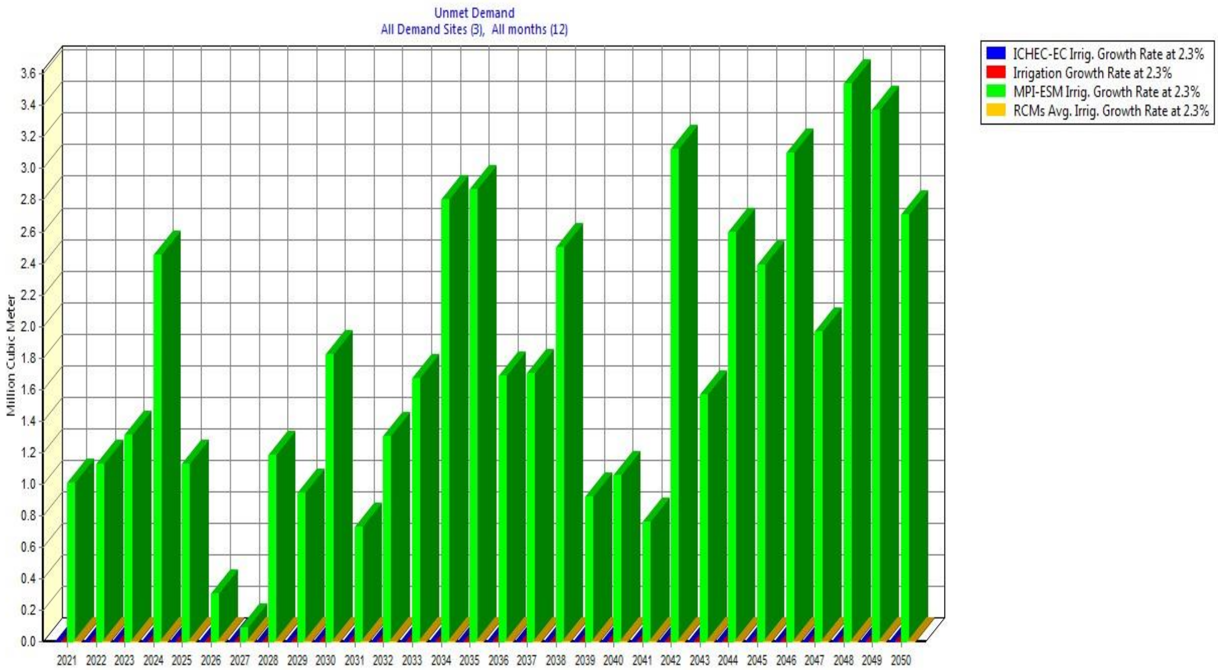


Figure 6.5: *The water availability situation in the period 2021-2050 if irrigation continues to expand at the rate of 2.3% with business as usual (current proportions of crops & efficiency of 50%)*

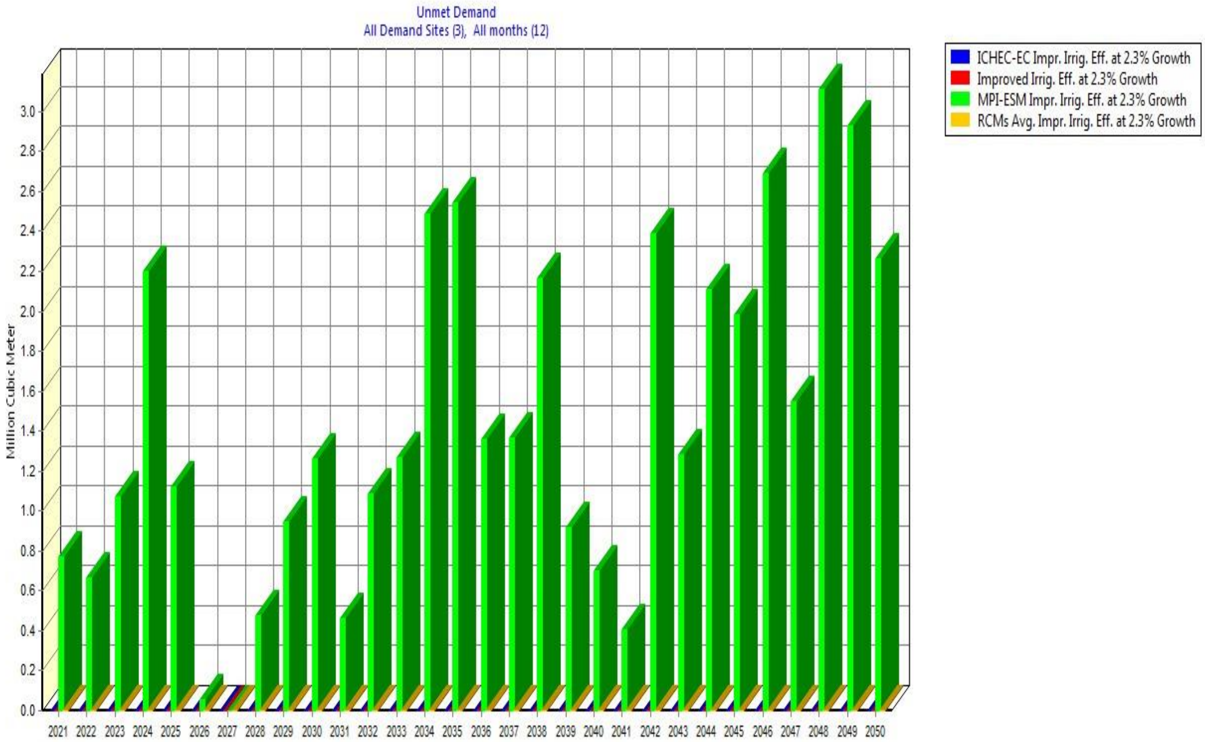


Figure 6.6: *The water availability situation in the period 2021-2050 if irrigation continues to expand at the rate of 2.3% with improved efficiency from 50% to 70%*

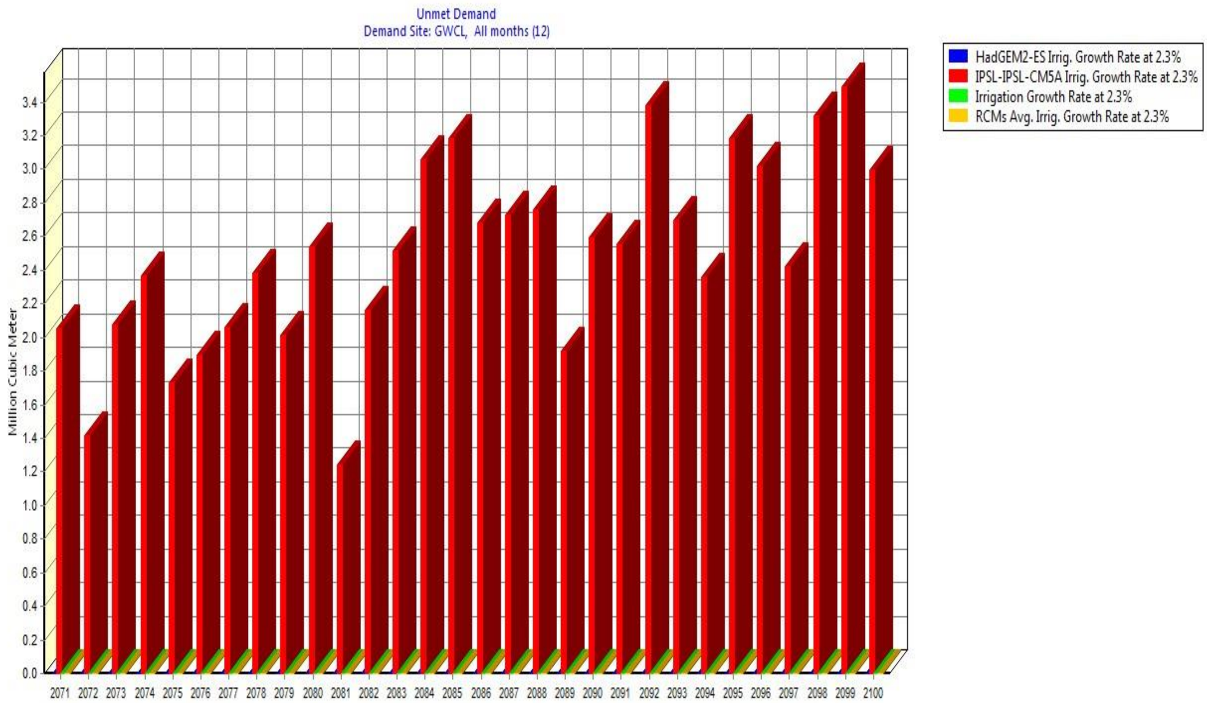


Figure 6.7: *The water availability situation in the period 2071-2100 if irrigation continues to expand at the rate of 2.3% with business as usual (current proportions of crops & efficiency of 50%)*

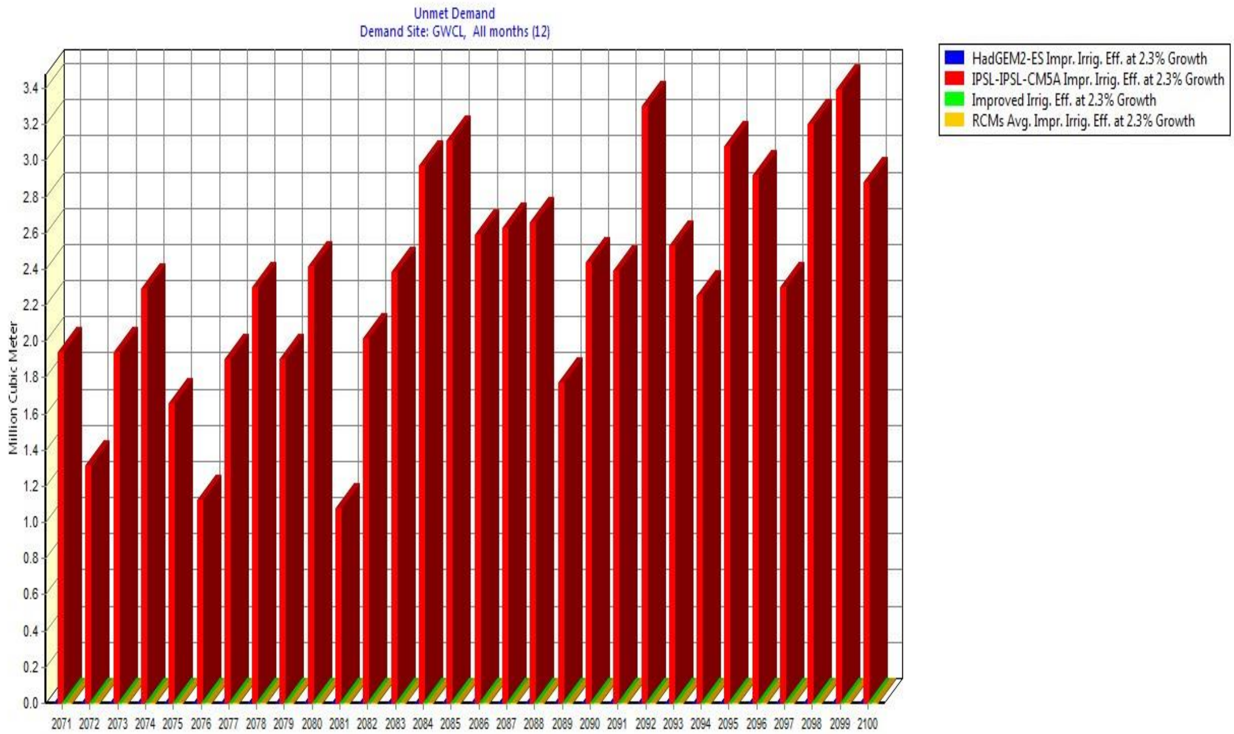


Figure 6.8: *The water availability situation in the period 2071-2100 if irrigation continues to expand at the rate of 2.3% with improved efficiency from 50% to 70%*

6.2.2.2 Domestic water supply coverage

Table 6.5: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if irrigation expands at a rate of 2.3% under current irrigation efficiency of 50%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	21.2	16.2	21.8	21.9	31.5	96.1	100	100	100	83.4	58.8	33.8
Average scenario	100	100	100	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.5 indicates that for the period 2021-2050, if irrigation expands at the rate of 2.3% with business as usual (current proportions of crops & efficiency of 50%) then there would be considerable shortfall in domestic water supply coverage under the dry scenario (MPI-ESM model). However, with improvement in irrigation efficiency from 50% to 70%, there would be significant corresponding increase in water supply coverage as shown in Table 6.6.

Table 6.6: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if irrigation expands at a rate of 2.3% under improved irrigation efficiency from 50% to 70%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	32.9	28.0	26.3	24.4	35.0	98.1	100	100	100	89.3	67.7	47.8
Average scenario	100	100	100	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.7 depicts that for the period 2071-2100, if irrigation expands at the rate of 2.3% with business as usual (current proportions of crops & efficiency of 50%) then there would be severe shortfall in domestic water supply coverage under the dry scenario (IPSL-IPSL-CM5A model). There would, however, be corresponding increase in water supply coverage with improvement in irrigation efficiency from 50% to 70%, as shown in Table 6.8.

Table 6.7: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if irrigation expands at a rate of 2.3% under current irrigation efficiency of 50%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	0	6.1	18.1	30.2	44.6	95.2	100	99.7	86.3	51.1	13.4	2.8
Average scenario	100	100	100	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.8: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if irrigation expands at a rate of 2.3% under improved irrigation efficiency from 50% to 70%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	3.3	8.0	18.1	30.2	44.6	97.3	100	100	92.2	59.5	27.2	5.9
Average scenario	100	100	100	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

6.2.3 The situation in the future if potential irrigable area (1400 ha) is developed under BAU

6.2.3.1 Annual unmet demands

A scenario where irrigation in the catchment could be expanded to cover the entire potential irrigable area (1400 ha) in a short distance future was also explored using WEAP. The results from WEAP as illustrated by figure 6.9 and 6.10 indicate that under the reference and the wet (ICHEC-EC model) scenarios, water resources in the catchment will be sufficient for all demands in the catchment during the period, 2021-2050. Similarly, with the average scenario derived from RCMs simulated conditions for the period (2021-2050), WEAP estimated that water resources in the catchment will be sufficient for all demands in the catchment during the period, except in the first year of the period, 2021. However, conditions simulated by the MPI-ESM model (dry scenario), indicates a rising annual unmet demands across the period with an average value of 3.2 x 10^6 m^3 and the total sum of unmet demands of 94.7 x 10^6 m^3 over the period (2021-2050) under the current irrigation efficiency of 50% (Fig. 6.9). With improvement in the irrigation efficiency from 50% to 70%, these values of the average annual unmet demand and the total sum of unmet demands for the period (2021-2050), will reduce to about 2.8×10^6 and 84.7×10^6 m^3 respectively; giving percentage reduction of about 11% in both values (Fig. 6.10).

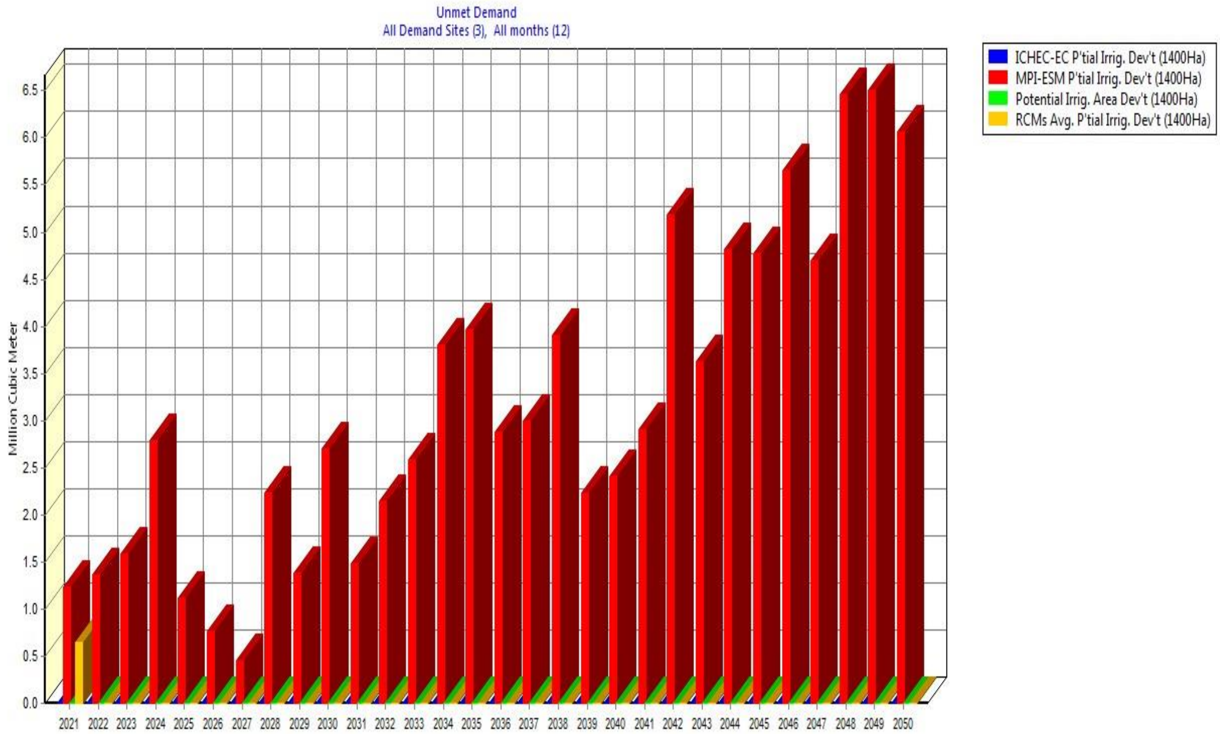


Figure 6.9: *The water availability situation in the period 2021-2050 if potential irrigable area (1400 ha) is developed with business as usual (current proportions of crops & efficiency of 50%)*

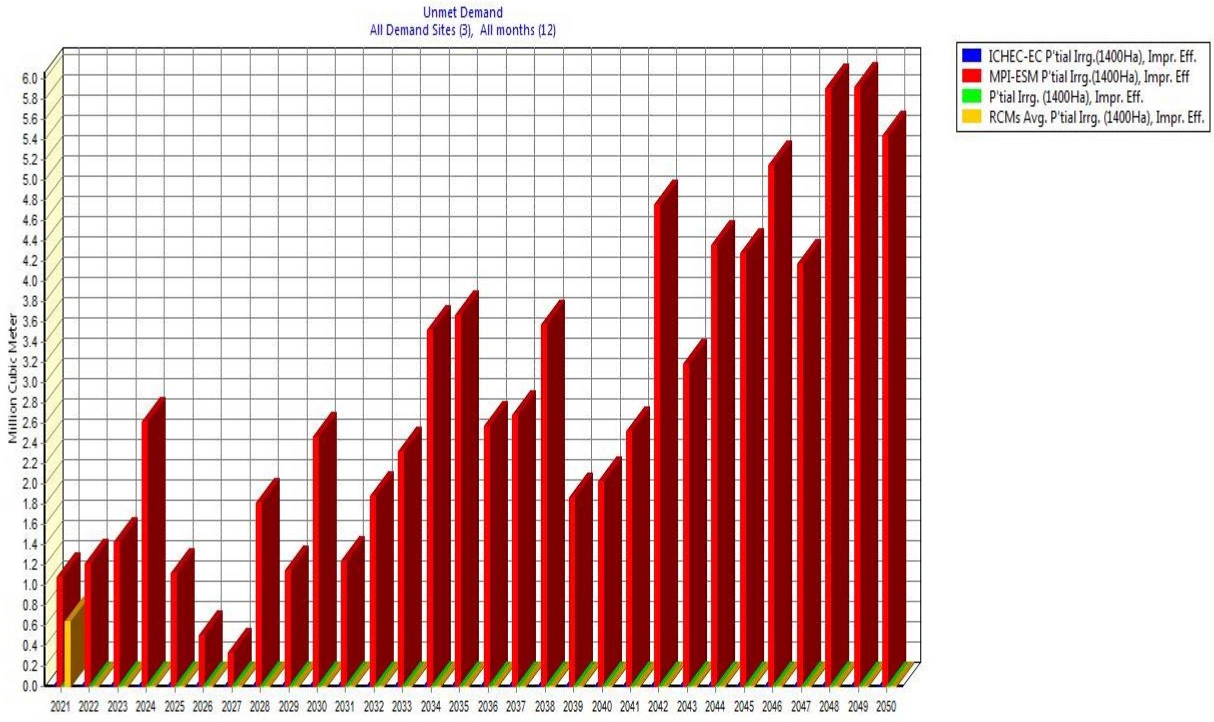


Figure 6.10: *The water availability situation in the period 2021-2050 if potential irrigable area (1400 ha) is developed with improved efficiency from 50% to 70%*

A vast difference exists between the situations in the near future (2021-2050) and the distance future (2071-2100) under the above scenario of irrigating the entire potential irrigable area (1400 ha). The WEAP results of the four different scenarios (reference, wet, dry and average) as illustrated by figure 6.11 and 6.12 indicate that water resources in the catchment will considerably be insufficient for the demands in the catchment during the distance period (2071-2100) under business as usual. While the reference condition (green in both Fig. 6.11 & 6.12) and the wet scenario (blue in both Fig. 6.11 & 6.12) showed considerable unmet demands only in the last half of the period (2071-2100), the dry and the average scenarios showed considerable unmet demands throughout the period, particularly the dry scenario. The situation is severer under the dry and the average scenarios than it is under the reference and the wet scenarios. The WEAP results of the dry scenario (IPSL-IPSL-CMSA model) showed the highest unmet demands of all. The average annual unmet demand and the total sum of unmet water demands as well as percentage changes in unmet water demands on improvement of irrigation efficiency from 50% to 70% (Fig. 6.12), for the distance future (2071-2100) are presented in Table 6.9.

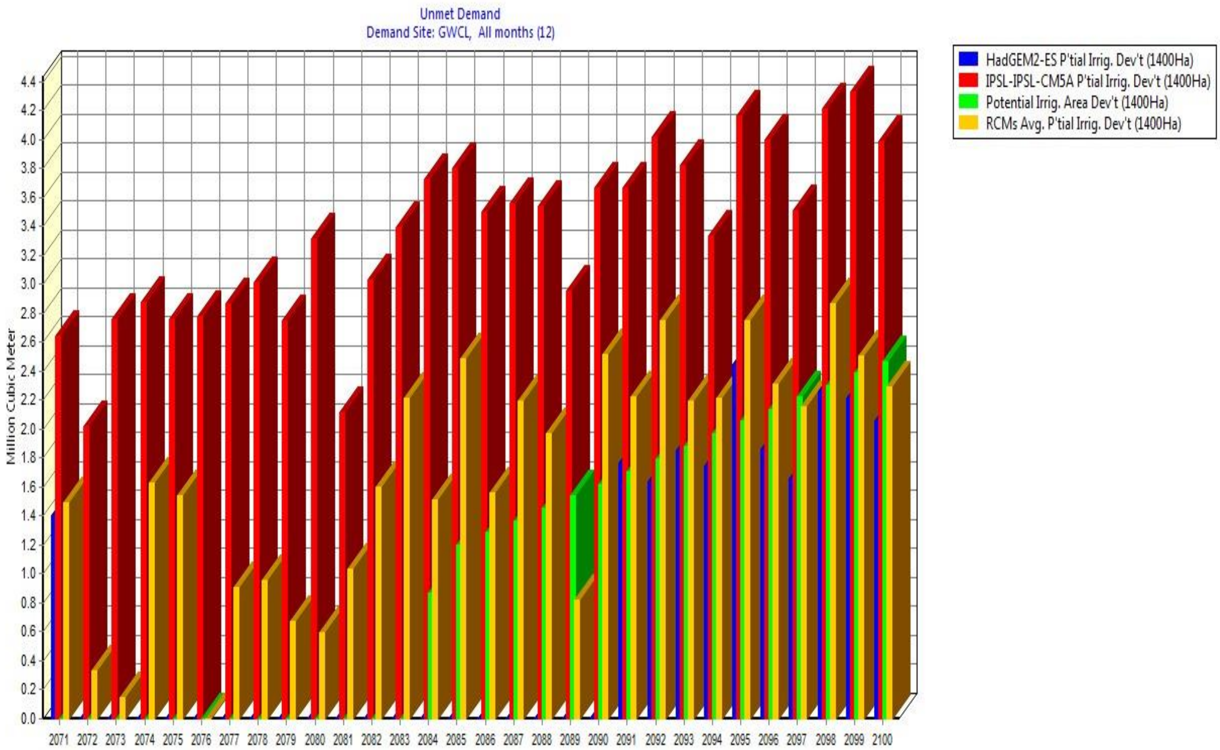


Figure 6.11: *The water availability situation in the period 2071-2100 if potential irrigable area (1400 ha) is developed with business as usual (current proportions of crops & efficiency of 50%)*

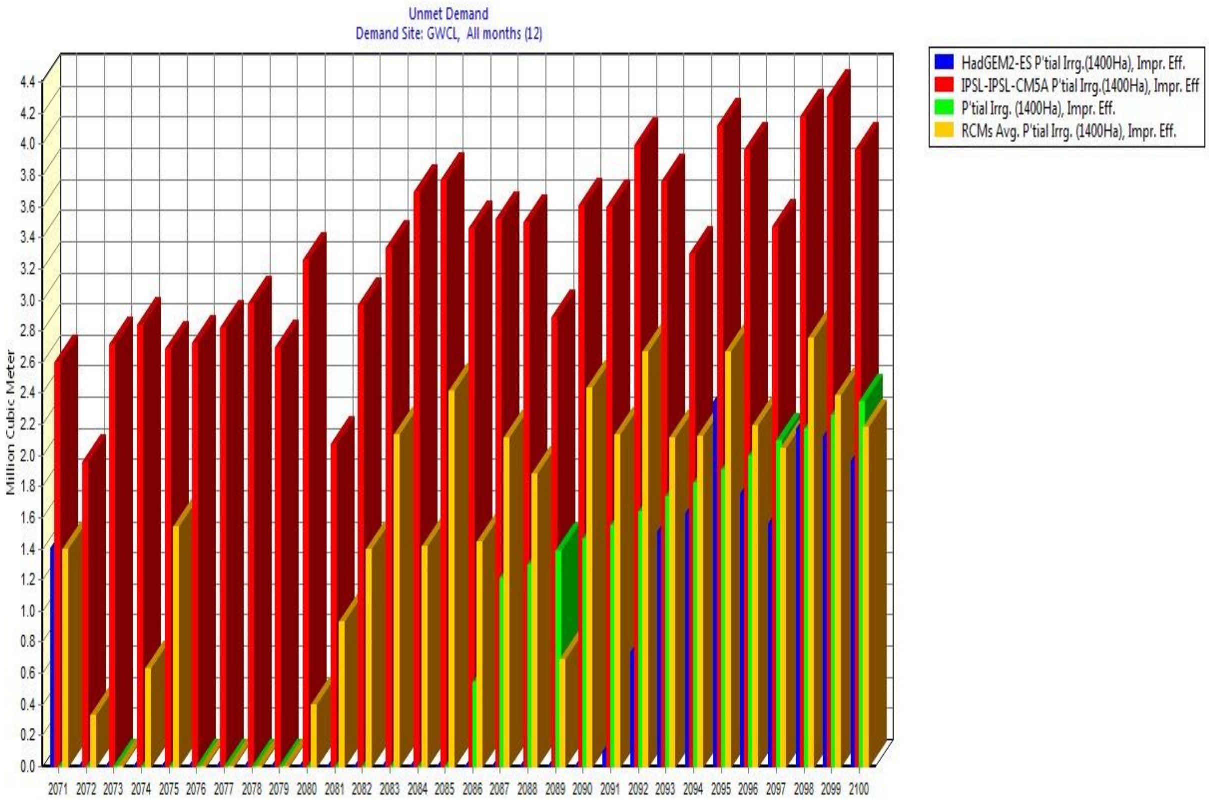


Figure 6.12: *The water availability situation in the period 2071-2100 if potential irrigable area (1400 ha) is developed with improved efficiency from 50% to 70%*

Table 6.9: *The WEAP results of the water availability situation in the period 2071-2100 if potential irrigable area (1400 ha) is developed*

SCENARIOS	With Irrigation efficiency of 50%		With Irrigation efficiency of 70%		Percentage (%) reduction on improved irrigation	
	Annual average unmet water demand (10^6 m^3)	The period total unmet demand (10^6 m^3)	Annual average unmet water demand (10^6 m^3)	The period total unmet demand (10^6 m^3)	Annual average unmet water demand	The period total unmet demand
Wet scenario	0.7	20.9	0.6	17.3	17.3	17.3
Dry scenario	3.3	100.1	3.3	98.8	1.3	1.3
Average scenario	1.7	50.4	1.5	44.4	11.9	11.9
Reference scenario	1.0	30.3	0.8	25.4	15.9	15.9

6.2.3.2 Domestic water supply coverage

Table 6.10: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if potential irrigable area (1400 ha) is developed under current irrigation efficiency of 50%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	7.1	10.5	15.5	17.5	30.3	96.1	100	100	91.8	61.8	31.9	12.3
Average scenario	96.7	96.7	96.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.10 shows that in the period 2021-2050 if potential irrigable area (1400 ha) is developed with business as usual (current proportions of crops & efficiency of 50%), there would be severe shortfall in average monthly domestic water supply coverage in each month in a year except in July and August, on account of the dry scenario (IPSL-IPSL-CMSA model). The months of January to March would also experience shortfall in domestic water supply coverage under the average scenario. Table 6.11, however, illustrates corresponding increase in water supply coverage if there is improvement in irrigation efficiency from 50% to 70%.

Table 6.11: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if potential irrigable area (1400 ha) is developed under improved irrigation efficiency from 50% to 70%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	9.0	11.0	20.4	17.5	30.3	96.1	100	100	94.6	65.0	39.2	15.9
Average scenario	98.5	98.5	98.7	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.12 indicates that in the period 2071-2100 if potential irrigable area (1400 ha) is developed with business as usual (current proportions of crops & efficiency of 50%), there would be severe shortfall in domestic water supply coverage in each year, on account of all the four scenarios (reference, wet, dry and average) under review. The situation would be more severe under the dry and the average scenarios compared with how it would be under the reference and the wet scenarios. Table 6.13 is an illustration of corresponding increase in

supply coverage if there is improvement in irrigation efficiency from 50% to 70% during the period (2071-2100).

Table 6.12: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if potential irrigable area (1400 ha) is developed under current irrigation efficiency 50%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	63.7	63.4	63.4	72.4	90.6	100	100	100	100	100	99.1	78.3
Dry scenario	0	6.1	18.1	30.2	44.6	95.2	75.2	48.8	9.6	0.3	0.1	0
Average scenario	15.5	33.3	49.5	71.3	88.0	100	98.4	97.7	93.4	68.1	35.8	18.2
Reference scenario	45.5	46.7	53.5	87.4	100	100	92.5	100	100	99.4	76.5	52.3

Table 6.13: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if potential irrigable area (1400 ha) is developed under improved irrigation efficiency from 50% to 70%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	72.1	70.1	66.8	75.5	91.1	100	100	100	100	100	100	85.0
Dry scenario	0.1	11.1	23.1	37.2	51.6	98.2	78.4	54.1	12.9	0.5	0.4	0.2
Average scenario	25.7	46.7	51.2	71.6	90.8	100	99.3	98.9	96.8	73.9	43.1	27.2
Reference scenario	53.3	54.8	58.9	88.5	100	100	95.1	100	100	100	84.3	60.3

6.2.4 The situation in the future if only rice is used for total developed irrigable area (850 ha)

6.2.4.1 Annual unmet demands

From analysis made in Chapter 5, it became clear that farmers in the study area could not compete favourably with their counterparts from Burkina Faso for the available local tomato market in Ghana. This is simply because their counterparts in Burkina Faso continuous to flood Ghana's local market with their fruitier and much attractive tomato compared with the locally produced variety which is described as watery and not eye-appealing. For that reason, most farmers had shifted to farming only rice, a situation which could lead to complete neglect of tomato farming in the area, which on the other hand, is the lowest irrigation water requiring crop compared with rice – the two major crops farmed in the area. Based on the above reason, there is a foreseeable situation where all irrigable lands in the area are used for rice cultivation if no appropriate intervention is made. The above scenario was therefore run in WEAP to assess the impacts of such a likely evolution on the water availability in the catchment during the two future periods, 2021-2050 and 2071-2100.

The results as shown in figure 6.13 and 6.14 for 2021-2050 and figure 6.15 and 6.16 for 2071-2100 indicate that the water resources in the catchment will be sufficient in both future time slices if all the developed irrigable land (850 ha) is being used for the cultivation of only rice with or without improved irrigation efficiency, given the reference and the wet scenarios. This applies to the WEAP results for the average scenario, except in the first year of each period where the latter scenario indicated unmet water demand. However, with the dry scenario applied in each period, WEAP indicates considerable annually unmet demands that increased across both future periods, 2021-2050 and 2071-2100, with much greater effects in the distance future (2071-2100) (Fig. 6.15 & 6.16) than in the near future 2021-2050 (Fig. 6.13 & 6.14).

If the whole developed irrigable land (850 ha) is used for rice only with the current irrigation efficiency of 50% (Fig. 6.13 & 6.15), the average annual unmet demand and the total sum of unmet demands, based on the dry scenario, are found as 1.5×10^6 and 45.2×10^6 m^3 respectively for the near future 2021-2050 and 2.0×10^6 and 58.8×10^6 m^3 respectively for the distance future 2071-2100. However, with the whole developed irrigable land (850 ha) used for rice only, but with improved irrigation efficiency from 50% to the targeted level of 70% (Fig. 6.14 & 6.16), the average annual unmet demand and the total sum of unmet demands will reduce considerably to about 1.2×10^6 and 36.8×10^6 m^3 respectively for the near future (2021-2050) and 1.8×10^6 and 52.7×10^6 m^3 respectively for the distance future (2071-2100). This gives reductions in the unmet water demands in both future periods of about 19% and 10% respectively for 2021-2050 and 2071-2100, owing to improvement in irrigation efficiency.

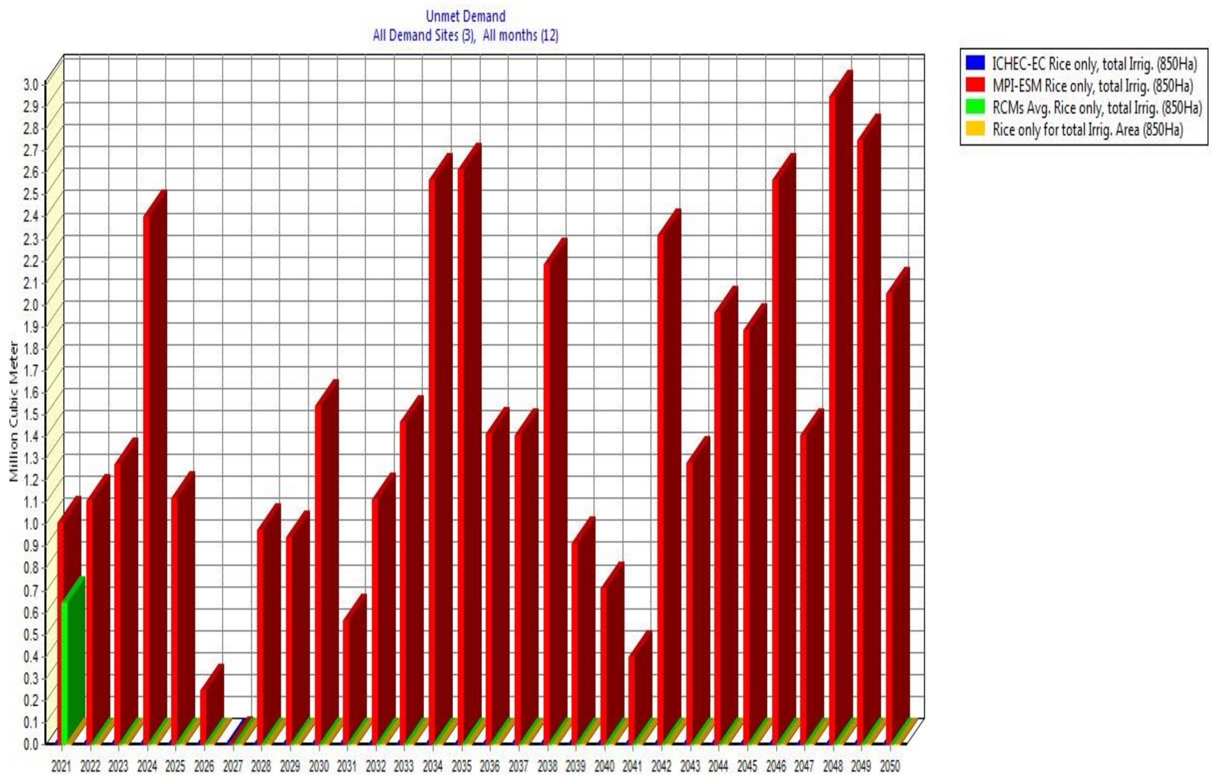


Figure 6.13: *The water availability situation in the period 2021-2050 if only rice is used for total developed irrigable area (850 ha) with current efficiency of 50%*

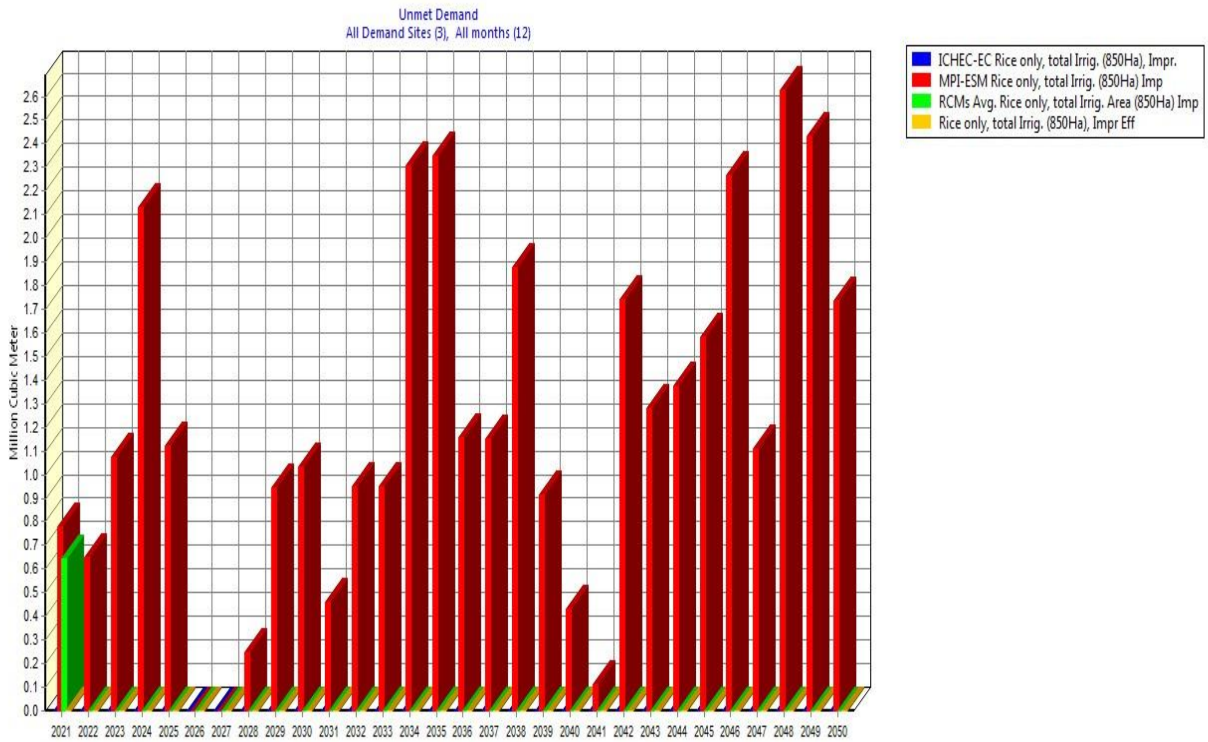


Figure 6.14: *The water availability situation in the period 2021-2050 if only rice is used for total developed irrigable area (850 ha) with improved efficiency from 50% to 70%*

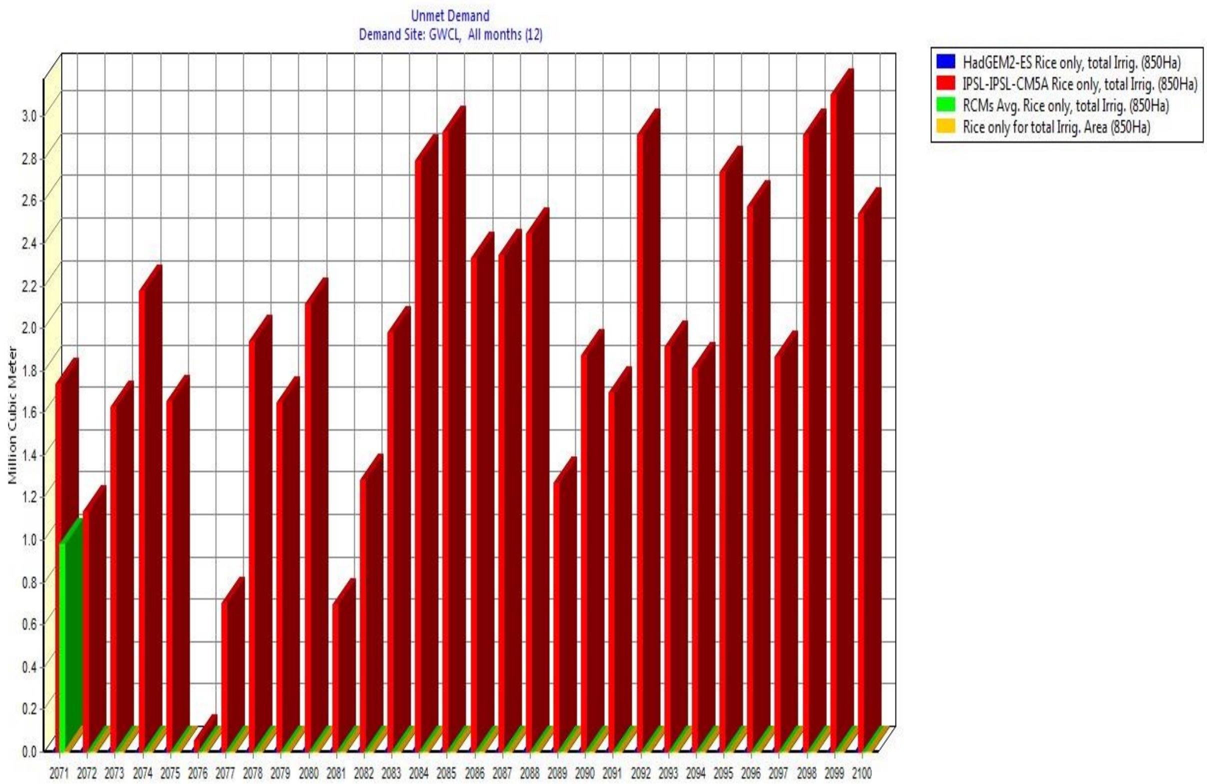


Figure 6.15: *The water availability situation in the period 2071-2100 if only rice is used for total developed irrigable area (850 ha) with current efficiency of 50%*

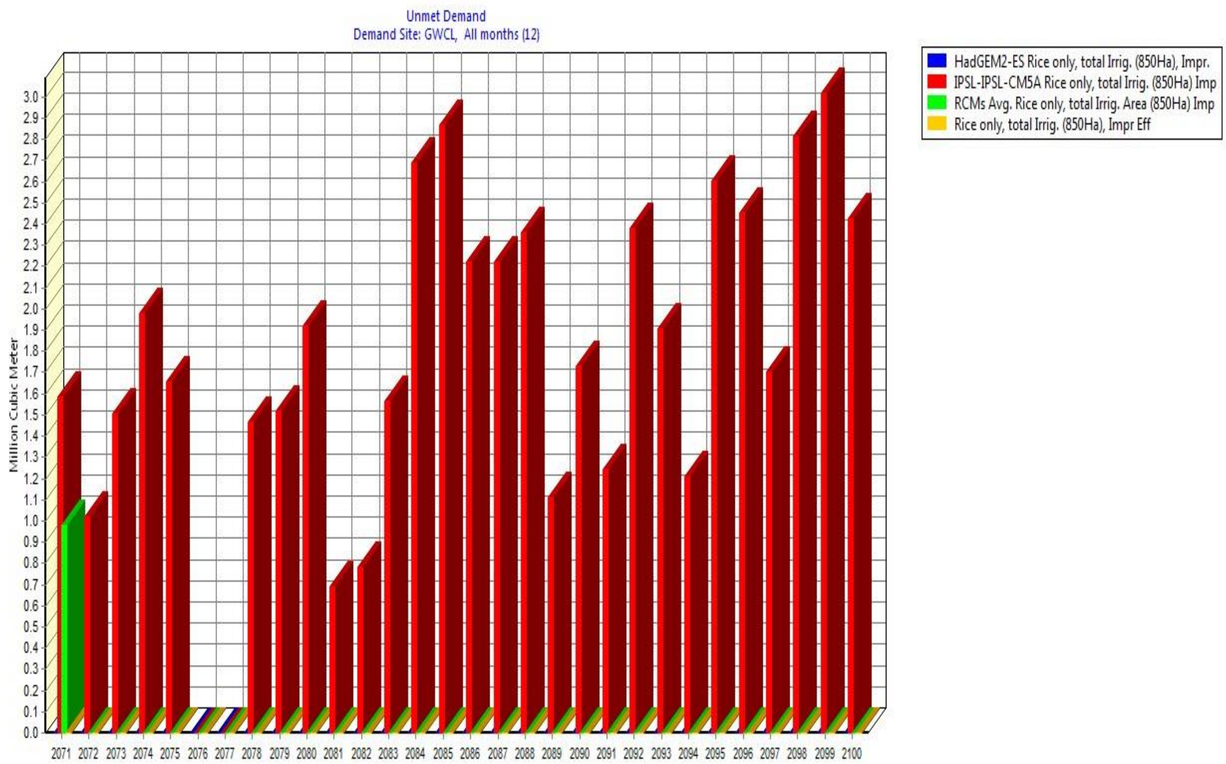


Figure 6.16: *The water availability situation in the period 2071-2100 if only rice is used for total developed irrigable area (850 ha) with improved efficiency from 50% to 70%*

6.2.4.2 Domestic water supply coverage

Table 6.14: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if only rice is used for total developed irrigable area (850 ha) under current irrigation efficiency of 50%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	25.7	25.8	25.8	24.0	32.8	96.1	100	100	100	89.6	65.1	43.9
Average scenario	96.7	96.7	96.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.14 indicates that in the period 2021-2050, if only rice is used for total developed irrigable area (850 ha) with current irrigation efficiency of 50%, there would be considerable shortfall in domestic water supply coverage in each year, under the dry scenario (MPI-ESM model). The months of January to March will also experience shortfall in domestic water supply coverage under the average scenario during the period. Table 6.15 illustrates improvements on the situation if irrigation efficiency is improved from 50% to 70% during the period (2021-2050).

Table 6.15: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if only rice is used for total developed irrigable area (850 ha) under improved irrigation efficiency from 50% to 70%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	40.0	30.6	33.7	27.5	37.2	96.1	100	100	100	93.8	74.0	57.4
Average scenario	98.5	98.5	99.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

The results of the situation in the period 2071-2100, if only rice is used for total developed irrigable area (850 ha) with current irrigation efficiency of 50%, is illustrated by Table 6.16. It is shown in the table that there would be considerable shortfall in domestic water supply coverage in each year under the dry scenario (IPSL-IPSL-CM5A model). The months of January to April will also experience shortfall in domestic water supply coverage under the average scenario during the period. On account of possible improvements on irrigation efficiency from 50% to 70%, Table 6.17 indicates improvement over the situation shown in Table 6.16 during the period (2071-2100).

Table 6.16: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if only rice is used for total developed irrigable area (850 ha) under current irrigation efficiency of 50%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	14.7	12.8	23.0	33.1	46.7	95.2	100	100	98.8	80.5	52.0	31.8
Average scenario	96.7	96.7	96.7	99.8	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.17: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if only rice is used for total developed irrigable area (850 ha) under improved irrigation efficiency from 50% to 70%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	28.1	23.6	23.6	36.1	50.4	95.2	100	100	99.5	85.5	61.4	40.1
Average scenario	98.6	98.6	98.7	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

6.2.5 The situation in the future if only rice is used for total potential irrigable area (1400 ha)

6.2.5.1 Annual unmet demands

A situation where no intervention is made to support farmers with improved variety of tomato to compete with their counterparts in Burkina Faso, yet other measures are given to improve the irrigation infrastructure in the catchment could also arise. If this happens, there is a possibility of expansion of irrigation activities to cover the entire potential irrigable area (1400 ha) for cultivation of only rice. The results of this scenario generated from WEAP are as shown in figure 6.17 and 6.18 for 2021-2050 and figures 6.19 and 6.20 for 2071-2100. These results indicate that, for 2021-2050, water resources in the catchment will meet all demands in such a case of all the potential irrigable land (1400 ha) being used for the cultivation of only rice under the reference condition and the wet scenario derived from RCMs simulated conditions (ICHEC-EC model). Apart from the first year, 2021, the WEAP results for the average scenario, also indicated that the water resources of the catchment would meet all demands in the rest of the period. The situation, based on the dry scenario (MPI-ESM model), however, indicated considerable amounts of annually unmet demands that will rise annually across the period (2021-2050) as in other previous scenarios. With the current irrigation efficiency (50%), the average annual unmet water demand and the total sum of unmet demands were 4.0 x 10^6 and 120.6 x 10^6 m^3 respectively for the period 2021-2050, based on the dry scenario (Fig. 6.17). However, if there is an improvement in the irrigation efficiency from 50% to 70%, these values could reduce to about 3.2 x 10^6 and 97.4 x 10^6 m^3 respectively, showing 19% reduction in both (Fig. 6.18).

The situation in the distance future (2071-2100) is, however, different with results of all the four scenarios (reference, wet, dry and average) under review, indicating that water resources in the catchment would be insufficient to meet demands if the entire potential irrigable land (1400 ha) is used for the cultivation of only rice during the period (Fig. 6.19 & 6.20). The situation is much severer if the climate conditions turn up as predicted by the dry scenario (IPSL-IPSL-CM5A model) (red in Fig. 6.19 & 6.20) or the average scenario (green in Fig. 6.19 & 6.20). The details of the average annual unmet demand and the total sum of unmet water demands for the distance future (2071-2100), based on the four scenarios (reference, wet, dry and average) under review, are presented in Table 6.18.

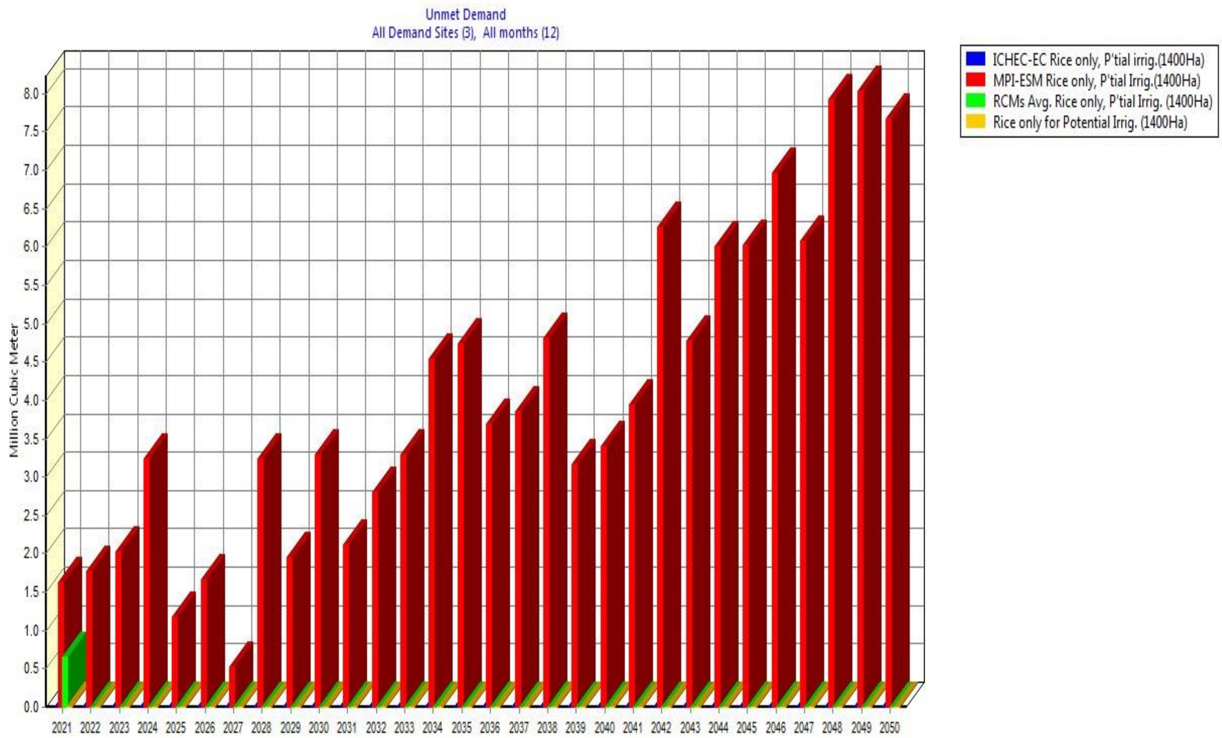


Figure 6.17: *The water availability situation in the period 2021-2050 if only rice is used for total potential irrigable area (1400 ha) with current efficiency of 50%*

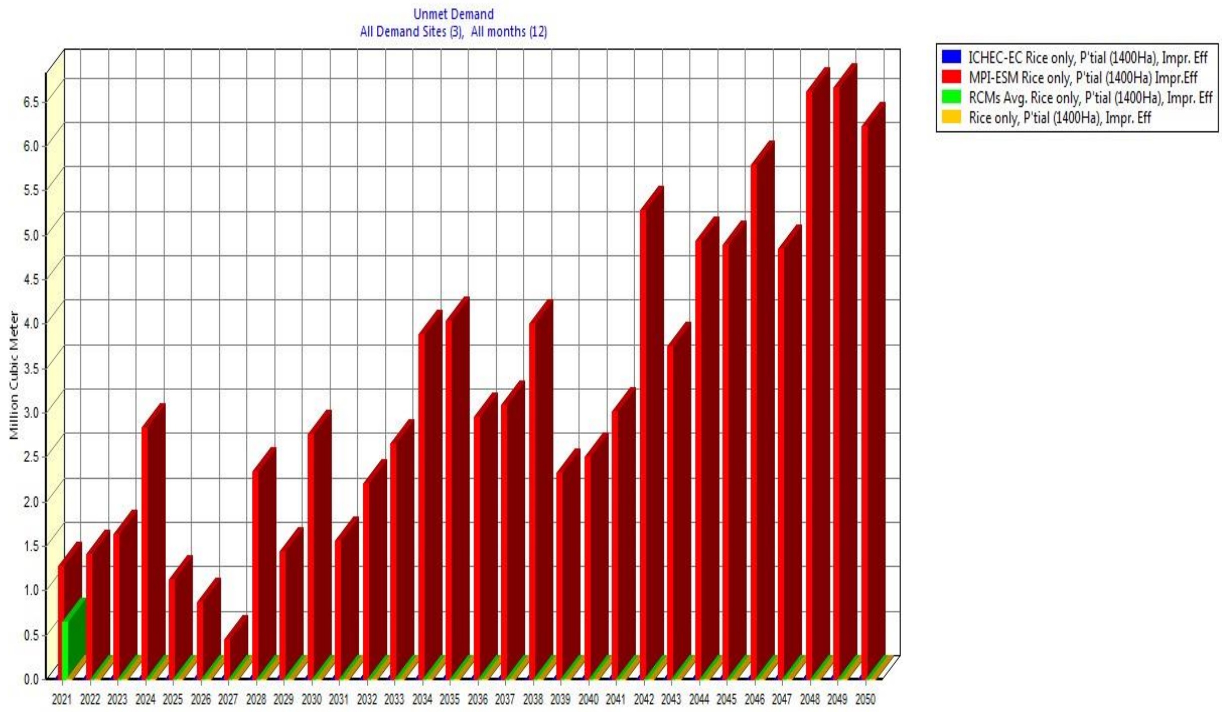


Figure 6.18: *The water availability situation in the period 2021-2050 if only rice is used for total potential irrigable area (1400 ha) with improved efficiency from 50% to 70%*

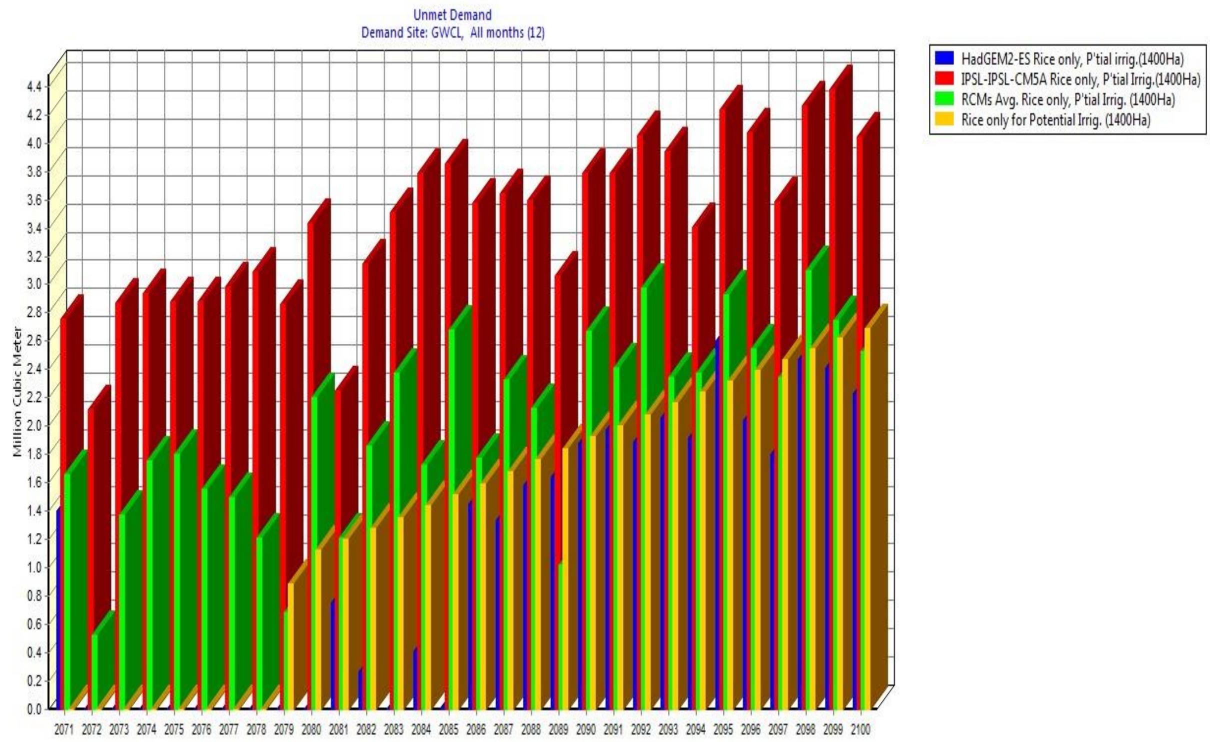


Figure 6.19: *The water availability situation in the period 2071-2100 if only rice is used for total potential irrigable area (1400 ha) with current efficiency of 50%*

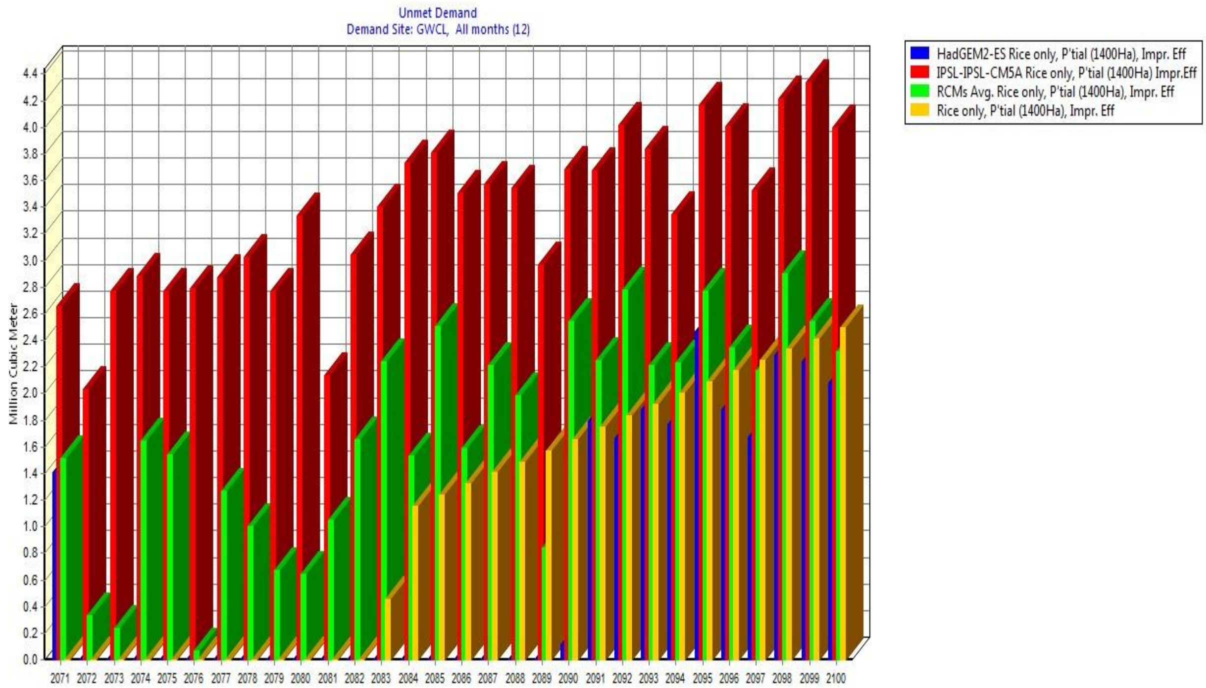


Figure 6.20: *The water availability situation in the period 2071-2100 if only rice is used for total potential irrigable area (1400 ha) with improved efficiency from 50% to 70%*

Table 6.18: *The WEAP results of the water availability situation in the period 2071-2100 if only rice is used for total potential irrigable area (1400 ha)*

SCENARIOS	With Irrigation efficiency of 50%		With Irrigation efficiency of 70%		Percentage (%) reduction on improved irrigation	
	Annual average unmet water demand (10^6 m^3)	The period total unmet demand (10^6 m^3)	Annual average unmet water demand (10^6 m^3)	The period total unmet demand (10^6 m^3)	Annual average unmet water demand	The period total unmet demand
Wet scenario	1.1	32.2	0.7	21.2	33.9	33.9
Dry scenario	3.4	102.8	3.3	100.4	2.3	2.3
Average scenario	2.0	60.3	1.7	51.6	14.6	14.6
Reference scenario	1.4	41.1	1.1	31.5	23.3	23.3

6.2.5.2 Domestic water supply coverage

Table 6.19: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if only rice is used for total potential irrigable area (1400 ha) under current irrigation efficiency of 50%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	0.5	4.4	15.5	17.5	30.3	96.1	99.8	99.7	83.4	52.7	19.1	6.4
Average scenario	96.7	96.7	96.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.19 shows results of monthly average domestic water supply coverage in the period 2021-2050 if only rice is used for total potential irrigable area (1400 ha) with current irrigation efficiency of 50%. The table depicts that under the dry scenario (MPI-ESM model); there would be severe shortfall in domestic water supply coverage in each year. The months of January to March will also experience shortfall in domestic water supply coverage under the average scenario during the period. Table 6.20 illustrates improvements on the situation if irrigation efficiency is improved from 50% to 70% during the period (2021-2050).

Table 6.20: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if only rice is used for total potential irrigable area (1400 ha) under improved irrigation efficiency from 50% to 70%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	7.1	8.9	18.5	23.4	39.3	98.7	100	100	90.8	60.9	30.3	11.5
Average scenario	96.7	96.7	96.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

For the distance future (2071-2100), Table 6.21 shows results of monthly average domestic water supply coverage in a scenario where only rice is used for total potential irrigable area (1400 ha) with current irrigation efficiency of 50%. The table depicts that under all the four scenarios (reference, wet, dry and average) under review, there would be very severe shortfall in domestic water supply coverage in each year in the period (2071-2100). Table 6.22 indicates considerable improvements on the situation if irrigation efficiency is improved from 50% to 70% during the period (2071-2100).

Table 6.21: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if only rice is used for total potential irrigable area (1400 ha) under current irrigation efficiency of 50%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	49.4	45.8	43.5	49.7	89.4	100	98.4	100	100	100	93.9	64.5
Dry scenario	0	6.1	18.1	30.2	44.6	95.2	66.1	38.2	5.5	0.2	0.1	0
Average scenario	3.3	26.2	40.8	64.9	87.3	100	95.7	93.0	87.5	52.6	21.2	5.9
Reference scenario	28.1	31.2	40.2	85.2	100	100	85.2	100	100	93.1	59.6	35.3

Table 6.22: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if only rice is used for total potential irrigable area (1400 ha) under improved irrigation efficiency from 50% to 70%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	63.7	63.4	63.4	72.4	90.0	100	100	100	100	100	98.7	76.6
Dry scenario	2.5	9.3	23.2	33.1	47.8	98.7	74.3	47.6	8.9	3.3	3.2	2.1
Average scenario	12.5	33.3	49.6	71.3	88.0	100	98.1	97.3	92.6	66.6	34.5	15.3
Reference scenario	43.3	45.9	50.8	86.9	100	100	91.7	100	100	98.9	74.5	50.4

6.2.6 The situation in the future if only tomato is used for total developed irrigable area (850 ha)

6.2.6.1 Annual unmet demands

The call by the farmers on authorities for support in respect to provision of new and improved variety of tomato that is competitive in the market could be heeded to. If this intervention is made, then almost all the farmers in the catchment could resort to the cultivation of tomato in the catchment. Additionally, government's current initiative of revamping Pwalugu Tomato Factory in the area as a measure to restore the local tomato market could further be a great motivation for farmers to expand tomato farming in the area. These factors could lead to rapid expansion of irrigation in the area where the entire developed irrigable area (850 ha) could be put under irrigation of only tomato production in the near future. The situation of how water resources availability in the catchment could evolve under the above scenario was simulated by WEAP and the results presented as in figures 6.21 and 6.22 for 2021-2050 and figures 6.23 and 6.24 for 2071-2100. With the reference and the wet (ICHEC-EC model) scenarios, WEAP results indicated that the water resources in the catchment will sufficiently meet the demands in both future periods. Similarly, the results for the average scenario indicate sufficient water availability to meet demands for both future periods, except in the first year of each period where the latter showed annual unmet water demands.

On the contrary, from the WEAP results of the dry scenario in each period, considerable annual unmet water demands persist throughout both future periods. Based on the dry scenario derived from MPI-ESM RCM simulated conditions, it is observed that if the entire developed irrigable land (850 ha) is used for only tomato cultivation with the current irrigation efficiency of 50%, the average annual unmet water demand and the total sum of unmet demands will be 1.0 x 10^6 and 28.8 x 10^6 m^3 respectively for the near future 2021-

2050. Improved irrigation efficiency from 50% to 70%, however, could result in considerable reduction of these figures to about 0.8 x 10^6 and 23.7 x 10^6 m^3 respectively for the near future 2021-2050, given about 18% reduction in each.

On the other hand, the WEAP results of the dry scenario (IPSL-IPSL-CM5A model) for the distance future (2071-2100), based on the current irrigation efficiency of 50%, indicated that the average annual unmet water demand and the total sum of unmet demands will be 1.5 x 10^6 and 45.7 x 10^6 m^3 respectively for the period. With improved irrigation efficiency from 50% to 70%, these could reduce to about 1.4 x 10^6 and 40.6 x 10^6 m^3 respectively in the period (2071-2100) - a reduction of about 11% in both figures.

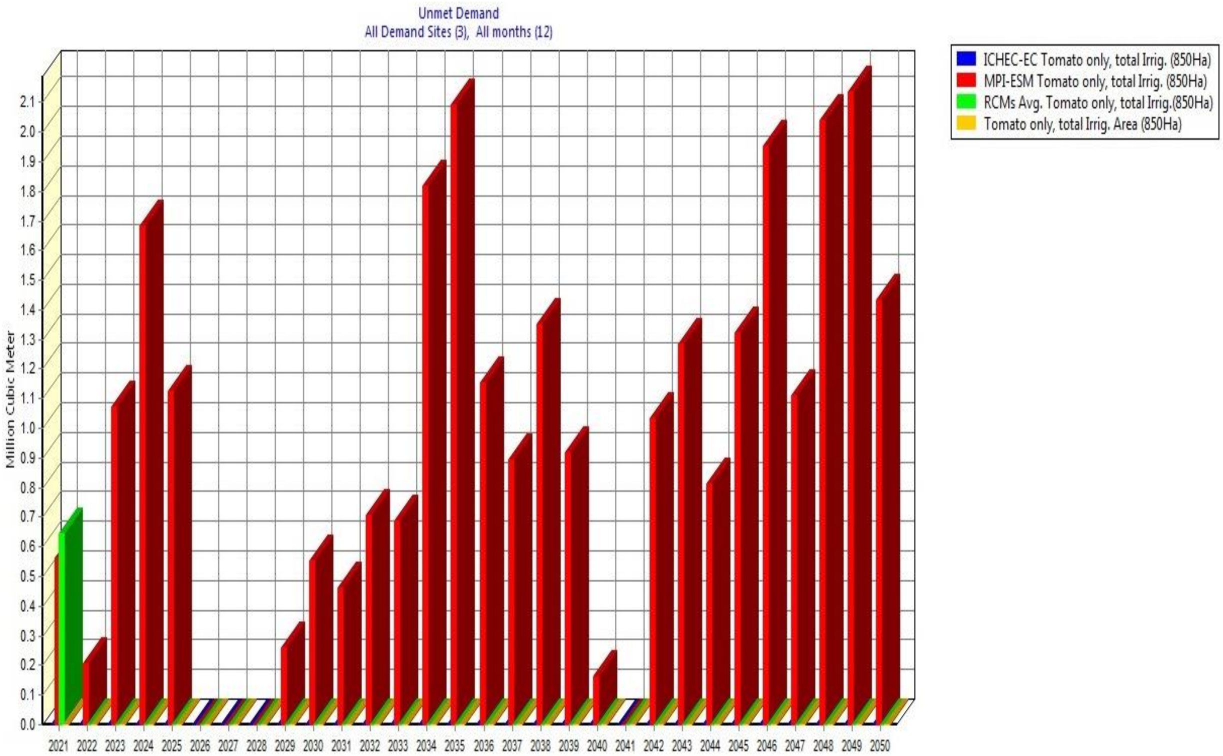


Figure 6.21: *The water availability situation in the period 2021-2050 if only tomato is used for total developed irrigable area (850 ha) with current efficiency of 50%*

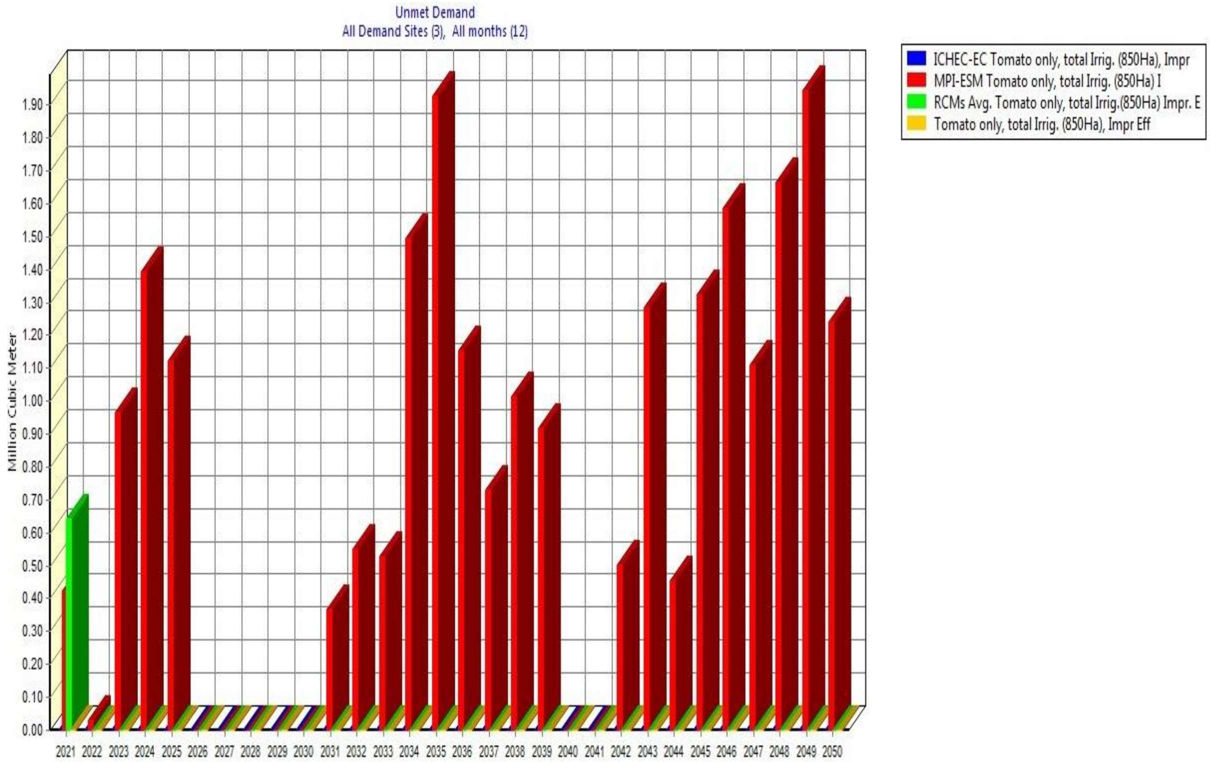


Figure 6.22: *The water availability situation in the period 2021-2050 if only tomato is used for total developed irrigable area (850 ha) with improved efficiency from 50% to 70%*

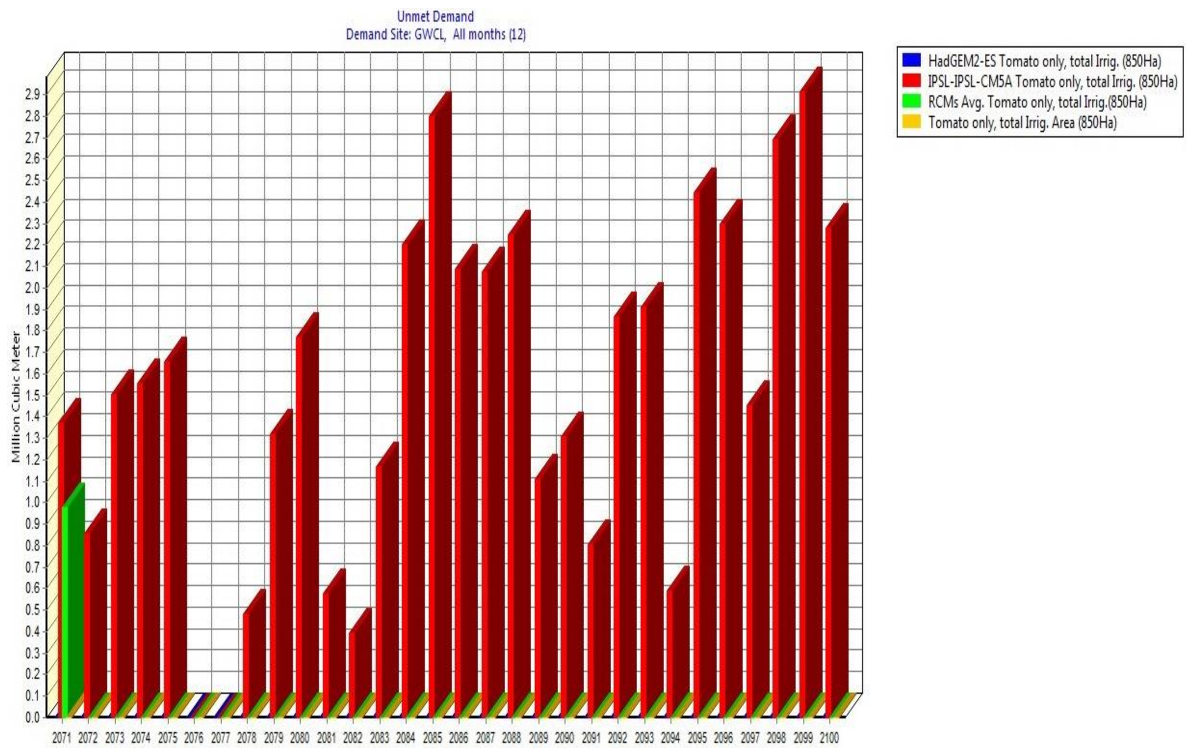


Figure 6.23: *The water availability situation in the period 2071-2100 if only tomato is used for total developed irrigable area (850 ha) with current efficiency of 50%*

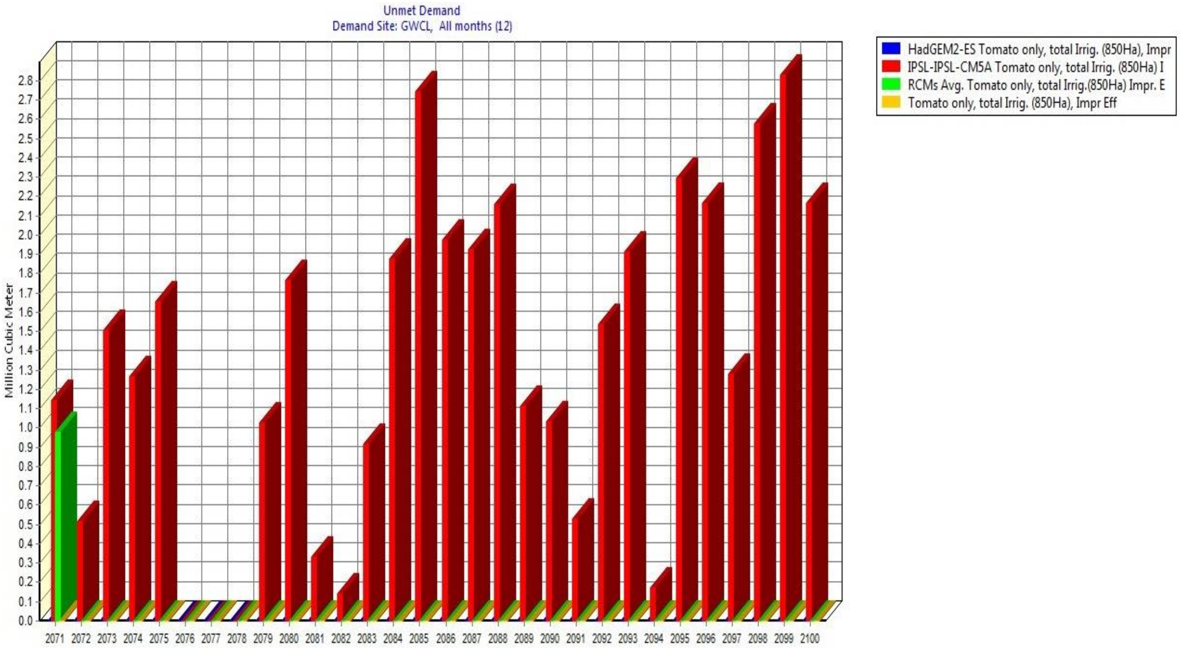


Figure 6.24: *The water availability situation in the period 2071-2100 if only tomato is used for total developed irrigable area (850 ha) with improved efficiency from 50% to 70%*

6.2.6.2 Domestic water supply coverage

Table 6.23 illustrates the results of monthly average domestic water supply coverage in the period 2021-2050 if only tomato is used for total developed irrigable area (850 ha) with current irrigation efficiency of 50%. The table depicts that under the dry scenario (MPI-ESM model); there would be considerable shortfall in domestic water supply coverage in the months of October to June each year within the period (2021-2050). The months of January to March will also experience shortfall in domestic water supply coverage during the period, under the average scenario derived from RCMs simulated conditions. Table 6.24 shows improvements on the situation if irrigation efficiency is improved from 50% to 70% during the period (2021-2050).

Table 6.23: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if tomato alone is cultivated on the total developed irrigable area (850 ha) under current irrigation efficiency of 50%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	60.1	47.4	40.3	36.9	41.9	96.1	100	100	100	97.8	79.0	66.5
Average scenario	96.7	96.7	96.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.24: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if tomato alone is cultivated on the total developed irrigable area (850 ha) under improved irrigation efficiency from 50% to 70%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	65.3	59.9	46.4	42.0	50.0	97.5	100	100	100	99.2	86.3	70.8
Average scenario	98.6	98.6	99.7	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.25 shows the results of monthly average domestic water supply coverage in the period 2071-2100 in a scenario where only tomato is used for total developed irrigable area (850 ha) with current irrigation efficiency of 50%. Similar to the situation in the period, 2021-2050, the table shows that under the dry scenario (IPSL-IPSL-CM5A model), there would be considerable shortfall in domestic water supply coverage in the months of October to June each year within the period (2071-2100). The months of January to April will also experience shortfall in domestic water supply coverage under the average scenario during the period (2071-2100). If the irrigation efficiency is improved from 50% to 70% during the period (2071-2100), there would be improvements in the situation as shown in Table 6.26.

Table 6.25: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if tomato alone is cultivated on the total developed irrigable area (850 ha) under current irrigation efficiency of 50%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	37.7	35.4	35.8	37.7	51. 7	95.2	100	100	100	90.9	71.7	48.5
Average scenario	96.7	96.7	96.7	99.8	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.26: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if tomato alone is cultivated on the total developed irrigable area (850 ha) under improved irrigation efficiency from 50% to 70%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	45.8	42.4	42.1	42.3	55.7	98.5	100	100	100	93.6	77.6	60.2
Average scenario	98.7	98.7	98.7	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

6.2.7 The situation in the future if only tomato is used for total potential irrigable area (1400 ha)

6.2.7.1 Annual unmet demands

The possibility for rapid irrigation development to cover the entire potential irrigable area (1400 ha) exists and could be foreseen from the analysis of the survey results discussed in chapter 5. Possible motivation factors as mentioned in the preceding sub-section, as well as other compelling factors like the rising temperature-driven-evapotranspiration (shown in chapter 4) in the area could make most farmers who had engaged in only rain-fed agriculture to all shift to irrigation farming. This could possibly lead to putting all the potential irrigable area (1400 ha) under irrigation for tomato production. The results from running this scenario in WEAP are as presented in figures 6.25 and 6.26 for 2021-2050 and figures 6.27 and 6.28 for 2071-2100.

The figures 6.25 and 6.26 depict that there will be sufficient water resources in the catchment to meet all demands if tomato is cultivated on the entire potential irrigable area (1400 ha) in the near future (2021-2050), provided climate conditions during the period is about the same as those of the reference scenario or the wet scenario (ICHEC-EC model). Similarly depicted in figures 6.25 and 6.26 is an indication that there will be enough water to meet all demands if the climate conditions in the near future (2021-2050) turn up as those of the average scenario, except for the first year, 2021, of the period. However, the WEAP results of the dry scenario (MPI-ESM model), indicate that there will be insufficient water resources in the catchment to meet demands if tomato is cultivated on the entire potential irrigable area (1400 ha) in the near future (2021-2050). Thus, on account of the dry scenario derived from MPI-ESM RCM simulated conditions, WEAP estimates that if the entire potential irrigable area (1400 ha) is used for only tomato cultivation with the current irrigation efficiency of 50%, the average annual unmet water demand and the total sum of unmet demands will be 2.5×10^6 and 75.1×10^6 m^3 respectively for the period 2021-2050. Figure 6.26, however, indicates that with improved irrigation efficiency from 50% to 70%, these values could considerably reduce to about 2.0×10^6 and 60.7×10^6 m^3 respectively; giving, in percentage terms, 19% reduction in each.

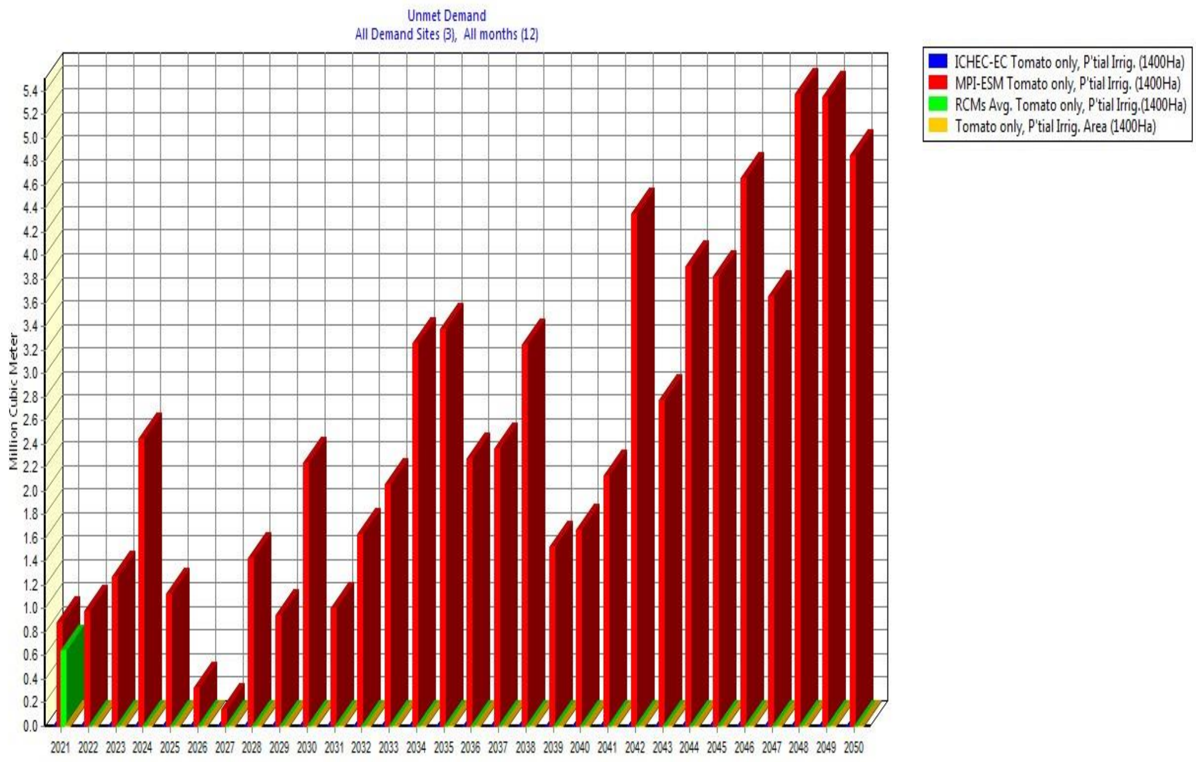


Figure 6.25: *The water availability situation in the period 2021-2050 if only tomato is used for total potential irrigable area (1400 ha) with current efficiency of 50%*

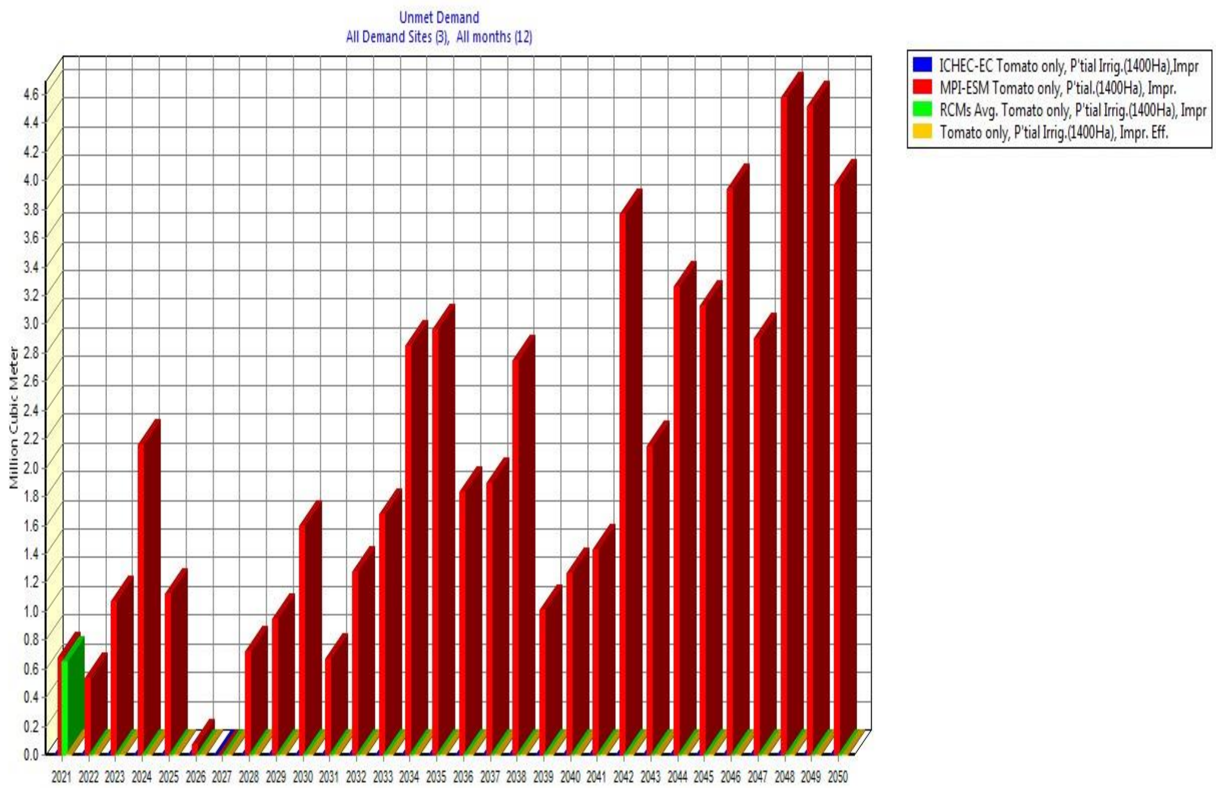


Figure 6.26: *The water availability situation in the period 2021-2050 if only tomato is used for total potential irrigable area (1400 ha) with improved efficiency from 50% to 70%*

In the case of the distance future (2071-2100), WEAP results of all the four different scenarios (reference, wet, dry and average) under review, have shown that there would be insufficient water resources in the catchment to meet demands if tomato is cultivated on the entire potential irrigable area (1400 ha). The severest case will be when the climate conditions turn up in the period as those of the dry scenario derived from the IPSL-IPSL-CM5A RCM simulations (red in Fig. 6.27 & 6.28). While the dry (IPSL-IPSL-CM5A RCM simulations) and the average scenarios indicate considerable unmet water demands right from the beginning of the period (2071-2100), the reference and the wet (HadGEM2-ES model) scenarios only indicate considerable unmet water demands in the second half of the period (2071-2100) (Fig. 6.27 & 6.28). The summary of the unmet water demands, based on the four different scenarios (reference, wet, dry and average) under review, are as illustrated in Table 6.27.

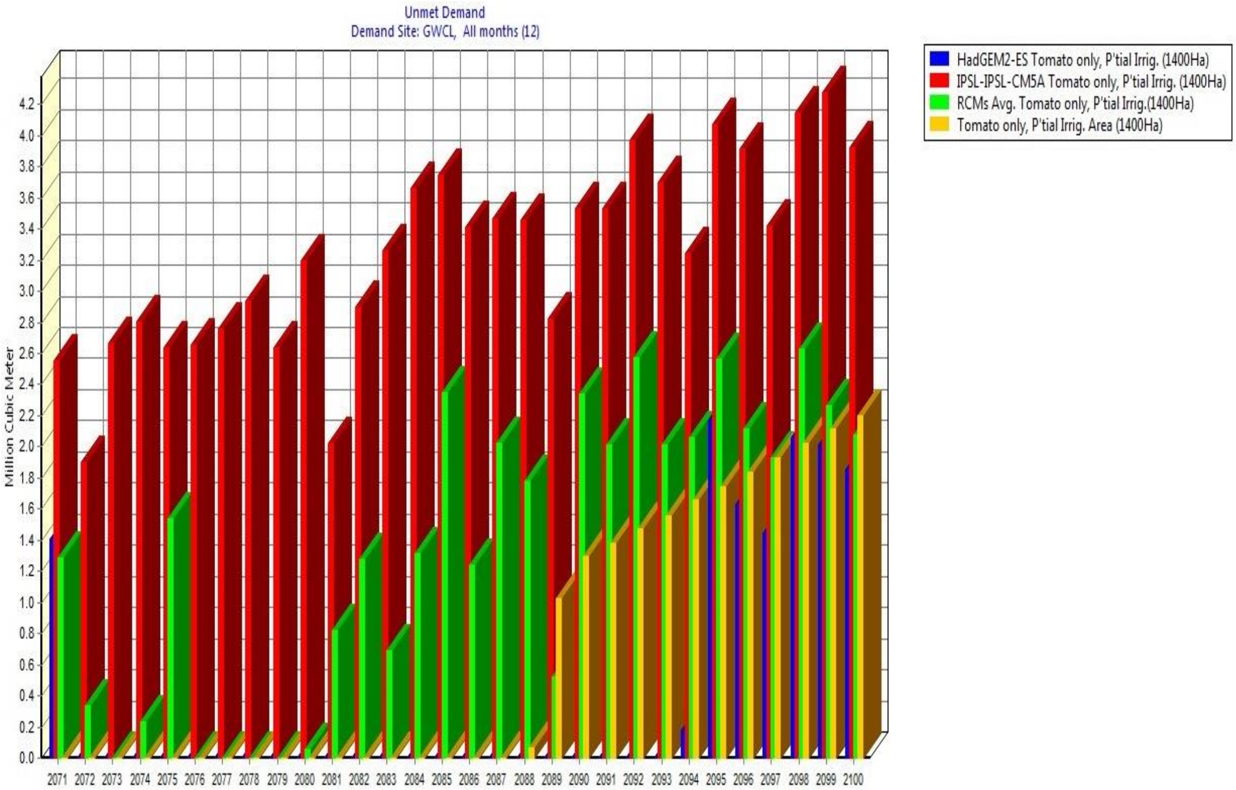


Figure 6.27: *The water availability situation in the period 2071-2100 if only tomato is used for total potential irrigable area (1400 ha) with current efficiency of 50%*

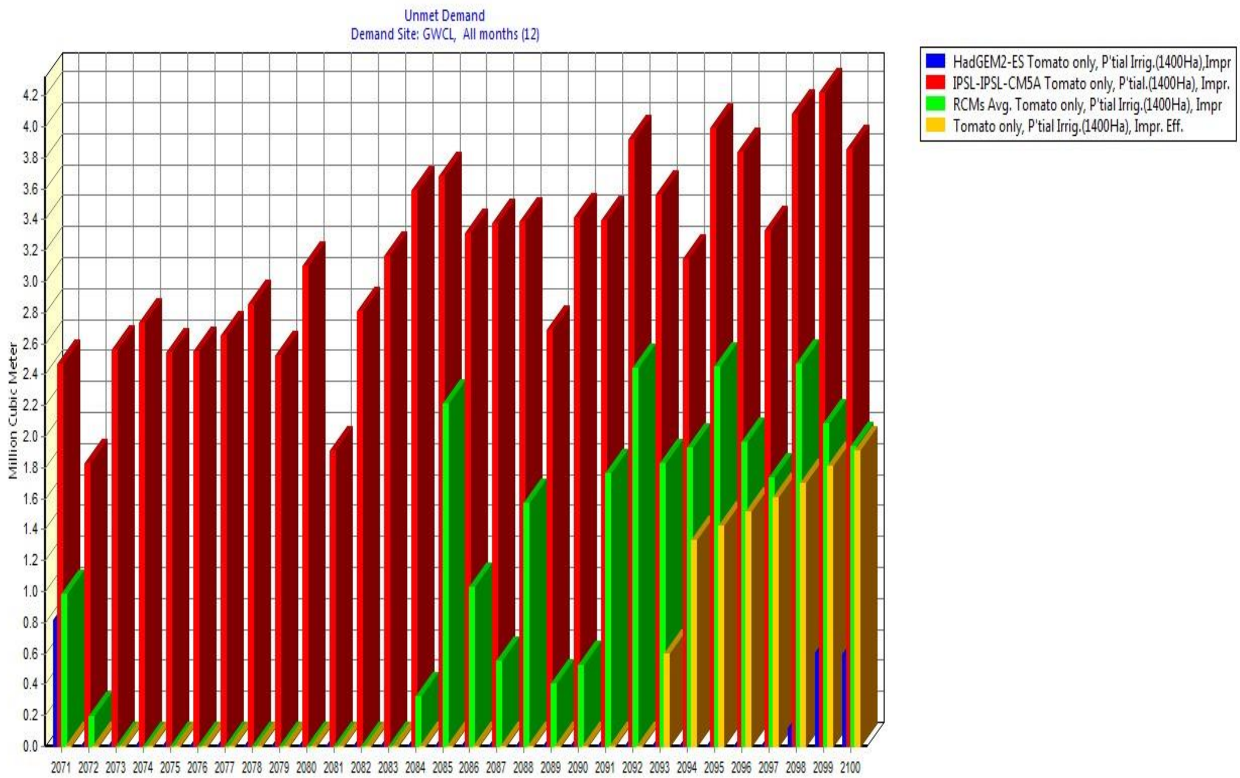


Figure 6.28: *The water availability situation in the period 2071-2100 if only tomato is used for total potential irrigable area (1400 ha) with improved efficiency from 50% to 70%*

Table 6.27: *The WEAP results of the water availability situation in the period 2071-2100 if only tomato is used for total potential irrigable area (1400 ha)*

SCENARIOS	With Irrigation efficiency of 50%		With Irrigation efficiency of 70%		Percentage (%) reduction due to improved irrigation	
	Annual average unmet water demand (10^6 m^3)	The period total unmet demand (10^6 m^3)	Annual average unmet water demand (10^6 m^3)	The period total unmet demand (10^6 m^3)	Annual average unmet water demand	The period total unmet demand
Wet scenario	0.4	12.8	0.1	2.1	83.2	83.2
Dry scenario	3.2	97.2	3.1	94.4	2.9	2.9
Average scenario	1.3	40.0	0.9	28.3	29.2	29.2
Reference scenario	0.7	20.3	0.4	11.9	41.4	41.4

6.2.7.2 Domestic water supply coverage

Table 6.28: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if tomato alone is cultivated on the total potential irrigable area (1400 ha) under current irrigation efficiency of 50%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	14.1	12.0	21.8	21.3	30.3	96.1	100	100	96.7	68.9	46.5	20.7
Average scenario	96.7	96.7	96.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.28 presents the results of monthly average domestic water supply coverage in the period 2021-2050 under a scenario where only tomato is used for total potential irrigable area (1400 ha) with current irrigation efficiency of 50%. The table indicates that under the dry scenario (MPI-ESM model simulations), there would be severe shortfall in domestic water supply coverage in all months of each year within the period, except in July and August. The months of January to March will also experience shortfall in domestic water supply coverage during the period (2021-2050), if climate conditions turn up as those of the average scenario. Table 6.29 shows the possible improvements in the situation if the irrigation efficiency is improved from 50% to 70% during the period (2021-2050).

Table 6.29: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 if tomato alone is cultivated on the total potential irrigable area (1400 ha) under improved irrigation efficiency from 50% to 70%*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	22.3	19.3	21.8	23.3	34.7	96.1	100	100	99.1	76.5	55.7	33.8
Average scenario	96.7	96.7	96.8	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

For the period (2071-2100), Table 6.30 shows the results of monthly average domestic water supply coverage under a scenario where only tomato is used for total potential irrigable area (1400 ha) with current irrigation efficiency of 50%, while Table 6.31 shows results of the same situation with the irrigation efficiency improved from 50% to 70% during the period (2071-2100). From both tables (6.30 & 6.31), it is shown that under all the four scenarios (reference, wet, dry and average) under review, there would be severe shortfall in domestic water supply coverage in each year within the period (2071-2100), if the activities in the catchment evolve as by that scenario of tomato used for the total potential irrigable area.

Table 6.30: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if tomato alone is cultivated on the total potential irrigable area (1400 ha) under current irrigation efficiency of 50%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	76.9	76.7	76.7	81.8	93.0	100	100	100	100	100	100	92.1
Dry scenario	0	6.1	18.1	30.2	44.6	95.2	81.5	60.4	16.5	0.7	0	0
Average scenario	29.0	50.0	54.6	73.8	90.9	100	99.6	99.6	99.7	78.2	53.8	34.9
Reference scenario	61.5	62.3	67.0	89.7	100	100	97.3	100	100	100	91.7	68.7

Table 6.31: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 if tomato alone is cultivated on the total potential irrigable area (1400 ha) under improved irrigation efficiency from 50% to 70%*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	99.5	94.4	91.5	96.2	100	100	100	100	100	100	100
Dry scenario	2.3	10.1	23.1	35.3	50.2	98.5	87.7	68.4	25.4	4.5	2.1	0.9
Average scenario	49.1	68.2	67.7	82.7	94.3	100	100	100	100	86.7	68.4	51.3
Reference scenario	76.7	76.8	77.9	93.1	100	100	99.7	100	100	100	99.2	83.8

6.2.8 The situation in the future if Vea irrigation reservoir serves domestic water supply to only Bongo District (Bongo and its environs)

6.2.8.1 Annual unmet demands

As noted during the institutional interviews analysed in Chapter 5, Ghana Water Company Limited (GWCL) in collaboration with the Ministry of Water Resources, Works and Housing has laid down plans to change the water supply system in the study area on foreseeing the constraints and the inadequacy of the present supply system. By that development, the plan is to dedicate the present system that sources from the Vea irrigation reservoir to Bongo and its surroundings. Based on that possible change, the above scenario was run in WEAP to assess the impacts on the water availability in the catchment, should that be the case in the future. The results are shown in figures 6.29 and 6.30 for the near future (2021-2050) and figures 6.31 and 6.32 for distance future (2071-2100).

If the system is made to serve only Bongo Township, then there will be sufficient water to meet all demands throughout the period of 2021-2050 as shown by all the four scenarios (reference, wet, dry and average) under review (Fig. 6.30). The situation would be the same for the distance future period (2071-2100), except that under the dry scenario (IPSL-IPSL-CM5A model simulations), there is an indication of unmet water demand in the first year, 2071, of the period (2071-2100) (green in Fig. 6.32).

On the other hand, if the system is made to serve the whole of Bongo and its surroundings, WEAP results, based on the dry scenario (MPI-ESM model simulations), indicate that the water resources in the catchment will be insufficient to meet demands throughout the near future period (2021-2050) (green in Fig. 6.29). Similarly, on account of the dry scenario (IPSL-IPSL-CM5A RCM simulations), WEAP results indicate that the water resources in the catchment will be insufficient to meet demands throughout the distance future period (2071-2100) (green in Fig. 6.31). For both time slices (2021-2050 & 2071-2100), WEAP results of the average scenario indicate unmet demands in the first year of each period (yellow in Fig. 6.29 & 6.31). Based on results of the dry scenario in each period, the average annual unmet demand and total sum of unmet demands for the period 2021-2050 were 2.2×10^6 and 66.7×10^6 m^3 respectively, while that for the period 2070-2100 were 4.1×10^6 and 122.7×10^6 m^3 respectively.

The results of WEAP based on the reference and the wet scenarios, however, indicate that the water resources in the area will be sufficient for all demands throughout both future periods (2021-2050 & 2071-2100) under both scenarios of supply to the entire Bongo District (Fig. 6.29 & 30) or to only Bongo Township (Fig. 6.31 & 6.32).

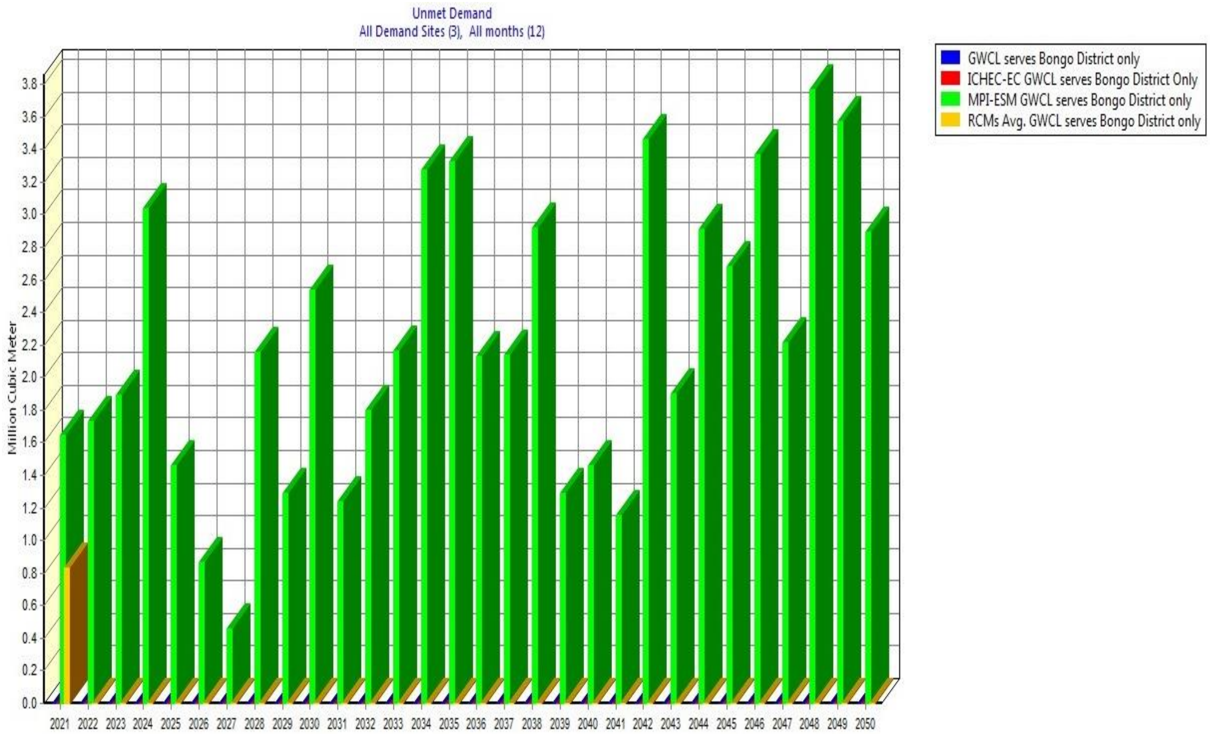


Figure 6.29: *The water availability situation in the period 2021-2050 if Vea irrigation reservoir serves domestic water supply to Bongo District and its environs*

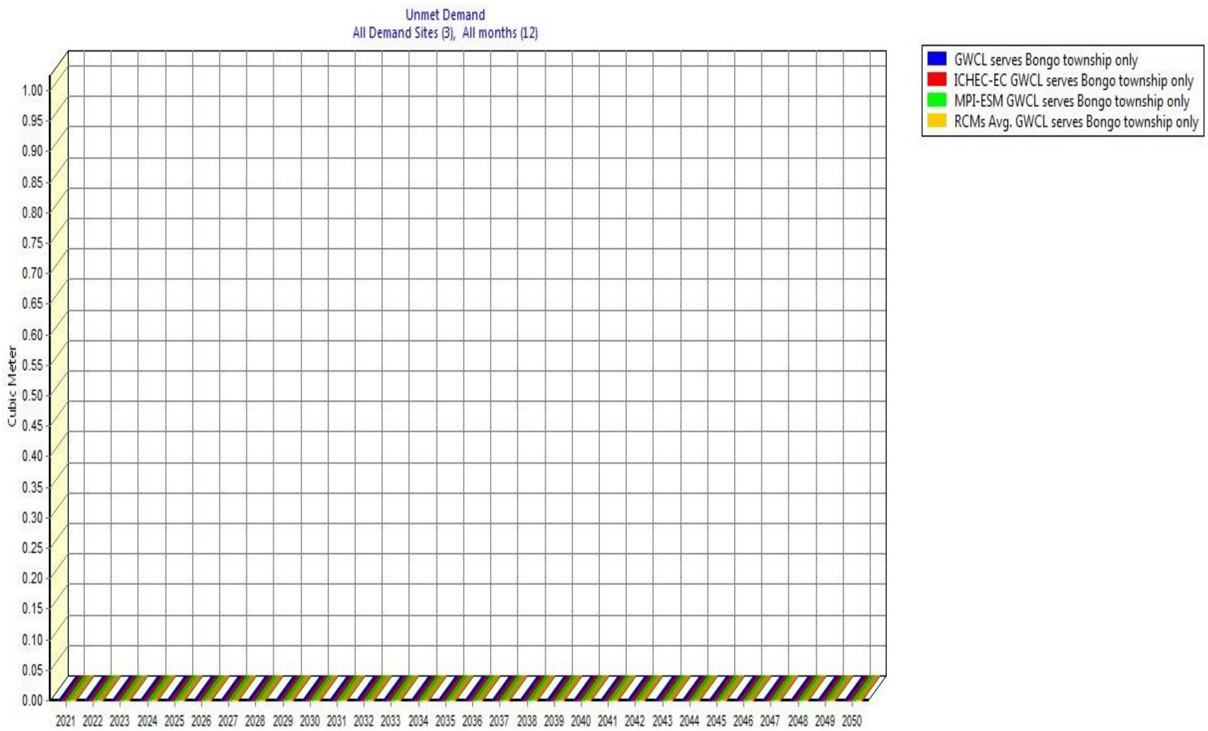


Figure 6.30: *The water availability situation in the period 2021-2050 if Vea irrigation reservoir serves domestic water supply to only Bongo Township*

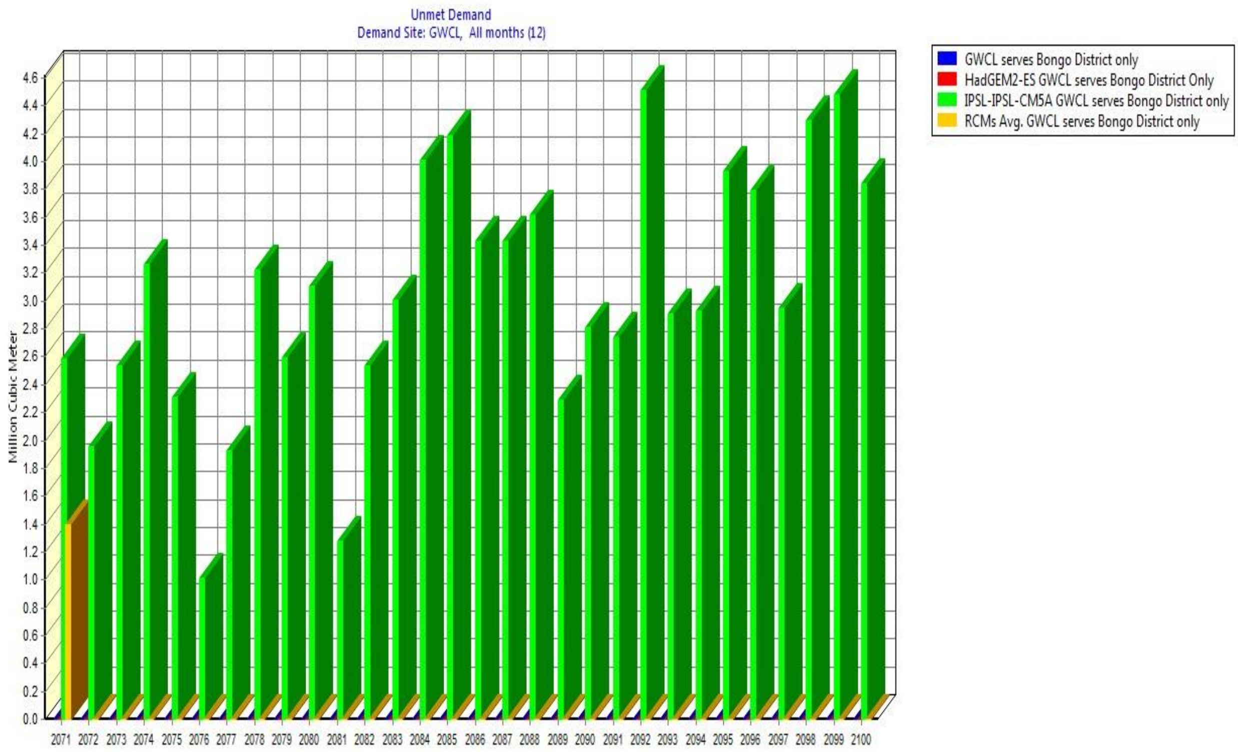


Figure 6.31: *The water availability situation in the period 2071-2100 if Vea irrigation reservoir serves domestic water supply to Bongo District and its environs*

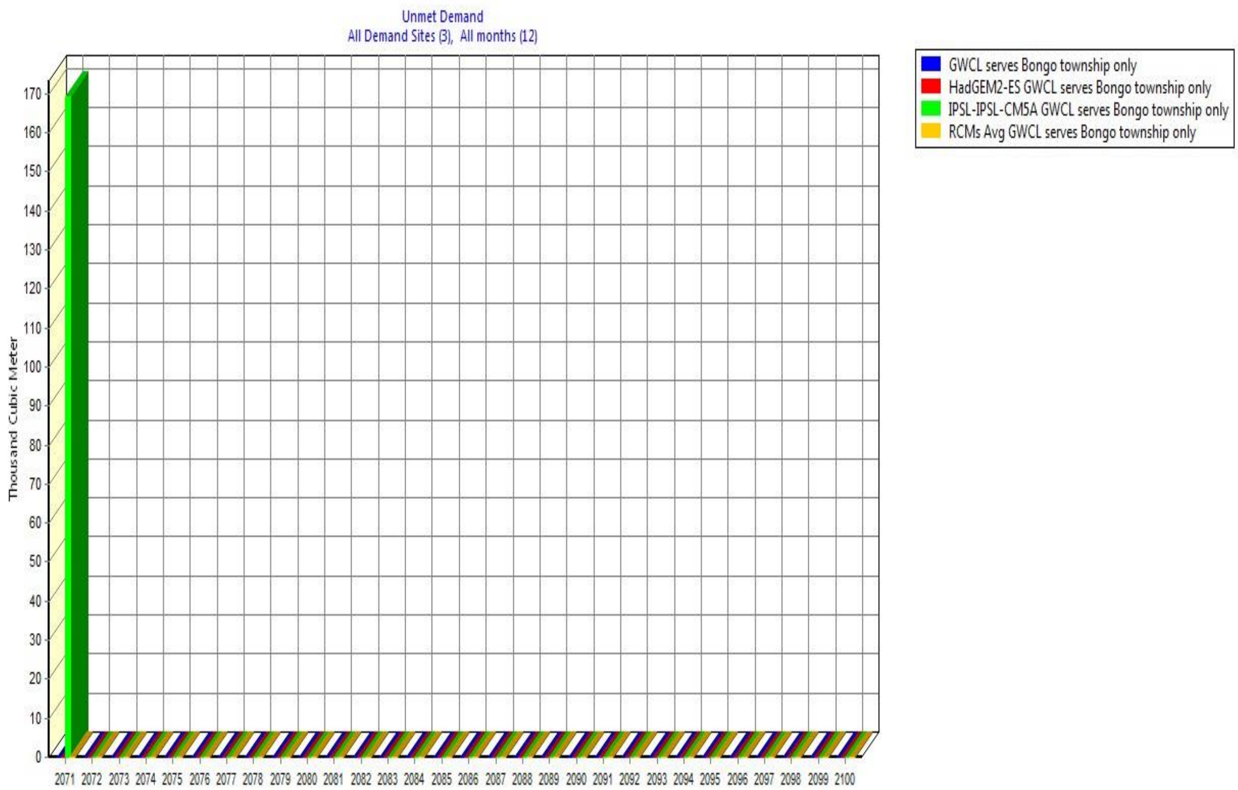


Figure 6.32: *The water availability situation in the period 2071-2100 if Vea irrigation reservoir serves domestic water supply to only Bongo Township*

6.2.8.2 Domestic water supply coverage

Table 6.32: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 where Vea irrigation reservoir serves Bongo District and its environs*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	14.9	10.7	13.5	15.1	24.0	94.0	100	100	98.8	78.7	56.0	27.6
Average scenario	96.7	96.7	96.7	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.32 shows the results of monthly average domestic water supply coverage in the period 2021-2050 under a scenario where the Vea irrigation reservoir is made to serve domestic water supply to Bongo District and its environs excluding Bolgatanga Municipality. The table indicates that under the dry scenario (MPI-ESM model simulations), there would be severe shortfall in domestic water supply coverage in all months of each year within the period, except in July and August as in previous scenarios. The months of January to March will also experience shortfall in domestic water supply coverage under the average scenario during the period (2021-2050). However, if the reservoir is dedicated to serve domestic water supply to only Bongo Township excluding its environs, there would be sufficient domestic supply coverage under all the four scenarios (reference, wet, dry and average) under review, as shown in Table 6.33.

Table 6.33: *Demand site percentage requirement coverage for domestic water supply for the period 2021-2050 where Vea irrigation reservoir serves Bongo Township only*

Period: 2021-2050	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	100	100	100	100	100	100	100	100	100	100	100	100
Average scenario	100	100	100	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

For the period 2071-2100, Table 6.34 shows the results of monthly average domestic water supply coverage under the scenario where the Vea irrigation reservoir is dedicated to serve domestic water supply to Bongo District and its environs. The results are similar to the situation in the near future (2021-2050). The table indicates that under the dry scenario (IPSL-IPSL-CM5A model), there would be severe shortfall in domestic water supply coverage in all months of each year within the period, except in July and August. The months of January to April will also experience shortfall in water supply coverage under the average scenario during the period (2071-2100). The situation of shortfall in coverage would, however, be marginal if the reservoir is dedicated to serve domestic water supply to only Bongo Township excluding its environs as shown in Table 6.35.

Table 6.34: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 where Vea irrigation reservoir serves Bongo District and its environs*

Period: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	6.0	8.6	16.9	23.8	37.3	90.4	100	100	94.0	67.7	41.0	15.2
Average scenario	96.7	96.7	96.7	99.0	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

Table 6.35: *Demand site percentage requirement coverage for domestic water supply for the period 2071-2100 where Vea irrigation reservoir serves Bongo Township only*

PERIOD: 2071-2100	Demand Site Coverage (% of requirement met) (Percent)											
	Demand Site: GWCL, All months (12), Monthly Average											
SCENARIOS	MONTH											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet scenario	100	100	100	100	100	100	100	100	100	100	100	100
Dry scenario	96.7	96.7	96.7	100	100	100	100	100	100	100	100	100
Average scenario	100	100	100	100	100	100	100	100	100	100	100	100
Reference scenario	100	100	100	100	100	100	100	100	100	100	100	100

6.3 Discussion

In a case where irrigation continuous to expand at the current rate of 1.1% under business as usual (BAU), there is a promising sign of adequate water resources in the area to meet all demands in both future periods (2021-2050 & 2071-2100) on account of the wet and average scenarios derived from 16 RCMs simulated conditions as well as the reference scenario, except for the dry scenario for each period. If the future climate conditions turn up as those of the dry scenario for each period, the catchment will experience severe water shortages right from the beginning of each period, in which irrigation in the area will be severely affected and forced to shut down and priority given to domestic supply. The above situation under irrigation growth at 1.1% with BAU applies to its growth at 2.3% in the area and in the case where the entire developed irrigation area (850 ha) is cultivated with either only rice or only tomato as well as where Vea irrigation reservoir serves domestic water supply to the entire Bongo District. It is also similar to the situation in the near future (2021-2050) where the potential irrigable area (1400 ha) is developed with BAU or used for only rice or only tomato.

In a situation where Vea irrigation reservoir is made to serve domestic water supply to only Bongo Township and the irrigation growth rate remains at the current rate of 1.1%, then there would be sufficient water to meet all demands during both future periods (2021-2050 & 2071-2100).

It will not be possible to put the potential irrigable area (1400 ha) under irrigation with BAU in the distance future (2071-2100) as there will be severe shortfall in the water resources availability in the area right from the beginning of the period to meet demands in that situation. This is particularly the case under the dry and the average scenarios and similarly applies to the case of putting the potential irrigable area (1400 ha) under irrigation for cultivation with either only rice or only tomato. The implication is that, it will be almost impracticable to put the potential irrigable area (1400 ha) available in the catchment under irrigation in the distance future (2071-2100), on account of all the four scenarios (reference, wet, dry and average) simulated in WEAP.

If irrigation efficiency is improved in the area, considerable amount of water could be saved from losses and meet other sectors demands. On the average about 19.21% of the total annual water demand in the catchment will be considerably reduced if the irrigation efficiency in the area is improved from the current 50% to 70%. This implies that poor irrigation efficiency is a serious drain on the water resources in the area. This calls for urgent improvement in irrigation efficiency which is based on technical scientific knowledge about the water availability and its application on the field from the irrigation management level to the farmer level. The technical scientific knowledge required of the irrigation management staff, who will intend pass on this knowledge to famers, include knowledge about water flows and availability as observed by Schiffer *et al.* (2008) as well as the appropriate application procedure on the field to avoid much losses.

Internationally recommended minimum amount of basic human water requirement is 50 litres per person per day as determined by Gleick (1996) through the development of a water scarcity index that serves as an indicator for determining the capacity of a resource to meet water requirements for basic human needs (Brown and Matlock, 2011). This translates to about 18.25 m^3 per capita per year. The current domestic per capita water demand per year in the study area is about 30.55 m^3 which is well above this recommended minimum universal standard. However, under both dry and average scenarios for both future periods (2021-2050 & 2071-2100), this current per capita water demand per year would not be met under most of the simulated scenarios of likely evolution of activities in the catchment. The situation will be severer under the MPI-ESM and IPSL-IPSL-CM5A RCMs simulated climate conditions from which the dry scenarios for the two future periods, 2021-2050 and 2071-2100, were respectively obtained. If the future climate conditions evolve as predicted by these two models during the respective future periods, then the domestic water supply in most cases would fall far below the recommended minimum standard of 18.25 m^3 per capita per year. That is, for all cases where domestic water supply coverage is about 60% and below. For instance, if the future climate conditions in the period 2021-2050 evolves as simulated by the MPI-ESM RCM model, then under almost all the future activities to be taken in the catchment, per capita water supply per year for domestic consumption would severely fall below the minimum recommended (18.25 m^3). This applies to the situation of the average scenario under other scenarios of likely evolution of activities such as the case where potential irrigable area (1400 ha) earmarked, is developed by the period 2071-2100 for irrigation.

On the other hand, if the future climate conditions evolves as simulated by ICHEC-EC and HadGEM2-ES RCM models (wet scenarios) respectively for the two future periods, 2021-2050 and 2071-2100, then the water resources in the catchment will meet all demands under most of the activity scenarios including the current domestic annual per capita water demand of 30.55 m^3. Under the climate conditions simulated by these two models in the respective periods, streamflow in the catchment will be higher than the reference streamflow and that implies more water availability than at present.

6.4 Summary and conclusion

This chapter assessed the impacts of CC on availability of water resources in the catchment to meet demands, particularly for irrigation in two future time slices (2021-2050 & 2071-2100), based on eight different water use scenarios of likely evolution of activities in the catchment and four scenarios of possible future climate conditions using WEAP. The four scenarios of possible future climate conditions examined were: the reference (1983-2012) rainfall (streamflow); and future with the highest rainfall (highest streamflow), lowest rainfall (lowest streamflow) and average rainfall (average streamflow) derived from 16 RCMs simulated climate conditions based on the highest emission scenario (RCP8.5). These four climate scenarios are herein referred to as: “reference”, “wet”, “dry” and “average” scenarios, respectively. The results obtained on running WEAP with these scenarios indicate that water resources and water demand in the catchment are sensitive to changes in climate. The impact of CC on water availability in the area could be negative or positive depending on the climate conditions simulated by the 16 RCM models. In view of the WEAP results obtained using the average scenario, it could be inferred that over half of the 16 RCMs simulated climate conditions indicates negative impacts of CC on water availability in the area. On the other hand, RCMs simulated climate conditions such as ICHEC-EC model simulations (wet scenario) for the period 2021-2050 and HadGEM2-ES model simulations (wet scenario) for the period 2071-2100 could result in positive impacts of CC on water availability in the area.

Based on both the reference and the RCMs simulated climate conditions, there will be severe shortfall in water resources availability in the distance future (2071-2100) to meet the projected demands, particularly for irrigation of the potential irrigable area earmarked. On account of the dry scenario for each period, the results indicate severer impact of CC on water resources which could compel the shutting down of the irrigation activities in the area by the beginning of the near future period (2021-2050). This could lead to grave consequences on the socio-economic development of the area since the water resources in the area serve as the major source of livelihoods for many families and the main source of domestic water supply.

Poor irrigation efficiency was also observed to be a serious drain on the availability of water in the area for other uses. The current increasing shift from tomato to the cultivation of rice owing to unfavourable competitive tomato market in the area could worsen the situation as rice is a more irrigation water requiring crop compared with tomato. Rice farming could lead to more water losses and further worsen the already poor irrigation efficiency in the area. These could further exacerbate the impacts of CC on the catchment water resources, if no urgent interventions are taken.

It is evidently shown that CC would affect domestic water supply coverage under almost all scenarios in both time slices if future climate evolves like conditions simulated by most of the RCMs. Severe water stress situation would occur under most scenarios of likely irrigation development in the area where domestic water supply would fall below 60% which gives an average per capita water supply lower than universally recommended standard of 50 litres per capita per day (18.25 m^3). The implication is that irrigation development in the area would in the end suffer the effects as obviously domestic water supply would be prioritised first in such situations.

CHAPTER 7: LAND USE AND LAND COVER CHANGES IN THE VEA CATCHMENT

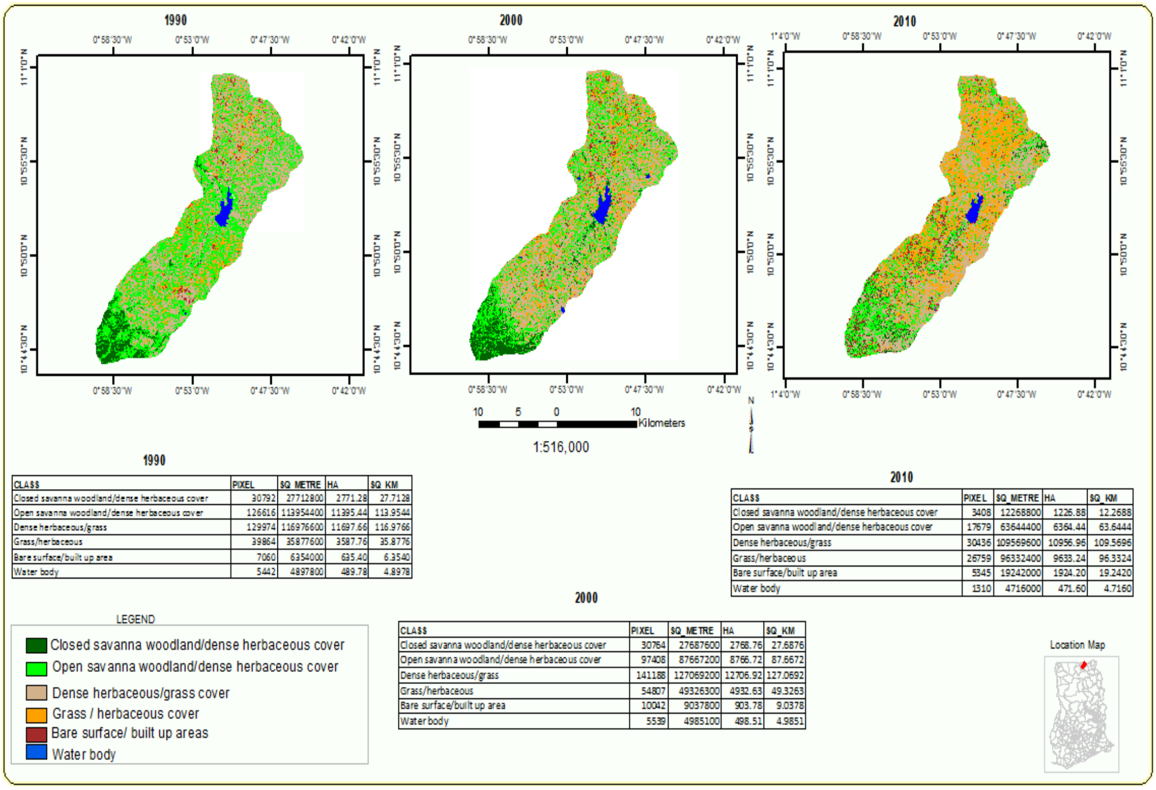
7.1 Introduction

This chapter presents the land use and land cover classification results of the analysis of Landsat ETM satellite images of the study area. It is organized under three sub-sections, namely: (1) results of analysis, (2) discussion and (3) conclusion and recommendation.

7.2 Results of analysis

There has been a considerable rising rate of deforestation in the catchment as evidently shown by the land cover maps of the study area for 1990, 2000 and 2010 (Fig. 7.1). The extreme lower part of the catchment shows a relatively visible forest cover. This downstream part of the catchment is made up of a forest reserve. The closer settlements to the forest reserve including Sherigu Kubelingu, Sherigu Punbungu, Sherigu Nyokoku and Sumbrungo Woebongo have expanded. Figure 7.1 further shows that the study area has experienced a high rate of deforestation over the past two decades. The catchment forest area including the forest reserve has continually depleted over the years. The forest depletion is most visibly severe in the vast upstream (Northern) portion of the catchment where settlements and intensive agriculture activities are concentrated. A closer observation of figure 7.1 patently reveals that the forest cover in this area has largely been converted to agricultural fields, second-growth vegetation, bare surface and settlements expansion. Though no evidence of new settlements established during the period under study could be observed, vast expansion of the existed communities and major towns like Bolgatanga municipality, Bongo, Sumbrungo and Gowri is visible. It can also be seen that while the water surface area increased between 1990 and 2000, it declined in the subsequent decade.

The pattern of changes in land use land cover types in the study area is as illustrated by Table 7.1 and figure 7.2. Table 7.1 depicts that the closed savanna woodland/dense herbaceous cover declined in percentage terms by 0.09% (0.01% per year) and 55.69% (5.57% per year) between 1990-2000 and 2000-2010 respectively, given an overall percentage loss of about 55.72% (2.79% per year) over the past two decades. Similarly, open savanna woodland/dense herbaceous cover declined by 23.07% (2.31% per year) and 27.41% (2.74% per year) between 1990-2000 and 2000-2010 respectively, with an overall decreased cover of about 44.15% (4.42% per year) over the past two decades. However, grass/herbaceous (agricultural lands) and bare surface/built up area cover increased considerably over the same period. The grass/herbaceous (agricultural lands) increased by about 37.49% (3.75% per year) and 95.28% (9.53% per year) between 1990-2000 and 2000-2010 respectively, given an overall increase of about 168.48% (16.85% per year) over the past two decades. Similarly, the bare surface/built up area increased by about 42.36% (4.24% per year) and 112.83% (11.28% per year) between 1990-2000 and 2000-2010 respectively, given an overall increase of about 202.99% (20.30% per year) over the past two decades. While dense herbaceous/grass (fallow agriculture) and water body increased during the first decade (1990-2000), both decreased during the second decade (2000-2010). The dense herbaceous/grass (fallow agriculture) increased by about 8.63% (0.86% per year) between 1990 and 2000 and decreased by about 13.77% (1.38% per year) in the period 2000-2010, given a net decrease of about 6.33% (0.63% per year) over the two decades. On the other hand, the water body cover increased by about 1.63% (0.16% per year) between 1990 and 2000 and decreased by about 5.22% (0.52% per year) between 2000 and 2010, with net decrease of about 3.67% (0.37% per year) over the two decades. In general terms, therefore, tree forest vegetation has considerably given way to shrubs/grass and bare-surface/built up areas in the catchment over the two decades (1990-2010).



1990

CLASS	PIXEL	SQ_METRE	HA	SQ_KM
Closed savanna woodland/dense herbaceous cover	30792	27712800	2771.28	27.7128
Open savanna woodland/dense herbaceous cover	126616	113954400	11395.44	113.9544
Dense herbaceous/grass	129974	116976600	11697.66	116.9766
Grass/herbaceous	39864	35877600	3587.76	35.8776
Bare surface/built up area	7060	6354000	635.40	6.3540
Water body	5442	4897800	489.78	4.8978

2010

CLASS	PIXEL	SQ_METRE	HA	SQ_KM
Closed savanna woodland/dense herbaceous cover	3408	12268800	1226.88	12.2688
Open savanna woodland/dense herbaceous cover	17679	63644400	6364.44	63.6444
Dense herbaceous/grass	30436	109569600	10956.96	109.5696
Grass/herbaceous	26759	96332400	9633.24	96.3324
Bare surface/built up area	5345	19242000	1924.20	19.2420
Water body	1310	4716000	471.60	4.7160

2000

CLASS	PIXEL	SQ_METRE	HA	SQ_KM
Closed savanna woodland/dense herbaceous cover	30764	27687600	2768.76	27.6876
Open savanna woodland/dense herbaceous cover	97408	87667200	8766.72	87.6672
Dense herbaceous/grass	141188	127069200	12706.92	127.0692
Grass/herbaceous	54807	49326300	4932.63	49.3263
Bare surface/built up area	10042	9037800	903.78	9.0378
Water body	5539	4985100	498.51	4.9851

Figure 7.1: *Maps showing changes in land cover types with statistics indicating the changes from 1990, 2000 and 2010*

Table 7.1: *Matrix of land cover by class values for the years 1990, 2000 and 2010*

Class value	**Area of project area in km^2 occupied by a class**					
	1990	**%**	**2000**	**%**	**2010**	**%**
Closed savanna woodland/dense herbaceous cover	27.71	9.06	27.69	9.05	12.27	4.01
Open savanna woodland/dense herbaceous cover	113.95	37.27	87.67	28.67	63.64	20.81
Dense herbaceous/grass	116.98	38.26	127.06	41.56	109.57	35.84
Grass/herbaceous	35.88	11.73	49.33	16.13	96.33	31.51
Bare surface/built up area	6.35	2.08	9.04	2.96	19.24	6.29
Water body	4.90	1.60	4.98	1.63	4.72	1.54
	305.77	**100**	**305.77**	**100**	**305.77**	**100**

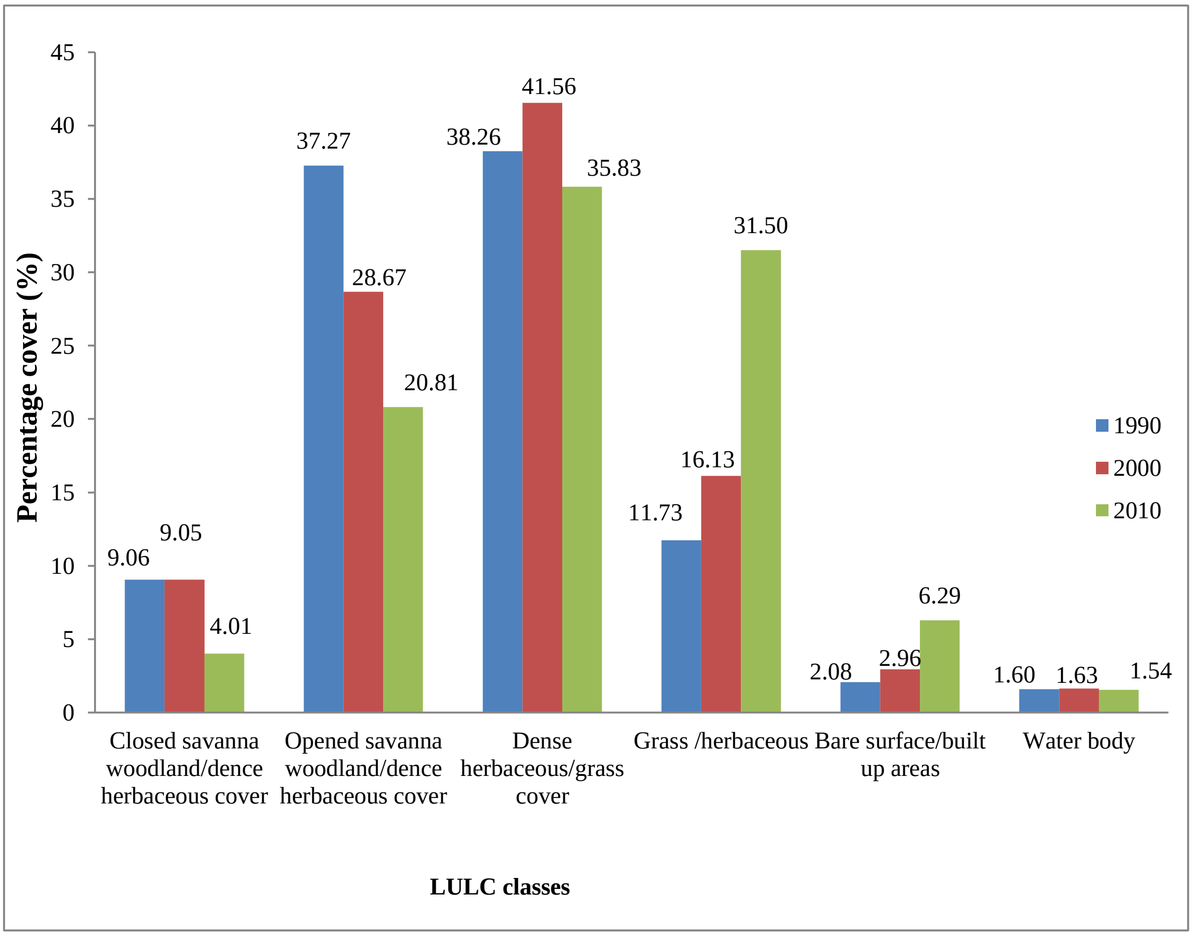


Figure 7.2: *Land use/cover classes*

7.3 Discussion

The analysis of satellite imagery for the catchment has disclosed high rates and extent of changes in vegetative cover of the area as well as the need for urgent and effective land cover restoration plan to be taken by policy makers. The land cover maps of the study area for 1990, 2000 and 2010 indicate rising pattern of deforestation. The land use land cover classifications and the changes found in the area are similar to the findings by related researches conducted in the Upper East Region (UER) by Duadze (2004) and Adanu *et al.* (2013).

Results from the analysis of the satellite data have shown that vegetation cover has undergone significant changes due to mainly human induced effects. Anthropogenic activities, particularly farming, charcoal burning, bush fires, increasing grazing due to increased animal population as well as increased urbanization and human settlement are the underlying causes of depleting natural vegetation cover in the area. This was based on the outcome of intensive reconnaissance field survey of the study area and a review of previous related studies. For instance, the much depleted closed and open savanna woodlands, giving way to the considerable increase in grass/herbaceous cover could largely be driven by increased farming activities, charcoal burning, firewood harvesting and felling of trees for rafters used for mud houses which could be seen on the field. The mud houses forms about 80.0% of all dwelling units in UER with closely 75.0% of these roofed with rafters from trees and thatch from grass (GSS, 2005). Trees are often cut down on preparation of farm lands and grass cover takes over when farming activities are halted. It is the reason the grass/herbaceous forms a very high proportion of the vegetation cover of the area. An increase in the proportion of dense herbaceous/grass cover between 1990 and 2000 was mainly due to fallow agriculture, while the conversion of the fallow fields back into agriculture fields resulted in the decline of dense herbaceous/grass cover land in the period 2000-2010.

The upsurge in bare-surface and built-up areas is attributable to rapid population growth and increased human settlements/urbanization. Jande and Nsofor (2004), as cited in Enaruvbe and Atafo (2014), observed that high rate of bare-surface/settlement expansion is linkable to rapid population growth, rapid urbanization and worsening economic conditions with resultant effects of increased demand for food production and other ecological goods. The linkage suggests that the high rate of vegetative cover degradation is mainly due to rising population growth and population density coupled with poor economic conditions in the study area. This linkage of population growth and poor economic conditions as well as the practice of shifting cultivation to high rates of deforestation is not uncommon (Mather & Needle, 2000; cited in: Lambin *et al.* 2001).

Adanu *et al.* (2013) noted that the expanse of grass/herbaceous cover and bare surface/built-up areas of the UER indicates that over 60% of the region's vegetation cover is degraded posing a difficult environmental and livelihood challenge to the people in the area. The intensity and upsurge in anthropogenic activities such as farming practices and charcoal burning in the area is directly linked to increased population and population density and scarcity of land, amidst the lack of alternative sources of income. In the absence of better alternative sources of income, the rising population growth means that more inhabitants could be engaged in agricultural activities which could largely be the underlying cause of vegetation cover degradation in the area. Agriculture and related activities engaged 66.4% of the regional population aged 15 years and above in 2000 and this further increased to 68.7% in 2010 (GSS, 2013a). Lambin *et al.* (2001) disclosed that the responses of people to economic opportunities play a key role in land-cover changes.

The UER is generally rural and characterized by intensive traditional agricultural activities and related works such as hunting, charcoal burning and firewood harvest/sales. The Region's population density which has consistently been higher than the national average and rose steadily over the last four decades (GSS, 2013a), is the major factor for the increased agriculture and related activities with the consequential effects on land cover changes in the area. As a result of high population density and intensive agricultural activities in the Region, all available land is being cultivated (Gyasi *et al.* 2006). This has led to severe depletion of the native savanna trees vegetation due to a practice of regular fires being used as the traditional cultivation method of land clearing and burning in the area (Gyasi *et al.* 2006). The depleted vegetative cover, especially tree cover in the Vea catchment is a result of the intensive agricultural activities across the catchment (Adongo *et al.* 2014). To an even larger extent, severe land degradation in the UER that include the depleted vegetative cover has been identified to be associated with the high population density in the area (Millar *et al.* 2004; cited in: Adanu *et al.* 2013).

Though Ghana's agricultural land area (13,638,179 ha) is generally available with only 5,300,000 ha under cultivation as of 1994, the agricultural land area in the UER is under increasing scarcity with reduced fallow periods due to rising population pressure (Karbo and

Agyare, 2002; EPA, 2003). The Vea catchment could be much affected and more vulnerable owning to the presence of one of the two major irrigation schemes in the Region as well as the many subsistent farming communities spread across the catchment.

Besides crop farming, livestock production has been the second most important agricultural activity for the people in the Region (GSS, 2013a). Of all the agricultural households in the Region, 96.7% are in crop farming and 82.8% are in livestock rearing (GSS, 2013b), indicating that most of the agricultural households engage in a combination of crop farming and livestock rearing for multiple reasons including food or financial security measure against any unexpected disaster and dowry payments. The payments of school fees and hospital bills are other reasons and determining factors for livestock rearing in the area (Ansah *et al.* 2015). Observation by experts from the Ministry of Food and Agriculture (MOFA) was that there had been a rising trend in livestock population during the 1990s and that was attributable to the cause of increasing land degradation in the Region (Dietz *et al*. 1999).

Besides the human population pressure, therefore, high animal population density, especially cattle, is a major contributor of land degradation in the UER (Gyasi *et al.* 2006). Indeed, local perceptions also indicate that deforestation and soil degradation were often the results of increased in both farming activities and livestock populations (Dietz *et al*. 2013). The high patronage in livestock rearing in the Region is the reason for the high livestock population density such us cattle, sheep and goats. The Region accounts for about 18% of Ghana's cattle production (GSS, 2005) and has the highest cattle population density in the country (Gyasi *et al.* 2006). The high cattle production/population in the Region is due to the prestigious view of cattle in the area and the associated prestige and wealthy fame placed on a cattle owner based on the number of cattle he/she owns (Kwamina and Benneh, 1995; Callo-Concha *et al.* 2012). The high population density of cattle in the Region may have resulted in overgrazing and other observed effects of bushfires caused by the cattle herdsmen in the area including deforestation.

Dietz *et al*. (1999) reported that as a result of free movements between Ghana and Burkina Faso bordering at the UER, some cattle herdsmen from Burkina Faso often migrate with their cattle to parts of the Region in search of feed and water during the dry season. This may have compounded the already high population density of cattle in the Region. The associated problem has been the upsurge of bushfires often set by these herdsmen with the aim of stimulating the sprout of fresh grass for their cattle on early rains (Dietz *et al*. 1999). Consequently, the study by Gyasi *et al.* (2006) disclosed that the UER was the second highest in terms of incidence of bush fires among the ten Regions of Ghana. The native vegetation in the Region has therefore been degraded and reduced to 'shorter grasses and a few fire-resistant trees' due to these regular fires coupled with intense agricultural activities (Gyasi *et al.* 2006).

Adanu *et al.* (2013) disclosed that almost the entire UER is classified as part of a high desertification risk zone of Northern Ghana. As observed by Gyasi *et al*. (2006), the overharvesting of fuel-wood is one of the leading causes of the depleted land cover and land degradation in the Region. Although, foreseeable consequences have compelled some communities, especially those around the irrigation reservoir, to carry out reforestation along the fringes of the reservoir, these efforts are being undermined by the felling of such protective trees as shown in figure 7.3 below. This is further confirmed by Adongo *et al.* (2014) in their recent study at the area where it was disclosed that the trees were being fell for logs and firewood as well as others being cleared to make way for sand winning along the Vea irrigation reservoir for construction purposes. Unfortunately still, the tree growing practice in the region is very marginal and obviously unattractive to the region's mainly subsistent farming communities due to considerably high initial investment and the long time required to achieve result/harvest (GSS, 2013a). These appear to be the reasons the existing forest cover recovery initiatives, if at all, have failed to achieve results in the area.

Impact of climate change (CC) could be an add-on effect. This is in line with observations by a previous study which indicated that the vegetation cover in the entire region was susceptible to the seasonal climate factors and being compounded by intensive agricultural activities and overgrazing leading to desertification (Gyasi *et al.* 2008; cited in: Asante & Amuakwa-Mensah, 2014). The depletion of the vegetation cover in UER could therefore be attributed to three main factors: intensive agricultural activities, overgrazing and climatic variability (Asante & Amuakwa-Mensah, 2014). This confirms in part the findings by Gyasi *et al.* (2006) that besides the anthropogenic activities, climatic factors, particularly dry spells and high wind speeds play a major role in the spread of bush fires in the region and Ghana as a whole. Dietz *et al.* (2004) also observed that the depletion of land cover in UER is due to adjustment factors such as agricultural land-use changes of relocating farms to/from valleys, southward shift of the cotton belt with its associated more land required for cultivation, increased population pressure and increased development of irrigation schemes. Conversely CC and socio-economic factors are the major determinants of agricultural land-use change in the study area (Badmos *et al.* 2014). Inherently, CC could be attributed to be a major driver of land cover depletion and land degradation in the study area. Frequent occurrence of drought, as is the case of UER, is the leading cause of desertification, particularly when appropriate land use systems adjustments to such climatic variations are not made (EPA, 2003).

In a similar research carried out by Duadze (2004) in the neighbouring Upper West Region (UWR), it was found that population pressure and the associated declining fertility has led to the continual usage of fresh savanna woodlands by farmers. While this is patently a factor in the study area, the land use/cover dynamics in the Vea catchment could be related to farmers' response to CC. This is because indirectly, the reasons for which the land use/cover changes have occurred are as a result of farmers conscious or unconscious responses to CC. For instance, the movements or relocation of farm lands to river valleys is as a result of farmers' perceived risks of droughts, or loss of moisture in the upland areas as reported in chapter 5 of this study. The increasing rate of deforestation and depleted land cover in the area as found in this study could be attributed to two main factors: increasing population density with its corresponding increase in agriculture and related activities and climatic variability/change.

The rate of deforestation within the last decade of the period of this study (2000-2010) is higher than the average deforestation rate for the entire investigated period. Enaruvbe and Atafo (2014) also reported similar deforestation rate in the Niger Delta Region of Nigeria and noted that such high rate of deforestation could lead to increased loss rate of biodiversity, forest goods, wildlife and marine animals as well as pose food security challenges.

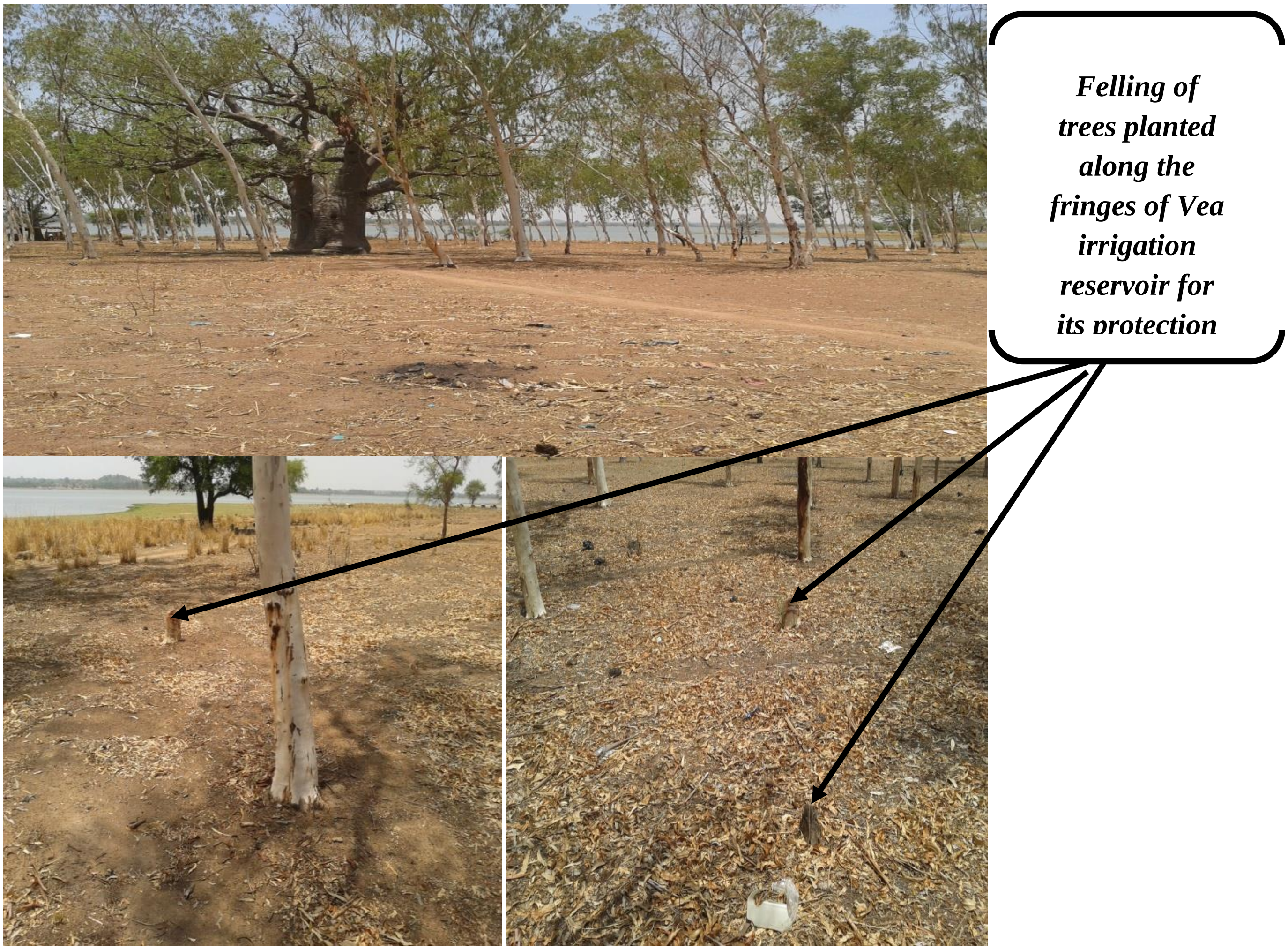


Figure 7.3: *Reforestation along the fringes of the Vea irrigation reservoir (Arrow lines showing felling of the planted trees)*

7.4 Conclusion and recommendation

It is evident that land cover changes have occurred in the studied catchment over the past two decades which are a result of a shift in land use. Changes in land use could affect the water yielding capacity of the catchment, the hydrological regime and the catchment reservoir storage. The high rate of deforestation and increase in the bare-surface/built-up areas could lead to siltation of the Vea irrigation reservoir which should be a source of great concern and this need to be further studied. The identified dynamics in the land use/cover changes include:

- Changes in intensity and extensification (size) of land under usage.
- Change in type of land use including transfer of reserved forest land into agricultural land and agricultural land into settlement lands or bare-surface areas.

- Relocation of farms from one area to another usually to ameliorate the effect of physical changes including climatic changes and demography.

- Land cover changes are significantly manifested in the form of transformations in vegetation classes in which poorer and less useful vegetation forms (in terms of productivity and usefulness) replace good and more useful forms.

In recommendation, this study suggests the following in response to the changing land cover forms and use types.

- Land cover restoration programmes or efforts are highly needed to curtail the persistent depletion of the vegetation cover. This will also help to deal with the dwindling value of the land and preserve its productivity.
- The population growth dynamics should guide land use planning in the area to ensure that population demands are taken into consideration and catered for in advance. The proper demarcation of the land for particular purposes such as farming and settlement will forestall the incidence of haphazard land use changes in the area.

CHAPTER 8: GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

The Vea catchment is of valuable importance to Ghana as it hosts one of the two major irrigation schemes in the Upper East Region of the country, inhabited by many rural farming communities and offers opportunity for all-year-round agricultural production for these communities. The catchment will continue to experience irrigation expansion and rising domestic and industrial water demands due to population growth and urbanisation. At present, the leading challenge of the catchment, however, is global climate change (CC) coupled with high pace of land use/cover changes and deforestation. The challenge of climate change, in particular, gives an impression of a distressing future for the water resources in the area. The design and implementation of any appropriate measures for efficient and sustainable management of the water resources of the catchment will only be informed by evidential understanding of the impacts of CC on the water resources.

The present study was an attempt to assess the future impact of CC on water resources (surface water) availability in the Vea catchment for irrigation and to examine land use/cover changes in the area. This included the assessment of the impact on domestic water supply as this is directly link to water availability for irrigation, since domestic supply would always be prioritized first in situations of water scarcity. The general structure of the methodology employed included:

- First, estimation of historical streamflow for the catchment (ungauged) by water mass balance method.

- Analysis of meteorological data (temperature, rainfall and evapotranspiration).

- Obtaining the understanding of both farmer and stakeholder institutional perceptions on CC, their adaptation measures and future adaptation plans, so as to gather relevant information on how they will likely adjust to the effects of CC in future, which could influence future water use/demand and water availability. This was done using three survey methods of household interviews, focus group discussions and institutional interview.

- Drawing from these perceptions and future planned adaptation measures, the scenarios of the future likely evolution of activities, developments and water demands in the catchment.

- Calibration and validation of the rainfall-runoff model (IHACRES) for prediction of future flow from future climate simulations by Regional Climate Models (RCMs)

- Then, using the Water Evaluation and Planning (WEAP) model to assess the future water availability situation in the catchment for irrigated agriculture based on the scenarios drawn from survey and the RCMs simulated future climate conditions. The outputs of the IHACRES model flow prediction served as inputs for the WEAP model.

Attempt was also made to assess the land use/cover changes in the catchment for informed recommendations of future research direction. The conclusions and recommendations drawn from findings of the present study are as follows.

8.2 Flux (runoff/flow) estimated by water mass balance method

The study area is an ungauged and data-poor catchment with no reliable historical streamflow. There are different methods of estimating streamflow for such ungauged catchment. The application of a particular method depends on the data available, simplicity and reliability of the method. The water mass balance (WMB) method has been widely applied at places where bathymetric data are available. The required streamflow for the present study was estimated by WMB method using reservoir bathymetric data (i.e. reservoir heights), surface area and storage (volume) determined by the storage-area-height relationship (function) at the reservoir site, abstractions, direct rainfall at the reservoir site, evaporation, spillage and seepage (negligible).

The correlation between the estimated streamflow and the catchment areal rainfall showed a good relationship and fairly consistent change between the two time series for all the years. This indicates that the estimated streamflow is fairly representative of the historical streamflow of the catchment. The cross-correlation function between the estimated streamflow and the catchment areal rainfall for all months in a year indicated that the catchment areal rainfall leads the estimated streamflow variations by less than one day.

Besides the soil and drainage properties of the catchment, this time lag or fast response between rainfall and the streamflow variations is also related to the small size of the catchment (305 km^2).

8.3 Impact of future climate change on surface hydrology and water resources

The current and future trends of rainfall, streamflow and evapotranspiration were examined in the context of CC. The KhronoStat software was used for the analyses of climate parameters (rainfall and temperature) for detection of trends and abrupt changes in data time series. Additionally, rainfall variability analysis was carried out using the F-ratio and F-distribution method. Findings showed no evidences of trends, abrupt changes and changes in variability in all the fourteen different time series of rainfall data derived from the primary daily dataset for analysis of different aspects of the rainfall time series (annual and monthly scales) of the study period (1972-2012). Nevertheless, as a semi-arid area, annual total rainfall have been generally lower than the long-term average confirming the description of the study area as a drought prone area and giving rise to high soil moisture deficits.

There will be decrease in monthly streamflow in the near future (2021-2050) due to projected CC. The decrease in streamflow is expected to persist in the distance future (2071-2100) except in the extreme RCMs simulated future climate conditions by HadGEM2-ES_ICTP-RegCM4 model which project increase in the monthly streamflow in the distance future (2071-2100).

There was a clear evidence of positive and persistent increasing trend in evapotranspiration (ET) in the study area. The continuous increasing trend in ET is projected into the future across the entire 21st century.

The findings indicate that the water resources in the area are very sensitive to CC. The projected decreased in future streamflows coupled with increasing trend in ET point to future decrease in reservoir storage and surface water resources availability.

8.4 Perceptions on climate change vis-a-vis observed climatic data and implications of planned adaptations

The study showed that the farmers were generally aware of the changing climate in the area and perceived increased in temperature and decreased rainfall over the past three decades. While their perception on temperature was confirmed by results of the analysis of observed data, their perception on rainfall was influenced by the rising temperature-driven-evapotranspiration in the area that could result in high soil moisture deficits. Evapotranspiration increased considerably over the study period (1972-2012) and expected to increase significantly over the ensuing decades as observed for the two future time slices, the near future (2021-2050) and the distance future (2071-2100).

Several adaptation measures are already being undertaken by farmers, which include: the intensification of the use of chemical fertilizers and pesticides/herbicides, use of different varieties and crop types, mulching and shifts of farm locations near river valleys, among others. The farmers, however, face several adaptation barriers including poverty, inaccessibility to loan facilities, lack of irrigation facilities, inadequate extension services and inaccessibility of climate information, inaccessibility of insurance, and so on.

Farmers planned future adaptation strategy was mainly adaptation of irrigated agriculture to move away from the long-held climate-sensitive rain-fed agriculture. Those who were already into irrigated farming have planned to intensify and expand their irrigation activities to move completely away from rain-fed farming, while those who were completely into rain-fed farming have planned to adopt more of irrigated farming or move completely into irrigation. The implications are obviously that, more pressure would be exerted on the water resources in the catchment.

The feasibility of the farmers' planned future adaptation strategies would depend on provisions made in the national development plan and policy. Nonetheless, a review of the current main national development plan, Ghana shared Growth and Development Agenda (GSGDA) and the sectoral policies on CC, agriculture and irrigation, showed the government commitment in implementing various CC adaptation measures including vigorous irrigation expansion and rehabilitation of existing irrigation infrastructure as well as conscious effort is intended to encourage the use of these facilities. These include support for the informal sector irrigation and small scale irrigation development and financial aid to smallholder farmers as in the case at the study area. Collaborative stakeholder institutional framework is being created for the successful implementation of these policy initiatives. The collaborating stakeholder institutions in the study area include the Ministry of Food and Agriculture (MOFA), Irrigation Company of Upper Region (ICOUR), Ghana Irrigation Development Authority (GIDA), Water Resources Commission (WRC), Hydrological Service Department

(HSD), Environmental Protection Agency (EPA), Ghana Water Company Limited (GWCL) and Community Water and Sanitation Agency (CWSA).

In collaboration with the government and the private sector, these institutions have already planned to implement some of the adaptation measures highlighted in the national policy plan as mentioned above, particularly expansion of irrigation facilities and rehabilitation of existing infrastructure, plans for introduction of new farming methods and technologies, drought resilient crop species and provision of market through rehabilitation of Pwalugu Tomato Factory in the area.

Conclusively, the farmers planned future adaptation strategies are adequately given provisions within the national development plan and policy on national CC adaptation strategy. It would therefore be possible for farmers to implement their planned adaptation measures with certainty, provided the commitments of the government and the stakeholder institutions are brought to bear in terms of action, coordination and resources allocation for the realization of these initiatives at the farmer level. Nonetheless, the overall feasibility and sustainability of these planned future adaptation initiatives would only be informed by empirical evidence of future water resources availability in the area, in view of CC.

8.5 Vulnerability of the study catchment to water stress conditions

The Water Evaluation and Planning (WEAP) model was configured and used to assess the potential water stress conditions in the catchment. This was done through comparison of the outcome of the WEAP model with standard definitions of water stress conditions in the literature. The findings generally showed that there would be severe constraints in future water availability to meet water demands in the area, especially under a projected condition where future climate in the catchment is drier than presently (future dry scenario). The area would be under severe water stress in the future, particularly in the distance future (2071-2100) even under the reference conditions (reference streamflow). Future CC as simulated by more than half of the 16 RCMs (i.e. compared with average RCMs-derived condition) will be an add-on effects that will further exacerbate the situation, and irrigation, which was the reason for the construction of the catchment reservoir, may probably be shut down to give first priority to domestic water supply. On account of both the lowest and the average RCMs-derived streamflow time series for both the near future (2021-2050) and the distance future (2071-2100), this current per capita water demand per year would not be met under most of the simulated scenarios of likely evolution of activities in the catchment. If the future climate conditions evolve as predicted by MPI-ESM and IPSL-IPSL-CM5A RCMs respectively for the two future periods, 2021-2050 and 2071-2100, then the domestic water supply would fall far below the internationally recommended minimum standard for basic human water requirement of 18.25 m^3 per capita per year. Besides the lack of adaptive capacity at both the institutional and individual levels, poor irrigation efficiency was observed to be a serious drain on the availability of water in the area for other uses. The current shift from tomato to the cultivation of rice as a result of poor tomato market in the area could worsen future water availability situation as rice is a more irrigation water requiring crop compared with tomato. Rice farming could lead to more water losses and further worsen the already poor irrigation efficiency in the area. These could further exacerbate the impact of CC on the catchment water resources.

8.6 Land use/cover changes in the catchment

Land use/cover in the area was observed to have considerably changed over the past two decades and attributable to anthropogenic activities, particularly farming, charcoal burning, felling of tree for rafters, bush fires, increasing grazing due to increased animal population, increased urbanization and human settlement. Forest tree cover was found to have greatly depleted giving way to fast increasing grass/herbaceous cover largely due to clearing of land for farming activities. Grass/herbaceous cover increased up to about 168.50% over the past two decades. Bare-surface/built-up area also increased up to about 202.83% over the same period, while the closed savanna woodland/dense herbaceous cover and open savanna woodland/dense herbaceous cover decreased by about 55.72% and 44.15% respectively, during the same period. Changes in land use/cover could affect the water yielding capacity of the catchment, the hydrological regime and the catchment reservoir storage. The considerable increase in the bare-surface/built-up areas could lead to siltation of the Vea irrigation reservoir which should be of great concern.

8.7 Final conclusion

The future influence of CC on water resources (surface water) availability in the Vea catchment for irrigation was assessed as well as the land use/cover changes in the area examined in the present study. Findings showed that in the next decades there would be considerable shortfall in future water availability for both irrigation and domestic supply in the catchment due to future CC. Land use/cover in the area has significantly changed over the past two decades and attributable to anthropogenic activities such as farming, charcoal burning, urbanization and human settlement.

8.8 Recommendations

This study has evidently shown that the adverse effects of CC are real in the study catchment. Consequently, farmers, who are the dominant inhabitants in the area, would continue to adjust to these effects in whichever way possible to them, regardless of the rippling effects of their adjustment methods. Nonetheless, irrigated agriculture remains their ultimate alternative to the current long-held climate-sensitive rain-fed agriculture. Water resources conservation including prudent and productive use of water in the area, therefore becomes critical, as water demands in the area could exceed the projected estimates. Every initiative that would result in water resources development, reduced water loss and waste urgently needs to be taken. To that effect, the following recommendations are therefore proposed.

As recommended by Misra (2014) for situations as in the study area, implementation of programs on sustainable water resources development that include effective watershed management initiatives, construction of rainwater harvesting systems, installation of artificial groundwater recharge facilities with floodwaters, rainwater and partially treated wastewater are very much needed in the area, particularly during the next decades of projected significant water supply deficits. These should go along with the development of alternative irrigation systems such as community-based cluster irrigation schemes, groundwater exploration for irrigation and hand fixed pumps as already proposed in the government development plan.

Introduction of improved irrigation systems with high agricultural water-use efficiency such as deficit irrigation methods for various crops (less water for same yield) is much needed in the study catchment as a measure to cope with the projected water deficit. Deficit irrigation as demonstrated and recommended by Du *et al.* (2015) for areas of limited agricultural water resources is an innovative irrigation method of reducing crop evapotranspiration without yield reduction and has benefits of saving water by controlling crop water use and regulating crop physiological responses like stomatal opening and crop's growth.

For all planned adaptation measures by government and stakeholder institutions to be efficient, there is the need to address constraints such as illiteracy among farmers through regular community sensitisation to enable them abandon outmoded practices and accept improved methods of farming and irrigation water use. The first step should begin with upgrading the Ministry of Food and Agriculture (MOFA) extension service in terms of numbers and expertise of personnel as well as provision of mobility (e.g. motor bikes and fuel) for better access to communities and farms. Farmers would greatly benefit from extension personnel trained on CC and adaptation strategies.

There is the need for MOFA to establish and effectively implement the modern agricultural extension system consisting of all four actors: public sector agencies, private service providers, farmer groups and non-governmental organizations as identified by Neuchâtel Group (1999) and ensure smooth coordination among these actors. This would greatly benefit farmers as their direct linkage and partnership with private actors would provide them access to a range of services such as farm inputs, loan facilities, market for produce, and so on. These will give them capacity and opportunity to embark on and adopt new farming methods and technology and improvements of their knowledge-base on climate related issues by easy transfer of ideas/information.

Some current major constraints to adaptation include competing land use demands and unavailability of markets for farm produce, particularly tomato. The information obtained from the interview of both farmers and stakeholder institutions indicates that the farmers in the study area had lost the local tomato market in the area as well as the entire Ghana to their counterparts in the neighbouring Burkina Faso, due to the attractive nature of the variety of tomato from Burkina Faso. This has since compelled most of the farmers to engage entirely in rice farming which requires intensive water use and leads to much water loss and poor irrigation efficiency, given the fact that most of the farmers are still unskilled in irrigated farming. This is coupled with the problem of inefficient irrigation facilities with broken canals and other dilapidated structures which all lead to much water loss. As a measure to restore tomato market in the area to curb the problem, government has embarked on the rehabilitation of Pwalugu Tomato Factory in the area to provide tomato market. However, this study has identified that this is not enough a solution to the problem, unless a competitive variety of tomato is introduced to the farmers in the area as a key intervention. The present study therefore recommends that MOFA and its allied public agricultural advisory research institutions, particularly Council for Scientific and Industrial Research (CSIR) and NGOs should intervene by introducing competitive new improved seeds, high quality and high yielding crops, specifically tomato and other drought resistant crops with low crop water requirement (CWR), and so on.

The dilapidated infrastructure of the Vea irrigation project including broken down canals, needs urgent rehabilitation to reduce water loss as a means of improving irrigation efficiency and water productivity. Dredging of the reservoir and revamping of Irrigation Company of Upper East Region (ICOUR) which manages the project should also be a matter of concern to government and its executing institutions, particularly MOFA and GIDA.

Land cover restoration programmes that includes incentives for protection of forest reserves are highly needed to curtail the high pace depletion of the vegetation cover in the area. This could include the government recent introduction of gas cylinders for cooking in some parts of the Northern Region of Ghana on pilot bases.

The water allocation model (WEAP) was valuable in the quantification and assessment of the future water availability situation in the area. However, only the surface water resource could be quantified due to lack of ground water data. Further study with WEAP that could employ data on both surface and ground water in the future will be important for understanding the feasibility and sustainability of exploring ground water resources for irrigation in the area. Additionally, this study could not assess the impact of possible siltation of the irrigation reservoir on water storage due to lack of sedimentation data, and hence might have overestimated daily water storage in the reservoir. A follow-up study would be important in assessing the reduction in volume of water storage in the reservoir due to siltation and effects of land use/cover changes.

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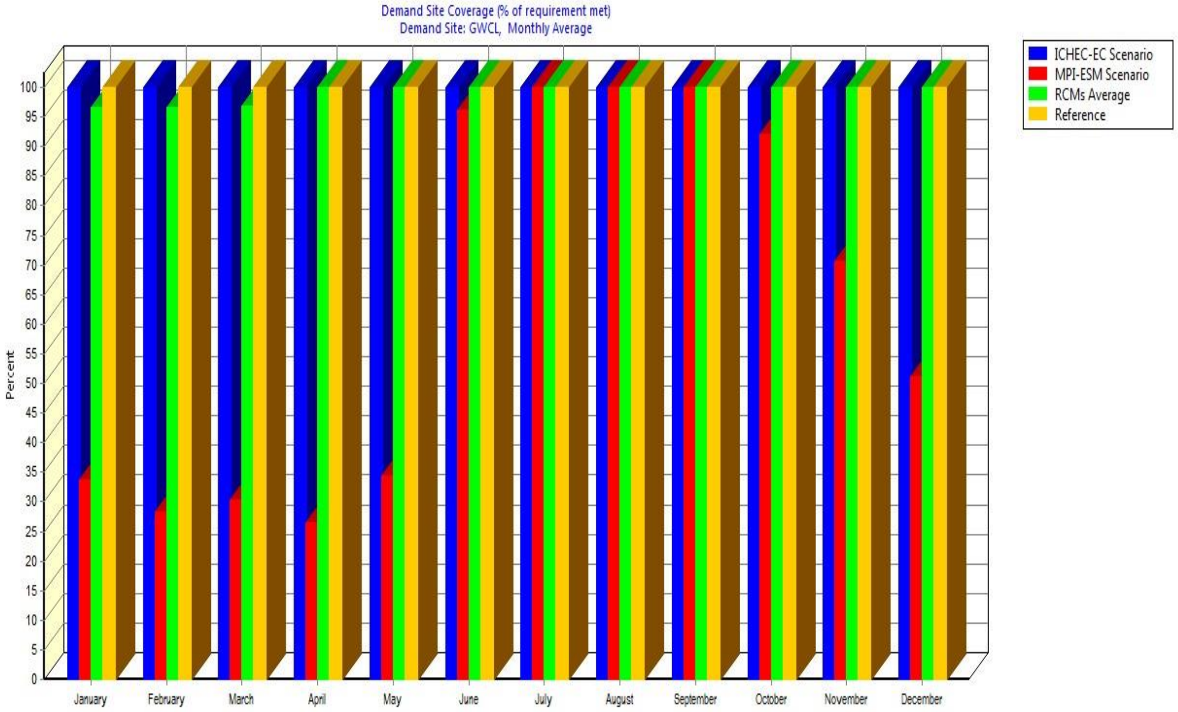
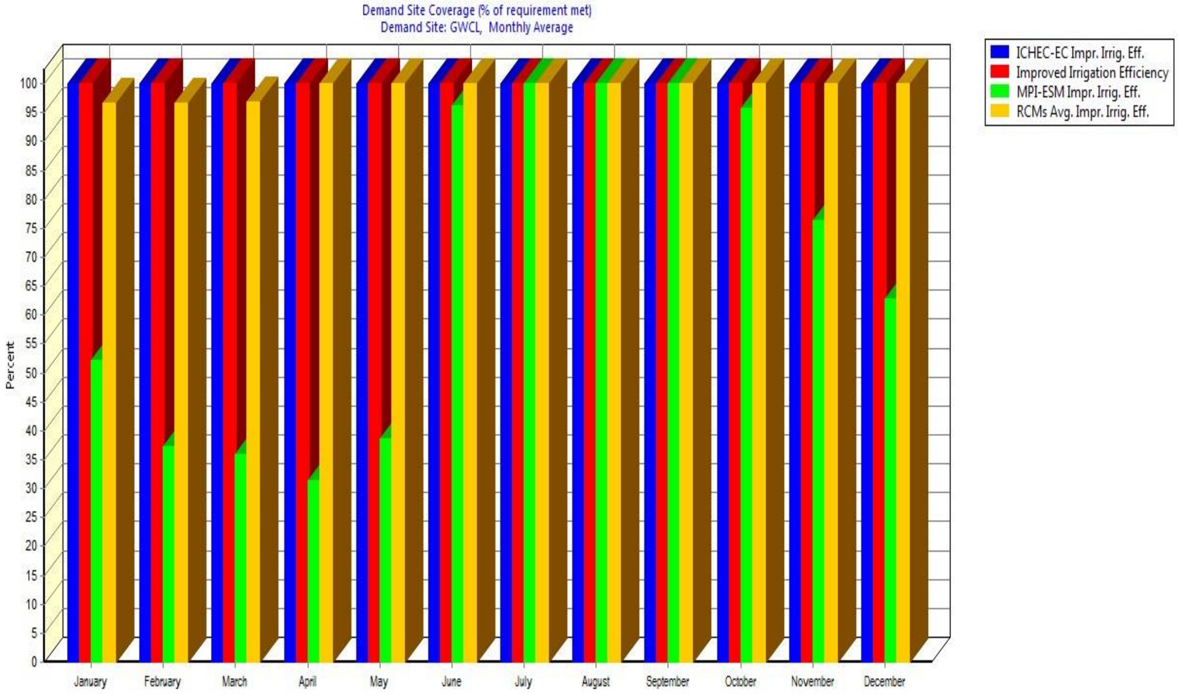
APPENDICES

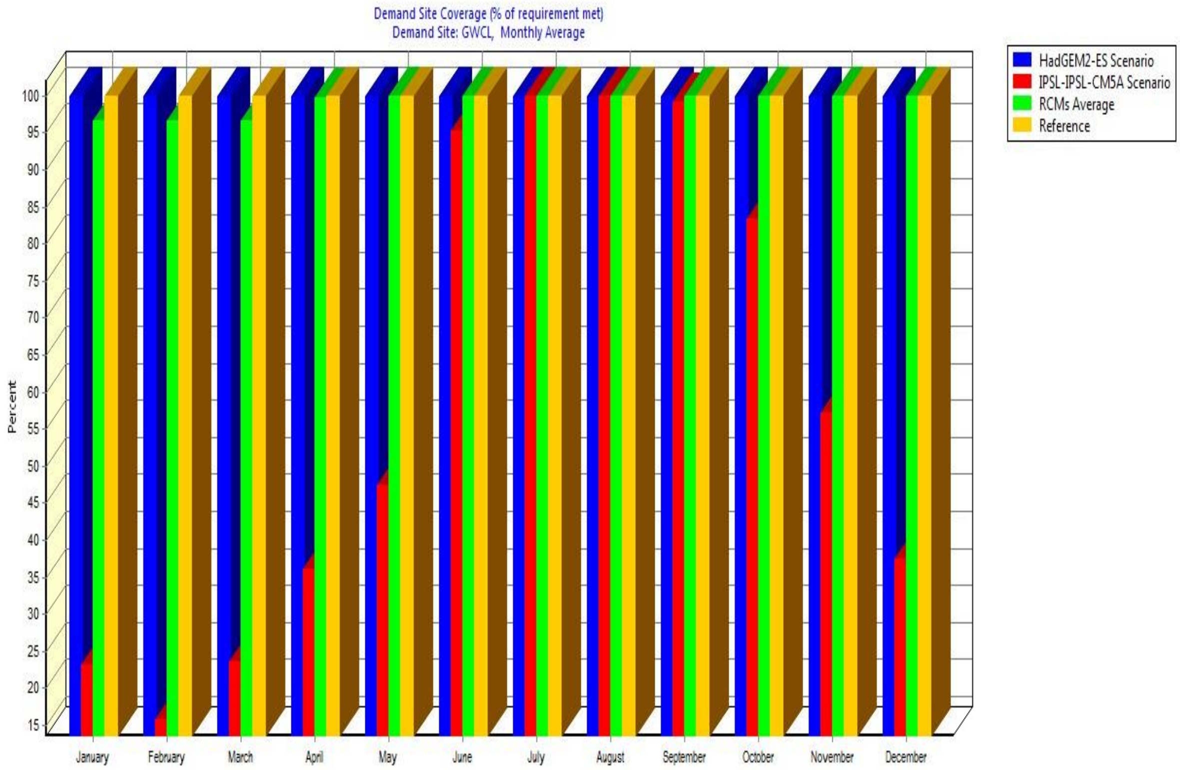
APPENDIX A: DOMESTIC MONTHLY WATER COVERAGE SITUATION



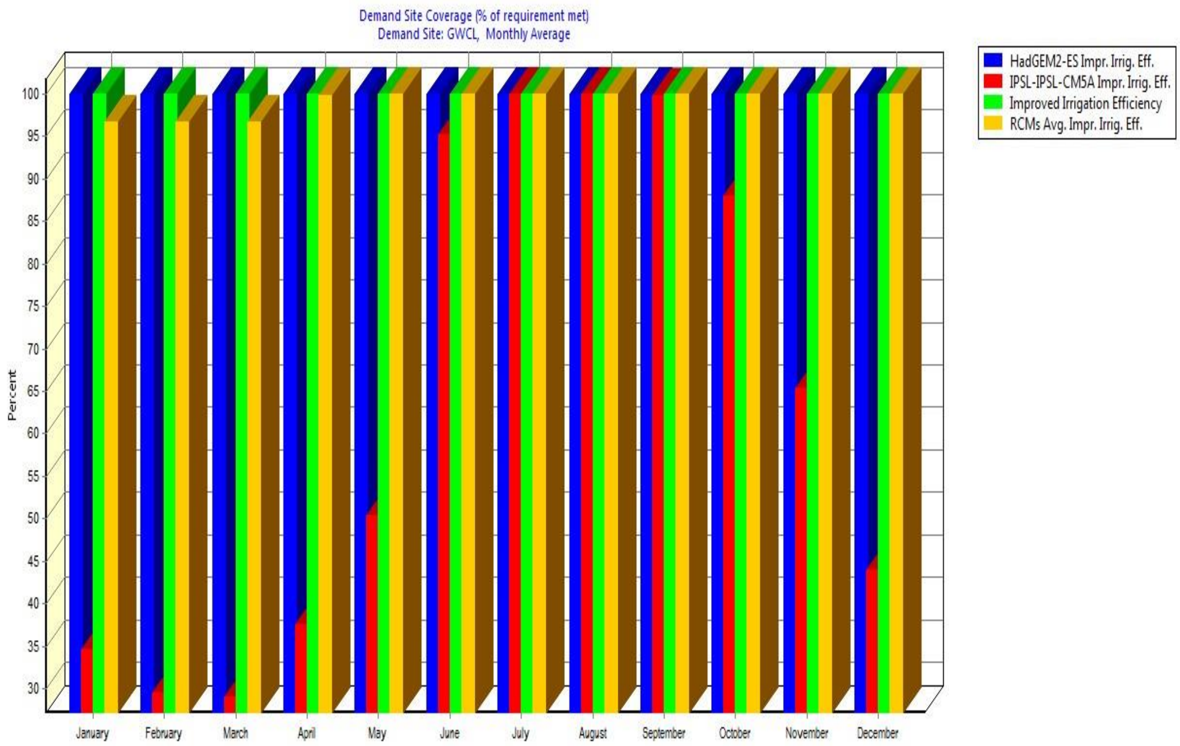
Appendix A1: *The situation of domestic monthly water coverage in the period 2021-2050 if irrigation continues to expand at the current rate of 1.1% with business as usual (current proportions of crops & efficiency of 50%)*



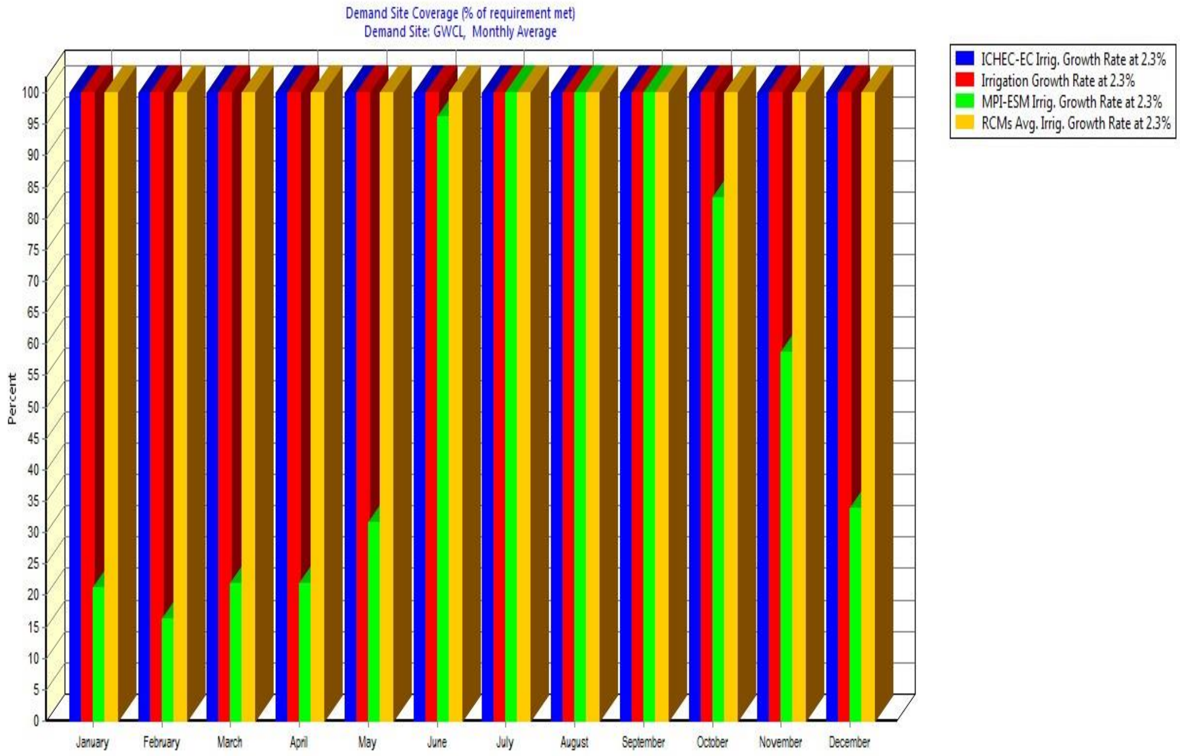
Appendix A2: *The situation of domestic monthly water coverage in the period 2021-2050 if irrigation continues to expand at the current rate of 1.1% with improved efficiency from 50% to 70%*



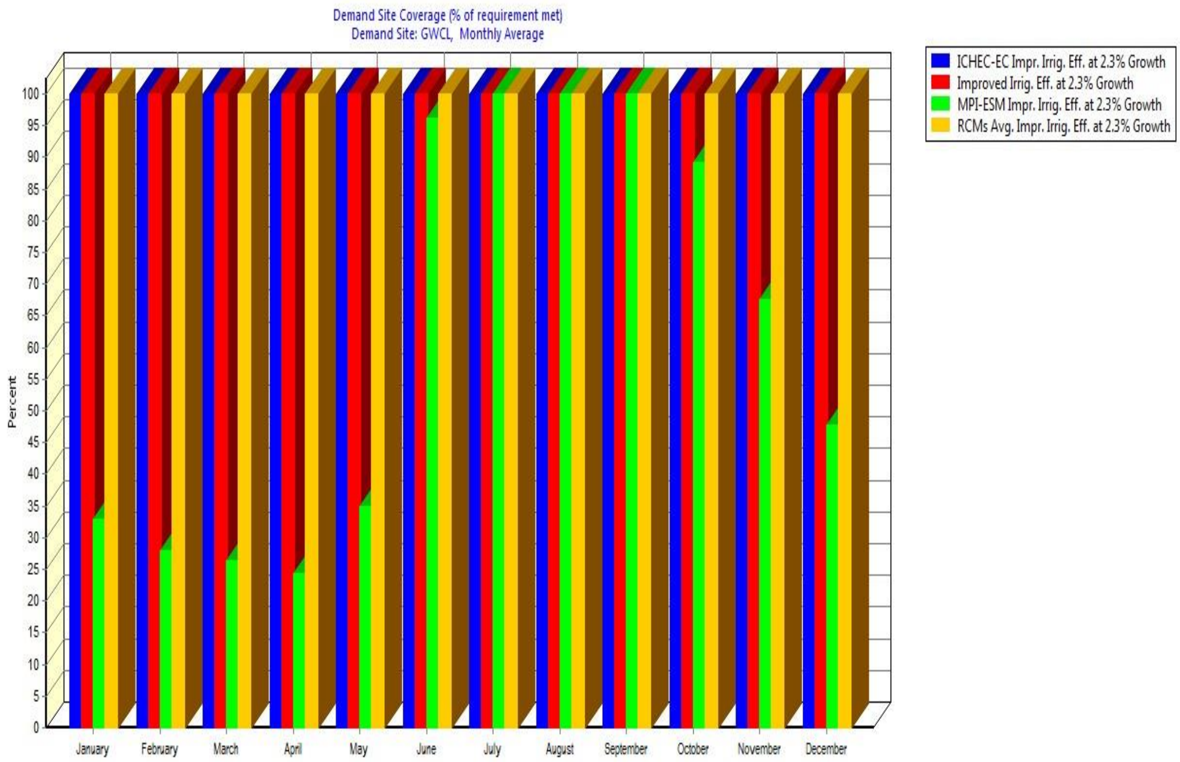
Appendix A3: *The situation of domestic monthly water coverage in the period 2071-2100 if irrigation continues to expand at the current rate of 1.1% with business as usual (current proportions of crops & efficiency of 50%)*



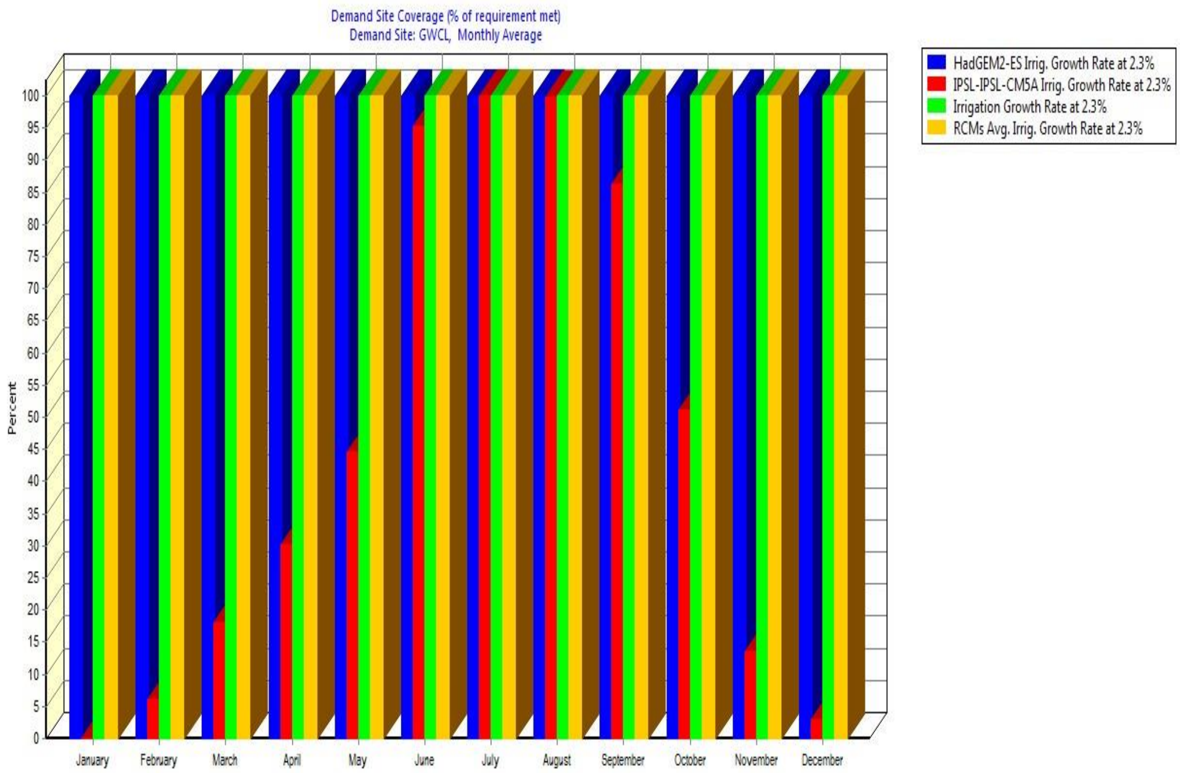
Appendix A4: *The situation of domestic monthly water coverage in the period 2071-2100 if irrigation continues to expand at the current rate of 1.1% with improved efficiency from 50% to 70%*



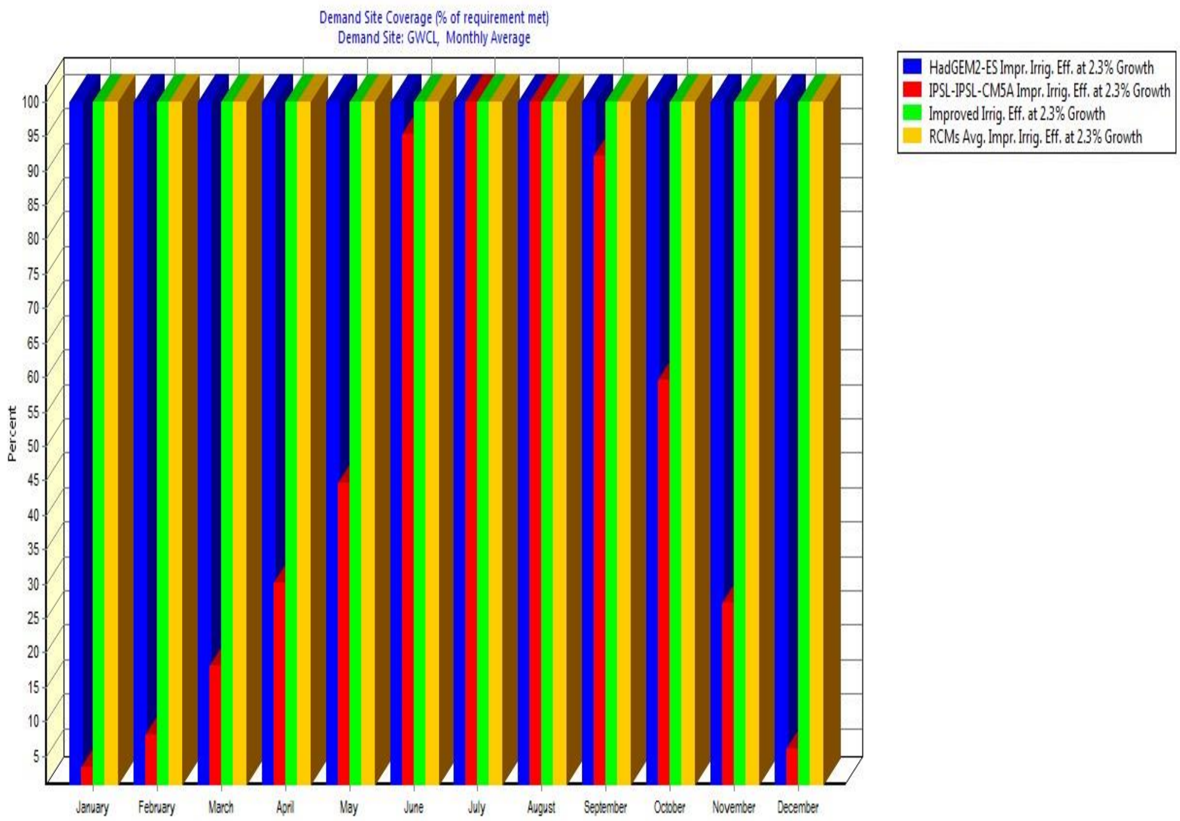
Appendix A5: *The situation of domestic monthly water coverage in the period 2021-2050 if irrigation continues to expand at the rate of 2.3% with business as usual (current proportions of crops & efficiency of 50%)*



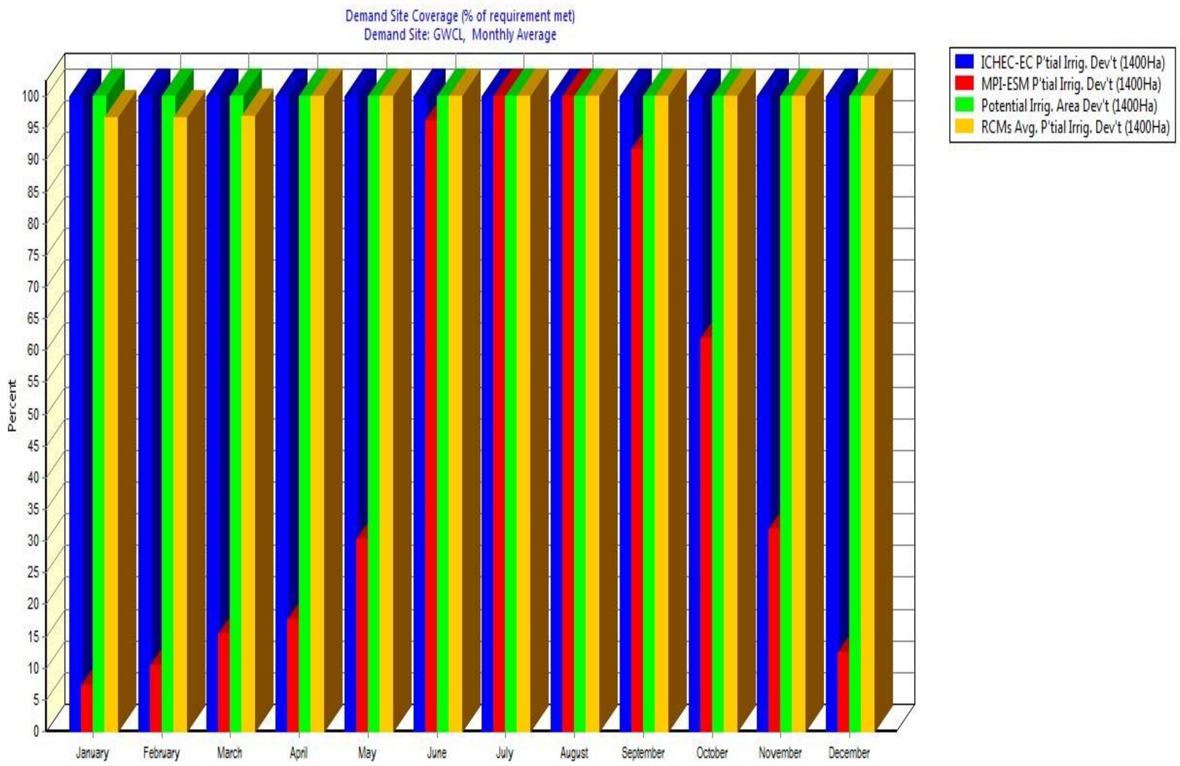
Appendix A6: *The situation of domestic monthly water coverage in the period 2021-2050 if irrigation continues to expand at the rate of 2.3% with improved efficiency from 50% to 70%*



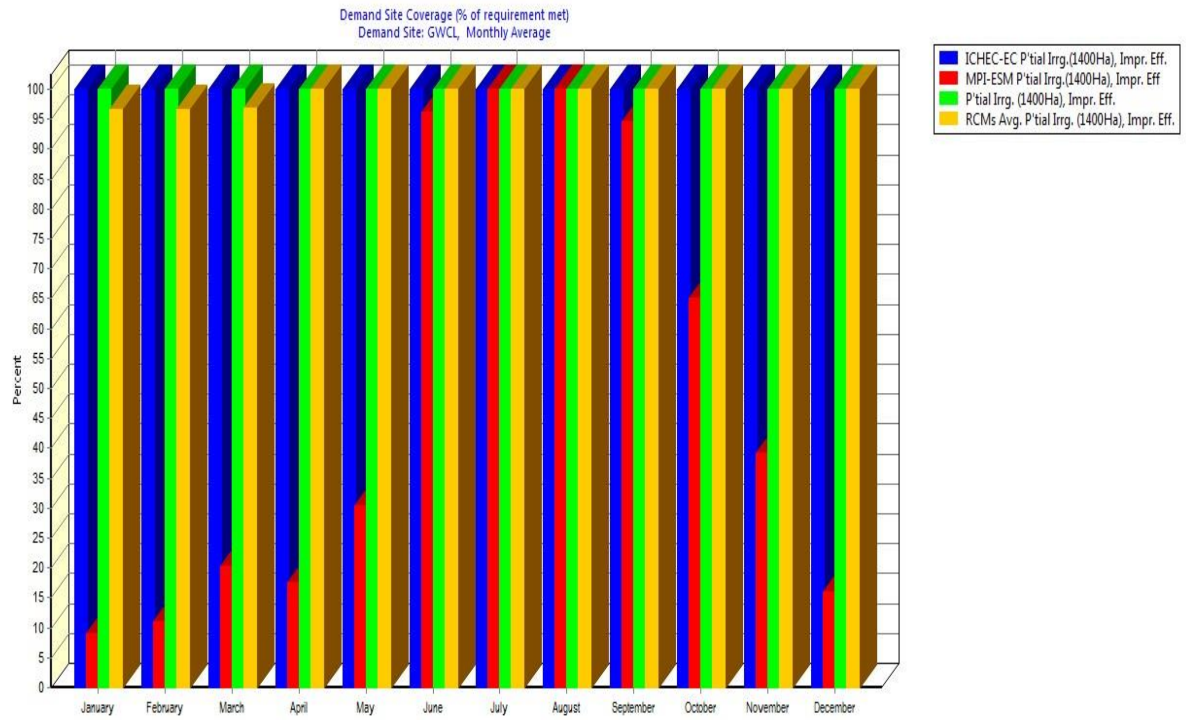
Appendix A7: *The situation of domestic monthly water coverage in the period 2071-2100 if irrigation continues to expand at the rate of 2.3% with business as usual (current proportions of crops & efficiency of 50%)*



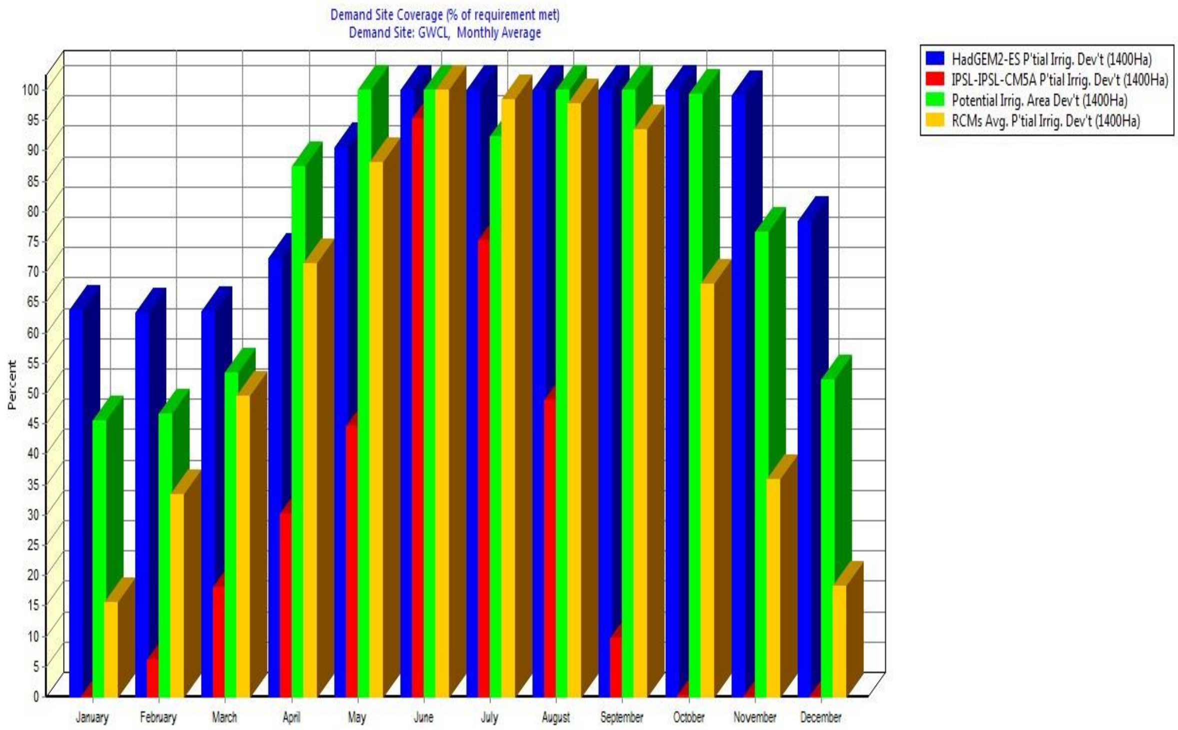
Appendix A8: *The situation of domestic monthly water coverage in the period 2071-2100 if irrigation continues to expand at the rate of 2.3% with improved efficiency from 50% to 70%*



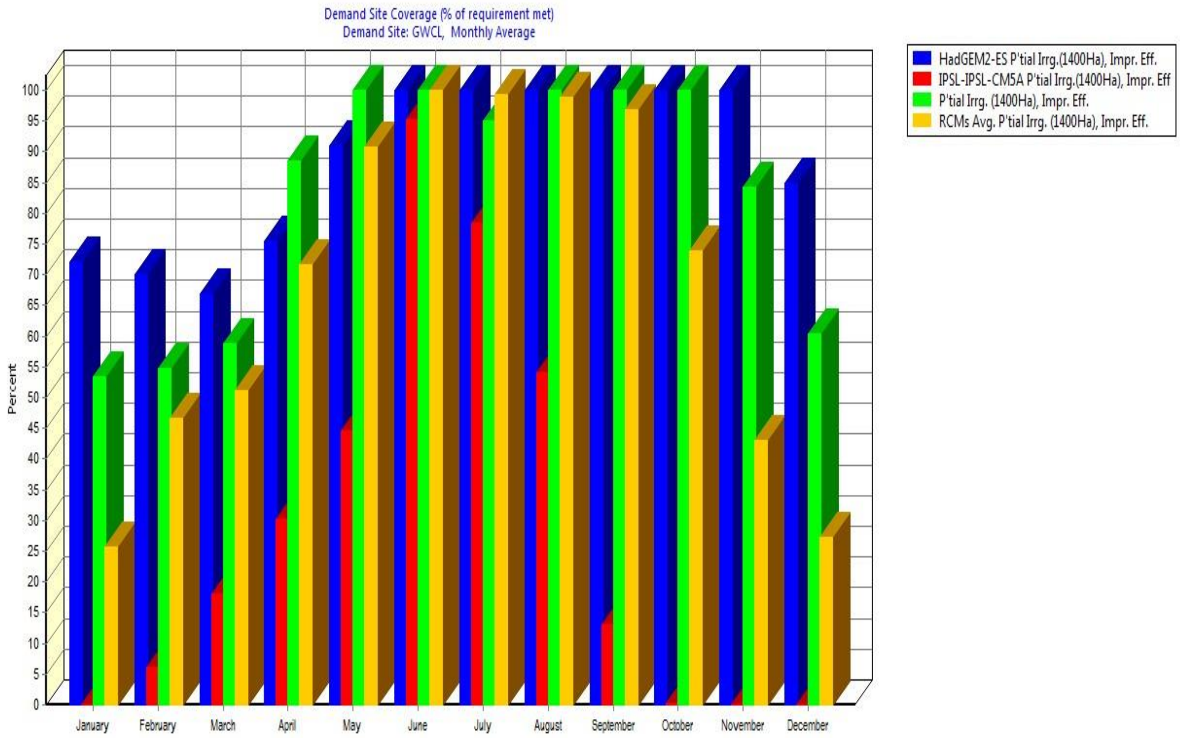
Appendix A9: *The situation of domestic monthly water coverage in the period 2021-2050 if potential irrigable area (1400 ha) is developed with business as usual (current proportions of crops & efficiency of 50%)*



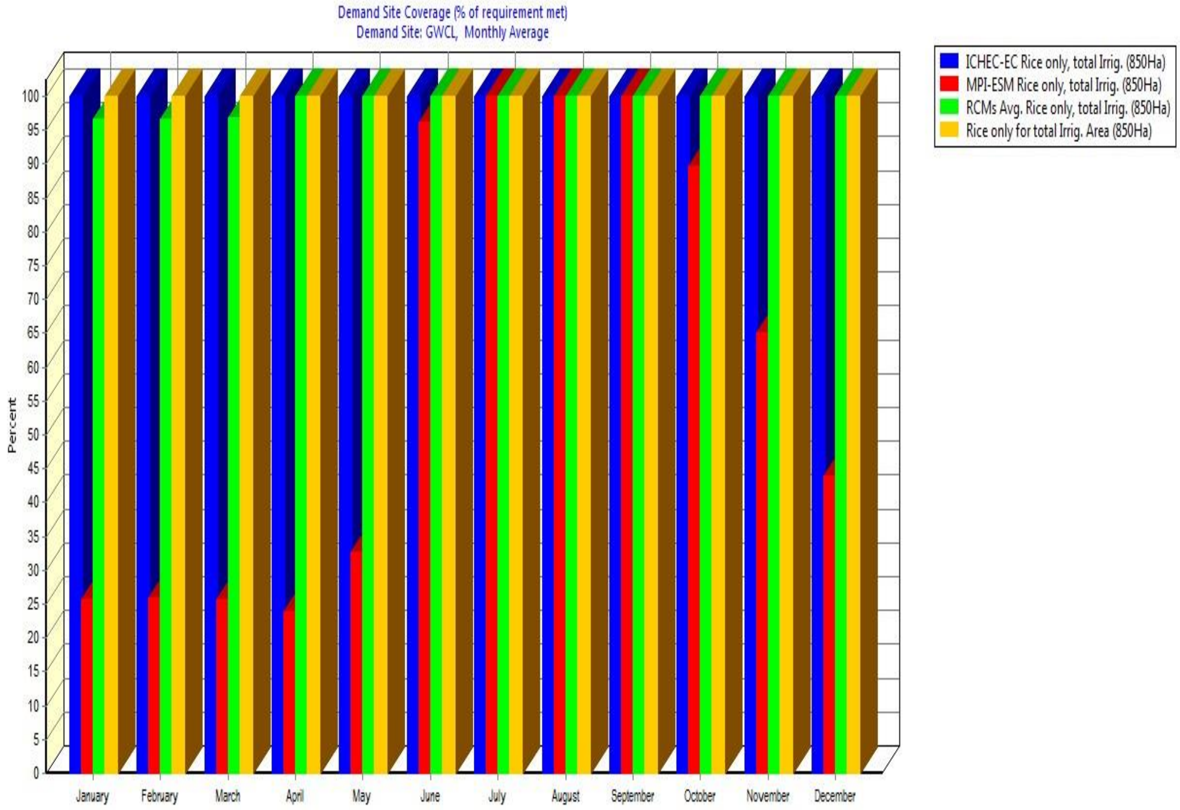
Appendix A10: *The situation of domestic monthly water coverage in the period 2021-2050 if potential irrigable area (1400 ha) is developed with improved efficiency from 50% to 70%*



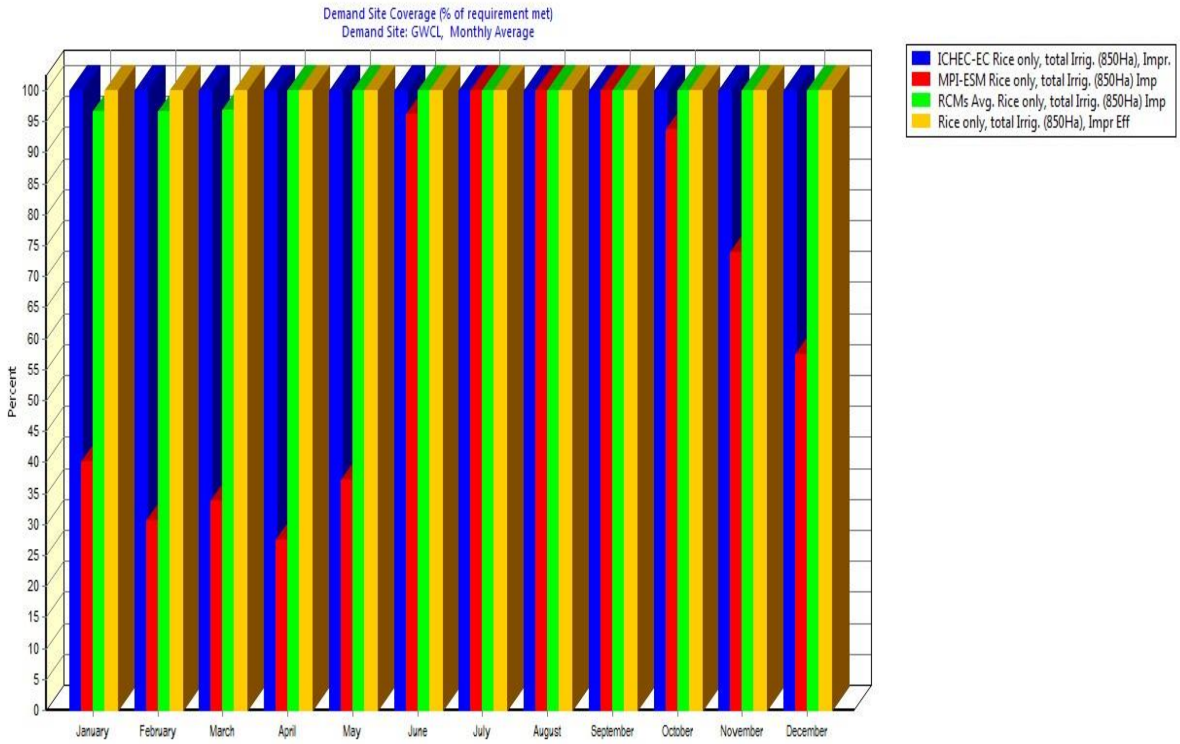
Appendix A11: *The situation of domestic monthly water coverage in the period 2071-2100 if potential irrigable area (1400 ha) is developed with business as usual (current proportions of crops & efficiency of 50%)*



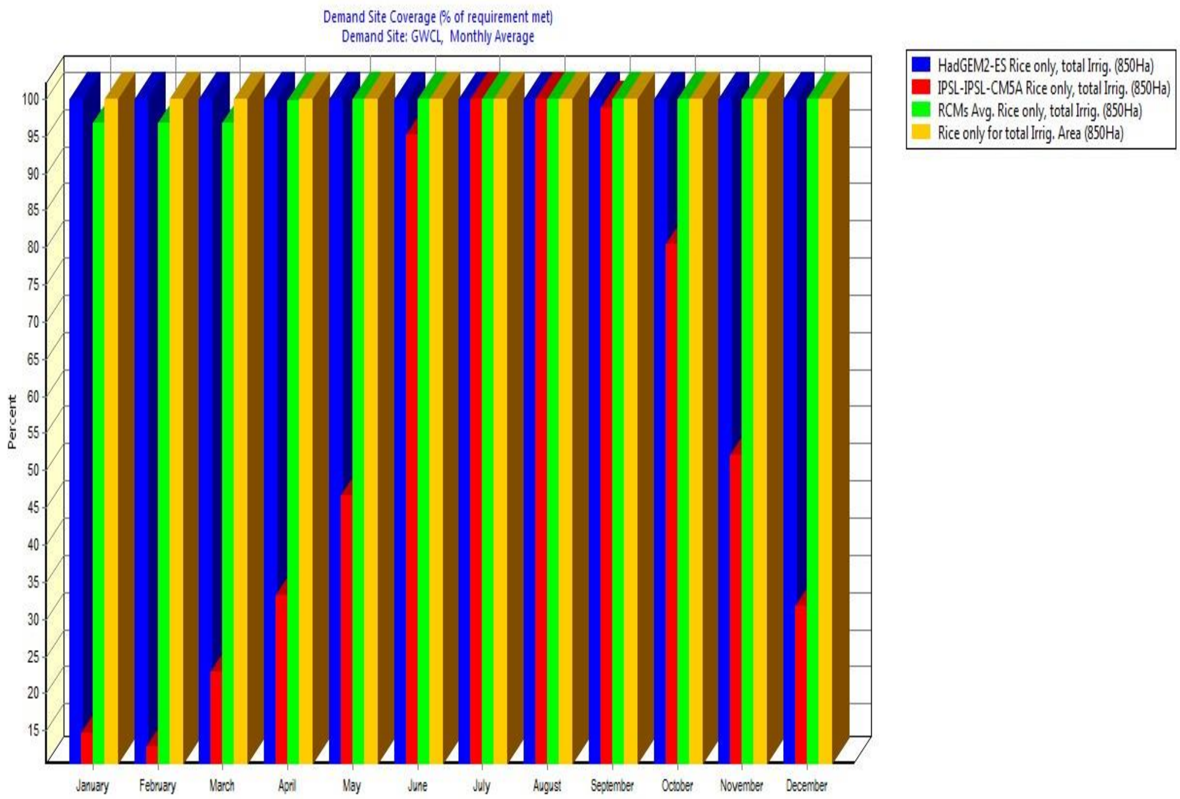
Appendix A12: *The situation of domestic monthly water coverage in the period 2021-2050 if potential irrigable area (1400 ha) is developed with improved efficiency from 50% to 70%*



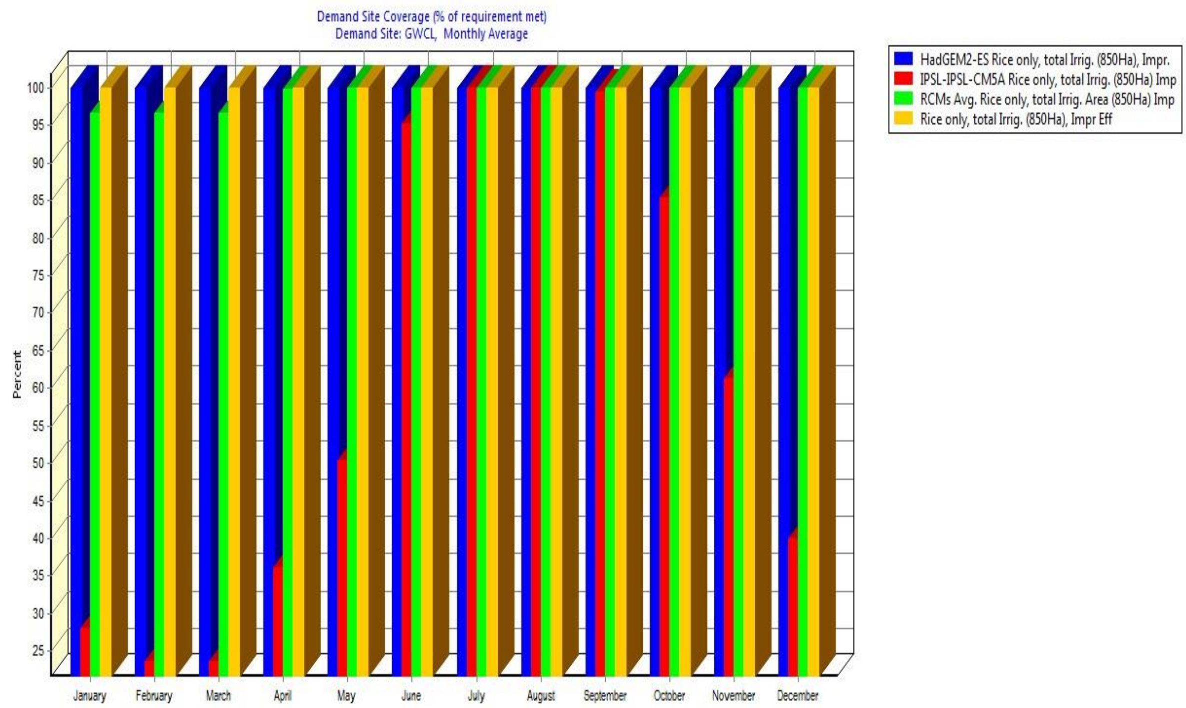
Appendix A13: *The situation of domestic monthly water coverage in the period 2021-2050 if only rice is used for total developed irrigable area (850 ha) with current efficiency of 50%*



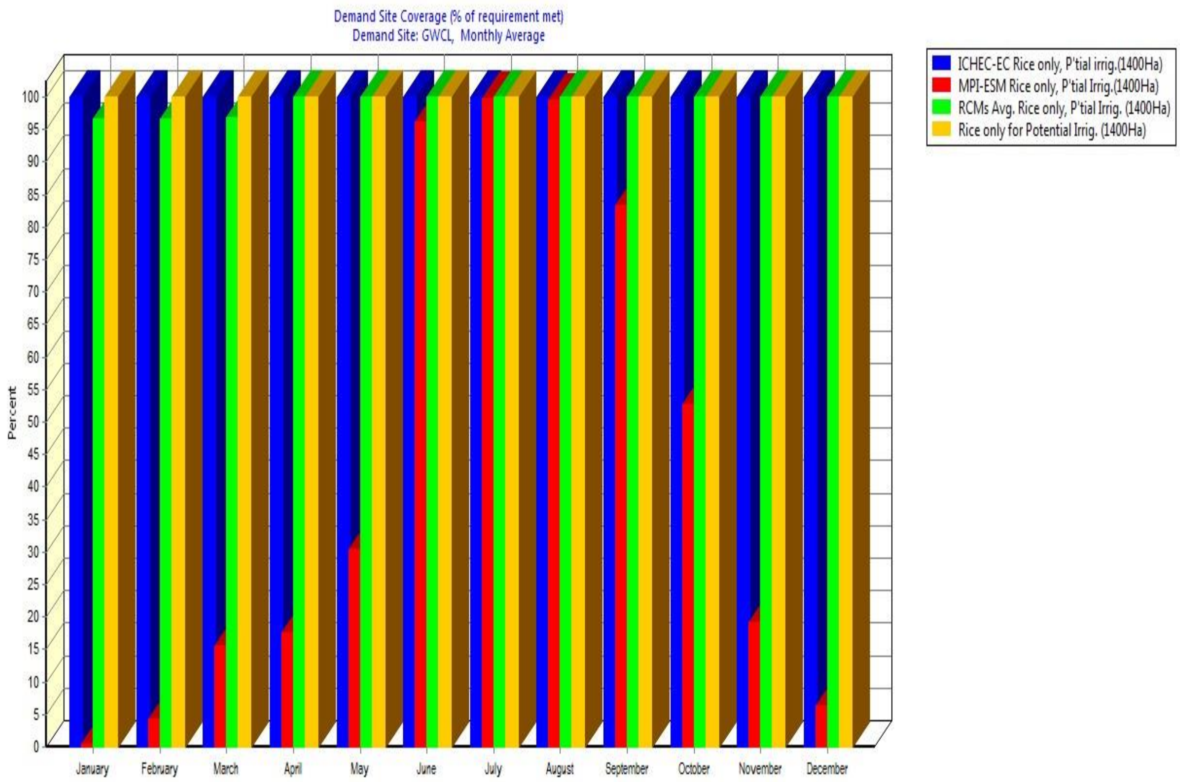
Appendix A14: *The situation of domestic monthly water coverage in the period 2021-2050 if only rice is used for total developed irrigable area (850 ha) with improved efficiency from 50% to 70%*



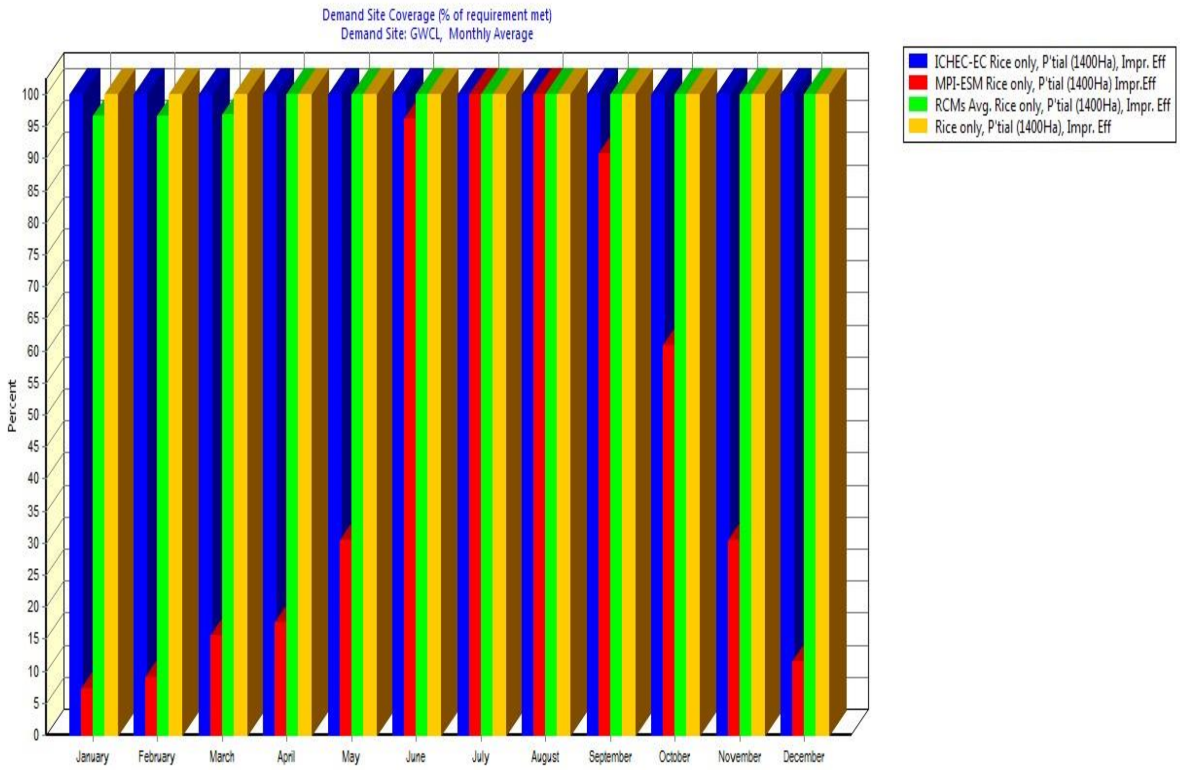
Appendix A15: *The situation of domestic monthly water coverage in the period 2071-2100 if only rice is used for total developed irrigable area (850 ha) with current efficiency of 50%*



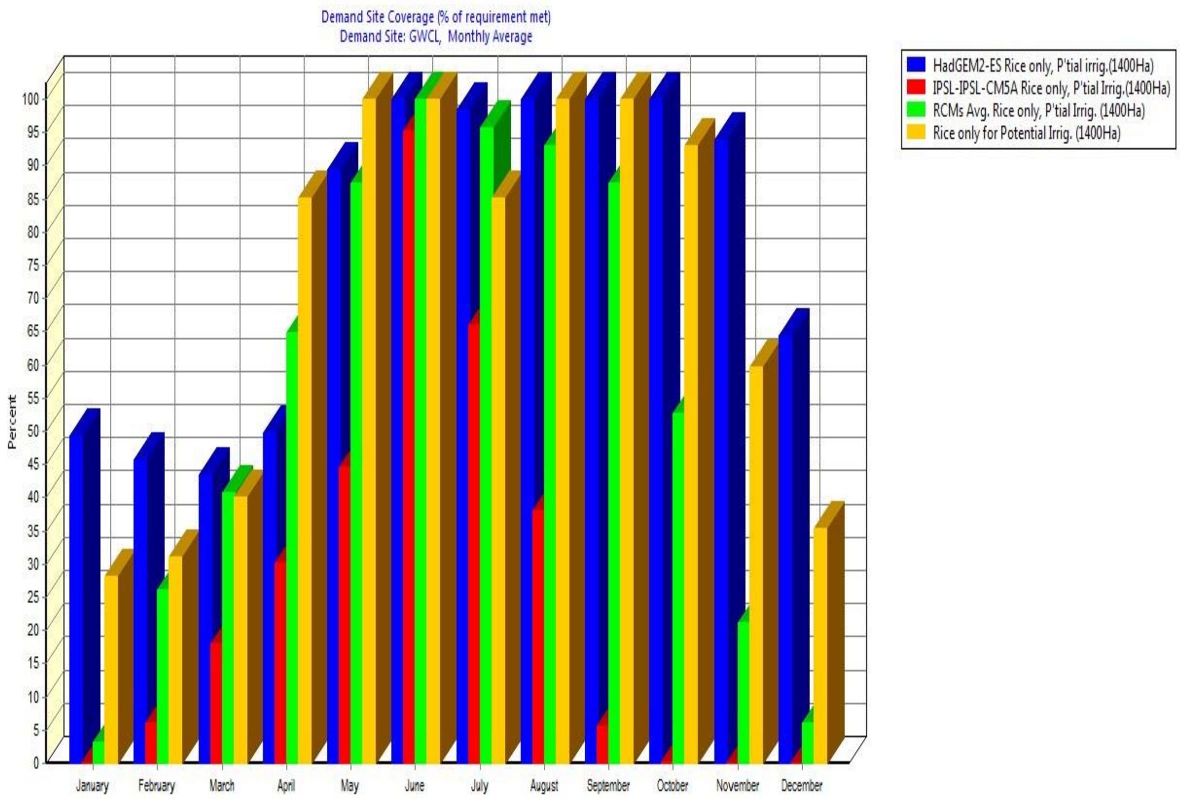
Appendix A16: *The situation of domestic monthly water coverage in the period 2071-2100 if only rice is used for total developed irrigable area (850 ha) with improved efficiency from 50% to 70%*



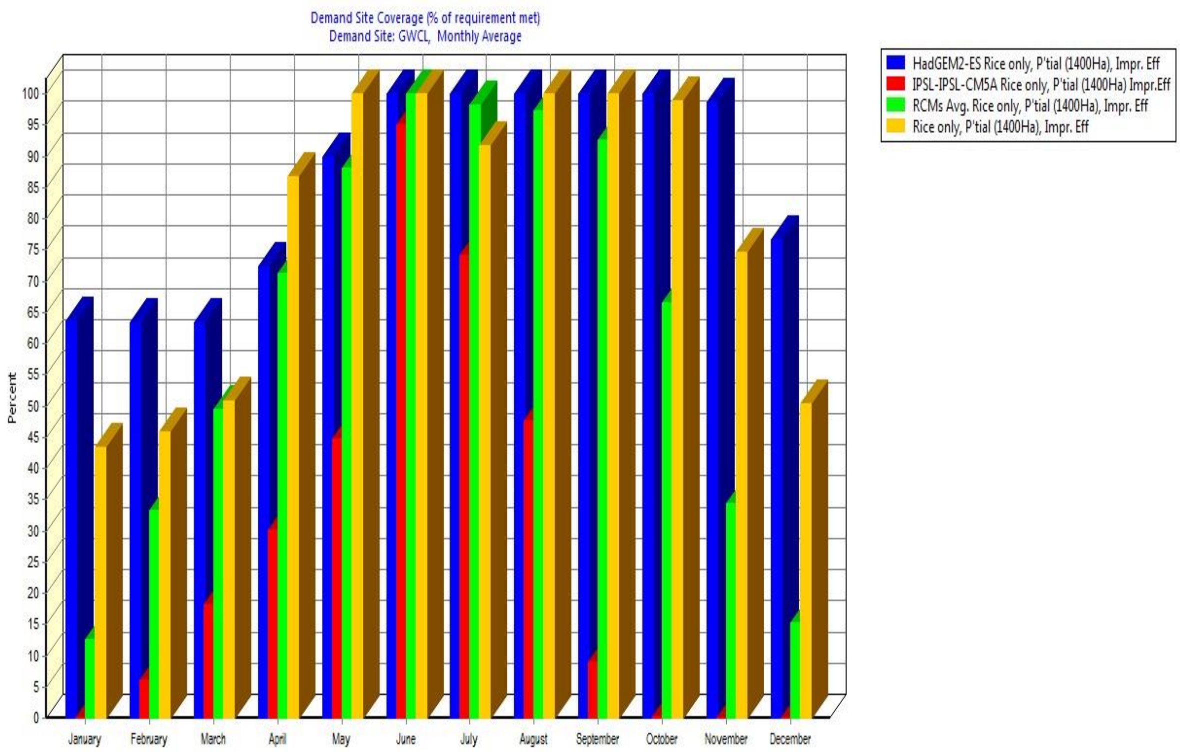
Appendix A17: *The situation of domestic monthly water coverage in the period 2021-2050 if only rice is used for total potential irrigable area (1400 ha) with current efficiency of 50%*



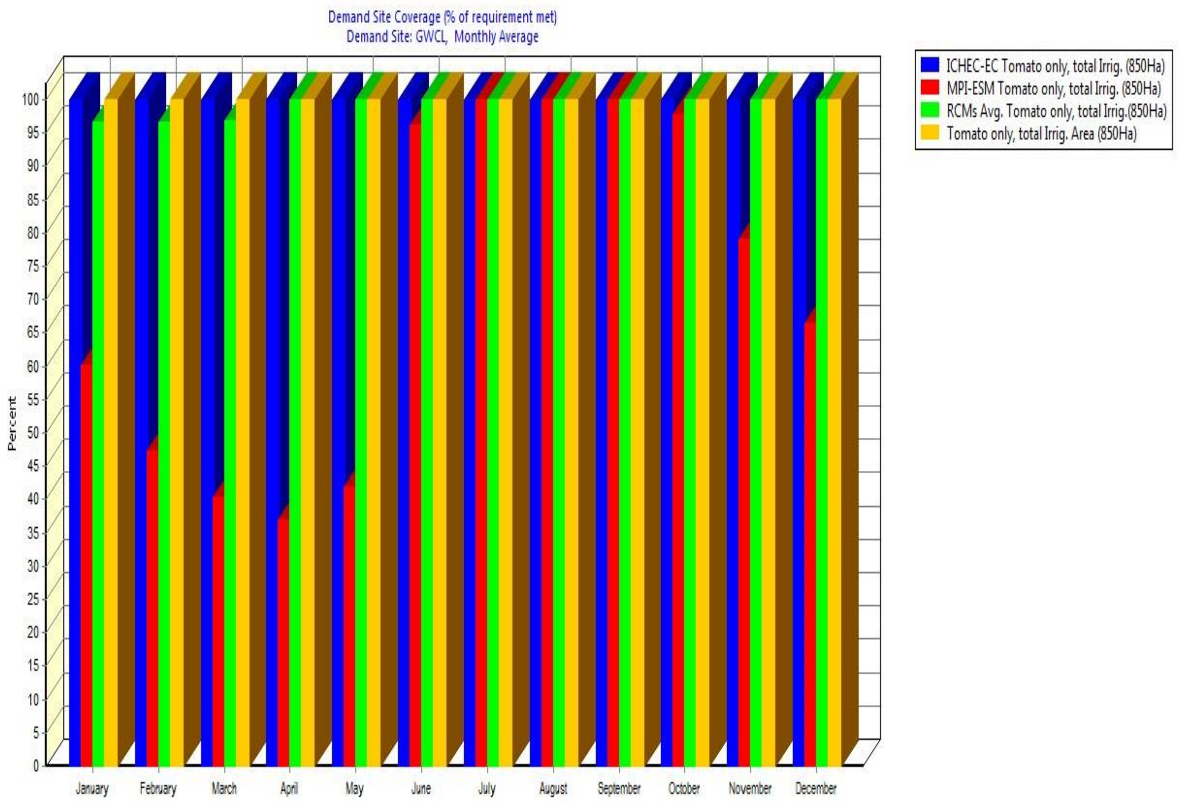
Appendix A18: *The situation of domestic monthly water coverage in the period 2021-2050 if only rice is used for total potential irrigable area (1400 ha) with improved efficiency from 50% to 70%*



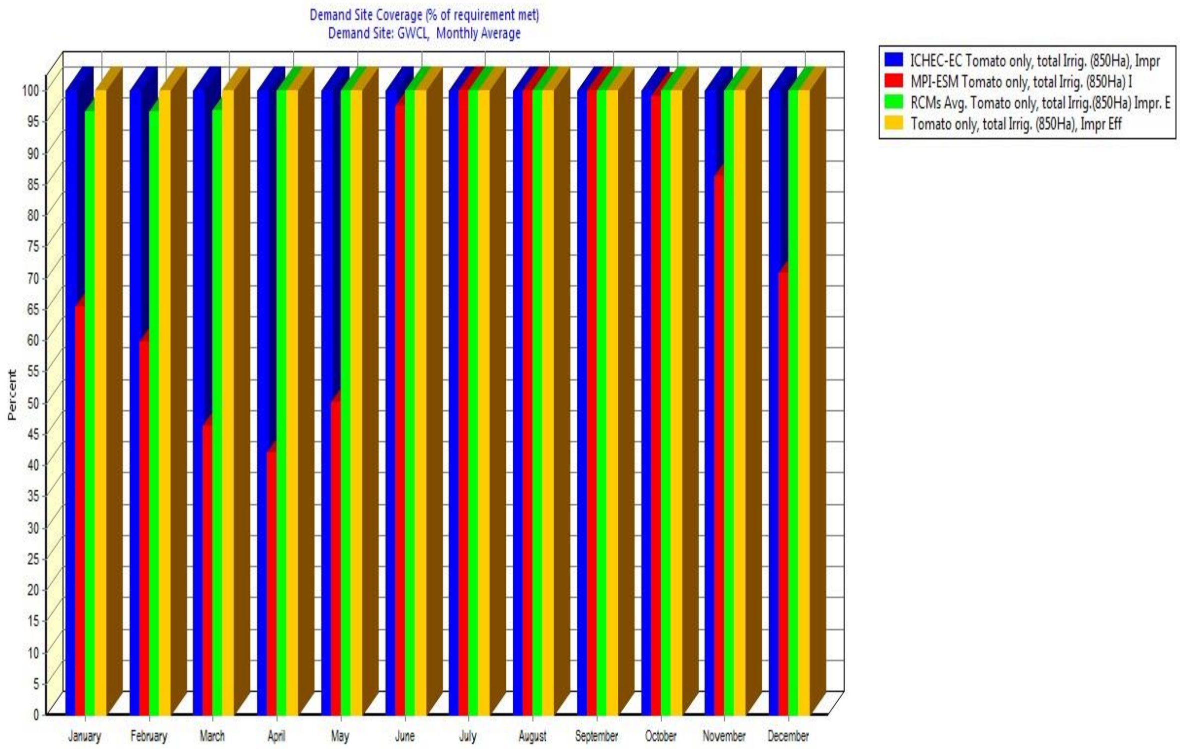
Appendix A19: *The situation of domestic monthly water coverage in the period 2071-2100 if only rice is used for total potential irrigable area (1400 ha) with current efficiency of 50%*



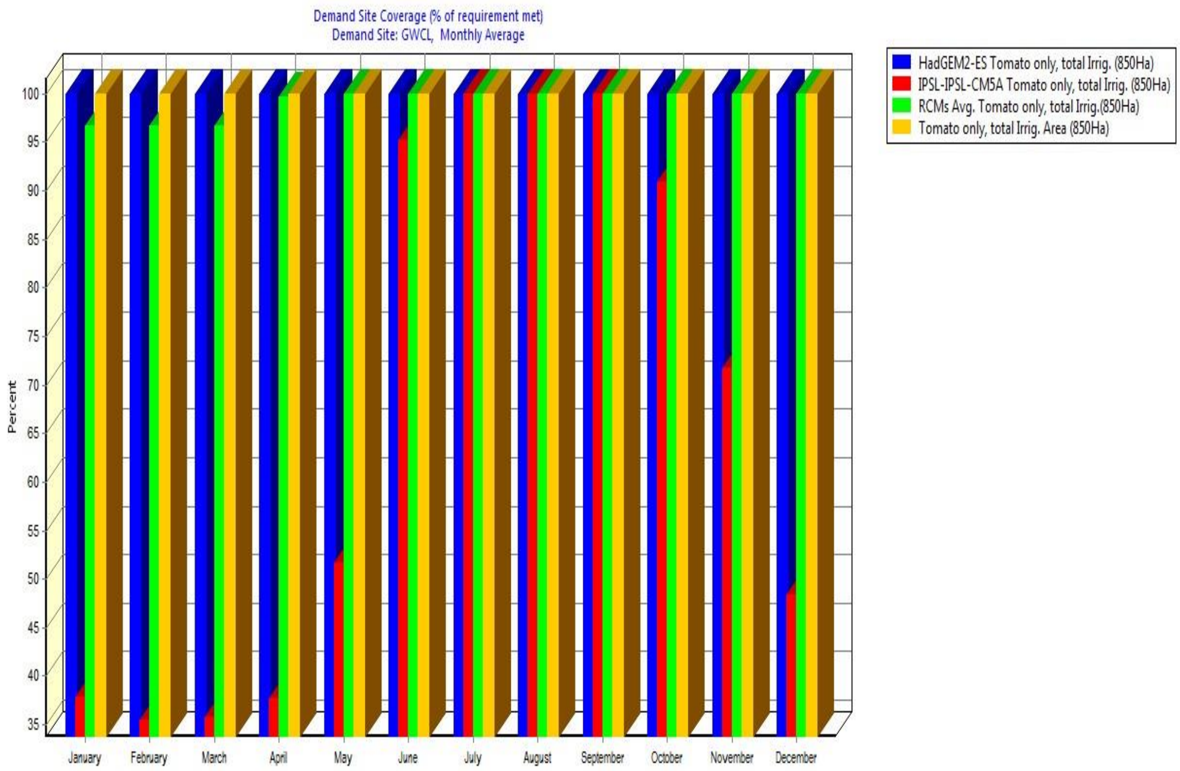
Appendix A20: *The situation of domestic monthly water coverage in the period 2071-2100 if only rice is used for total potential irrigable area (1400 ha) with improved efficiency from 50% to 70%*



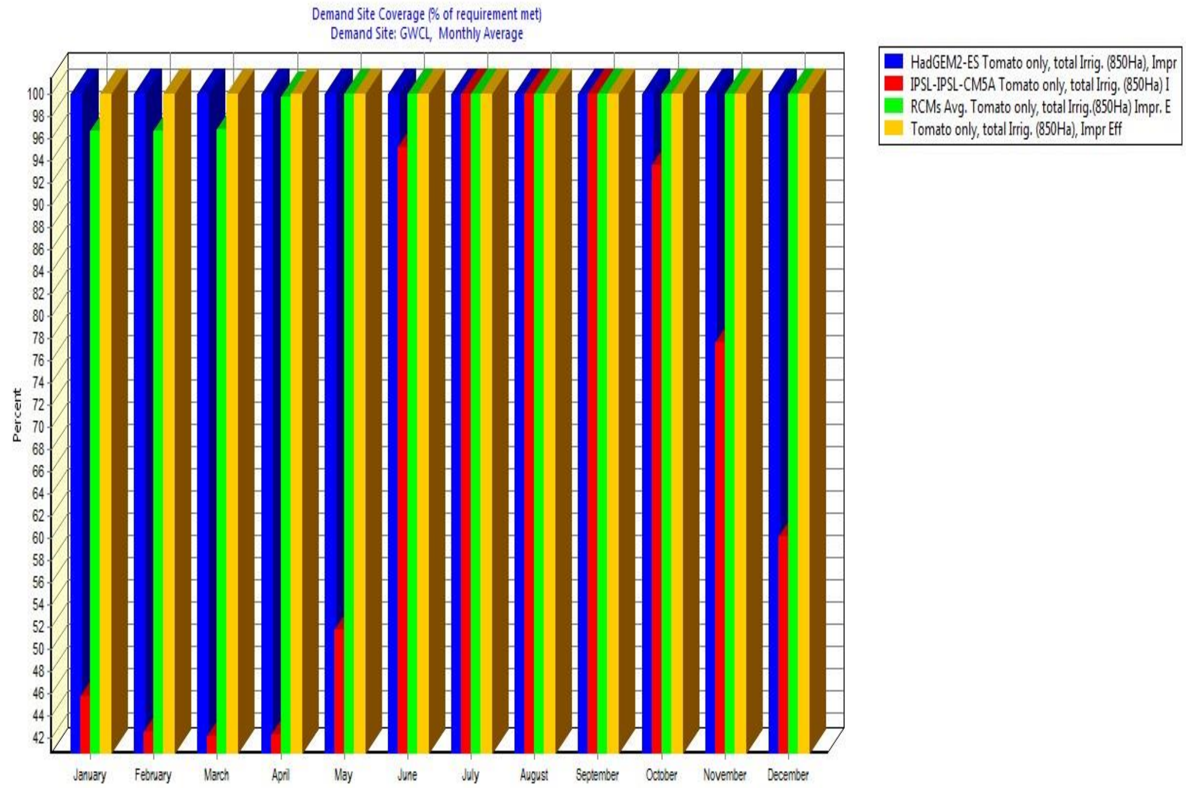
Appendix A21: *The situation of domestic monthly water coverage in the period 2021-2050 if only tomato is used for total developed irrigable area (850 ha) with current efficiency of 50%*



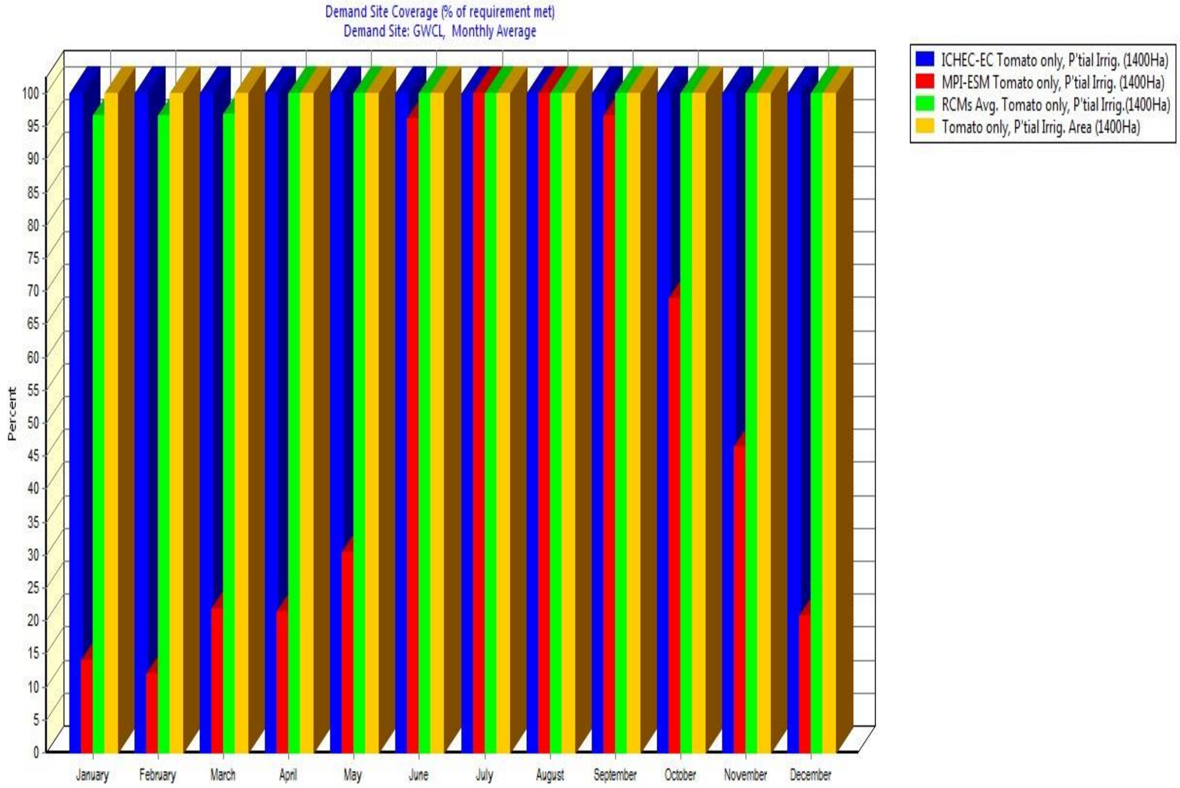
Appendix A22: *The situation of domestic monthly water coverage in the period 2021-2050 if only tomato is used for total developed irrigable area (850 ha) with improved efficiency from 50% to 70%*



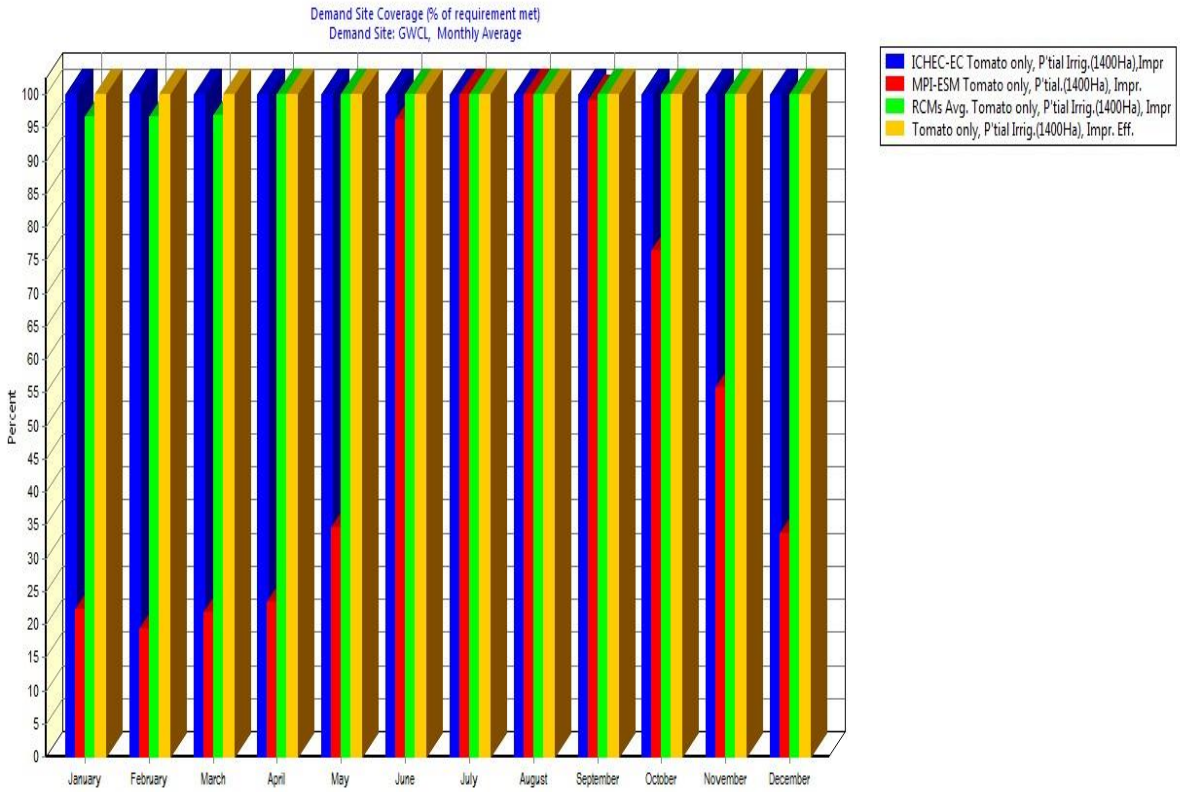
Appendix A23: *The situation of domestic monthly water coverage in the period 2071-2100 if only tomato is used for total developed irrigable area (850 ha) with current efficiency of 50%*



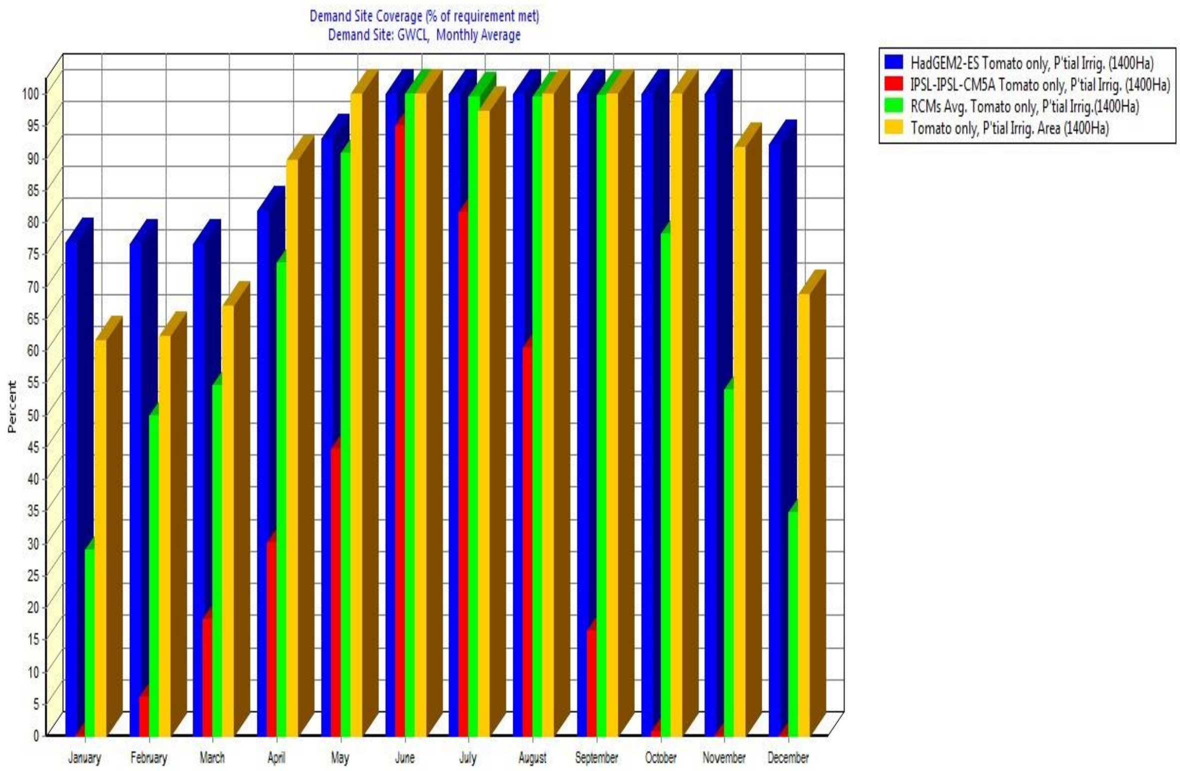
Appendix A24: *The situation of domestic monthly water coverage in the period 2071-2100 if only tomato is used for total developed irrigable area (850 ha) with improved efficiency from 50% to 70%*



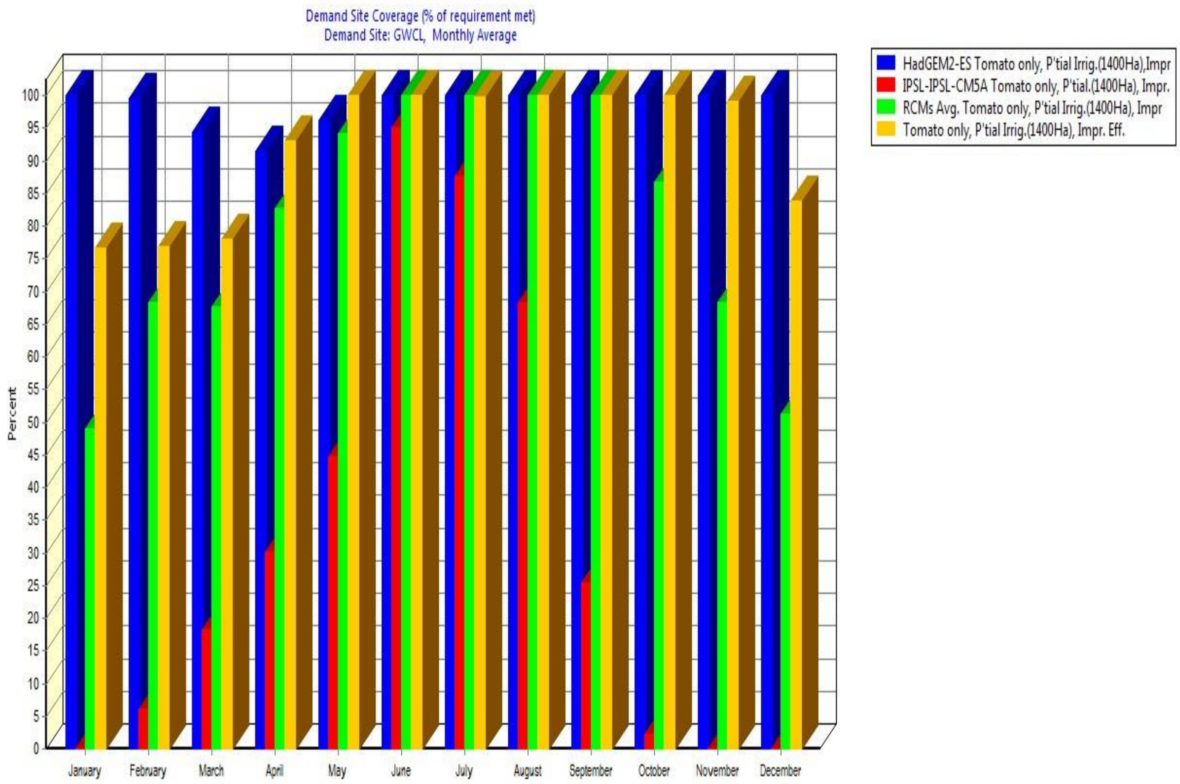
Appendix A25: *The situation of domestic monthly water coverage in the period 2021-2050 if only tomato is used for total potential irrigable area (1400 ha) with current efficiency of 50%*



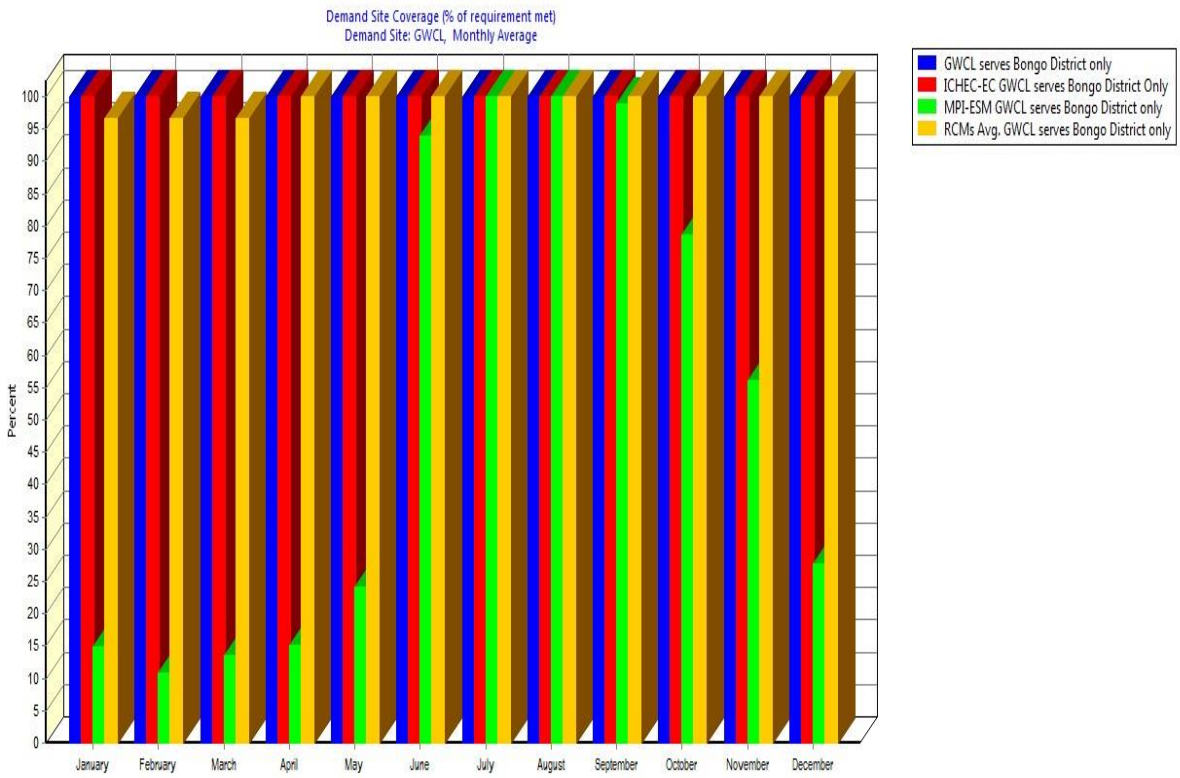
Appendix A26: *The situation of domestic monthly water coverage in the period 2021-2050 if only tomato is used for total potential irrigable area (1400 ha) with improved efficiency from 50% to 70%*



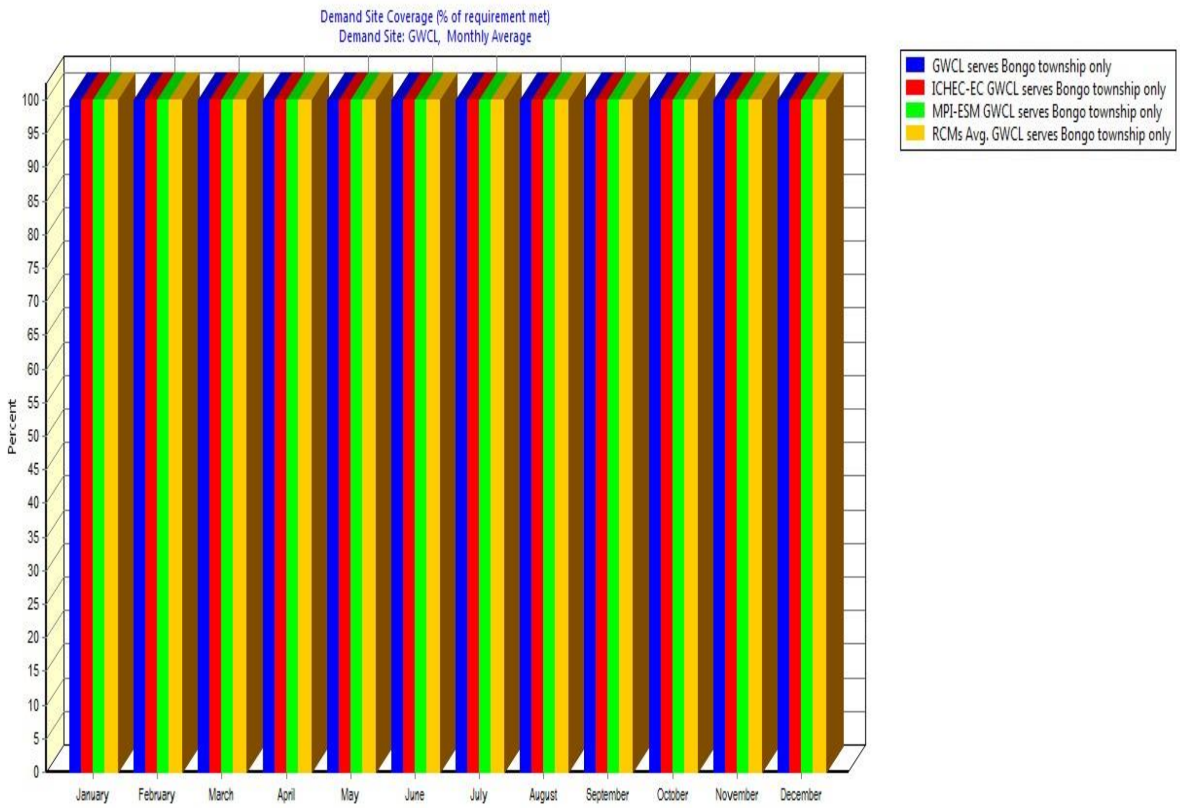
Appendix A27: *The situation of domestic monthly water coverage in the period 2071-2100 if only tomato is used for total potential irrigable area (1400 ha) with current efficiency of 50%*



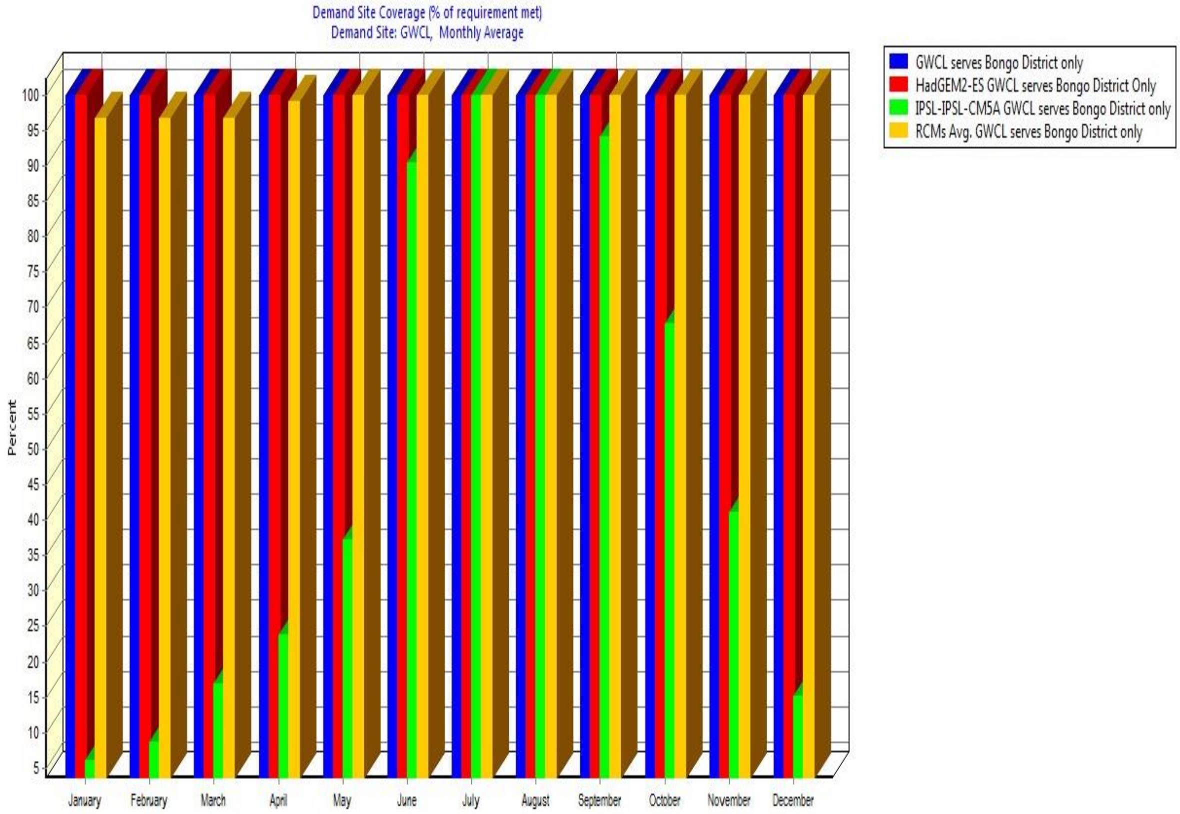
Appendix A28: *The situation of domestic monthly water coverage in the period 2071-2100 if only tomato is used for total potential irrigable area (1400 ha) with improved efficiency from 50% to 70%*



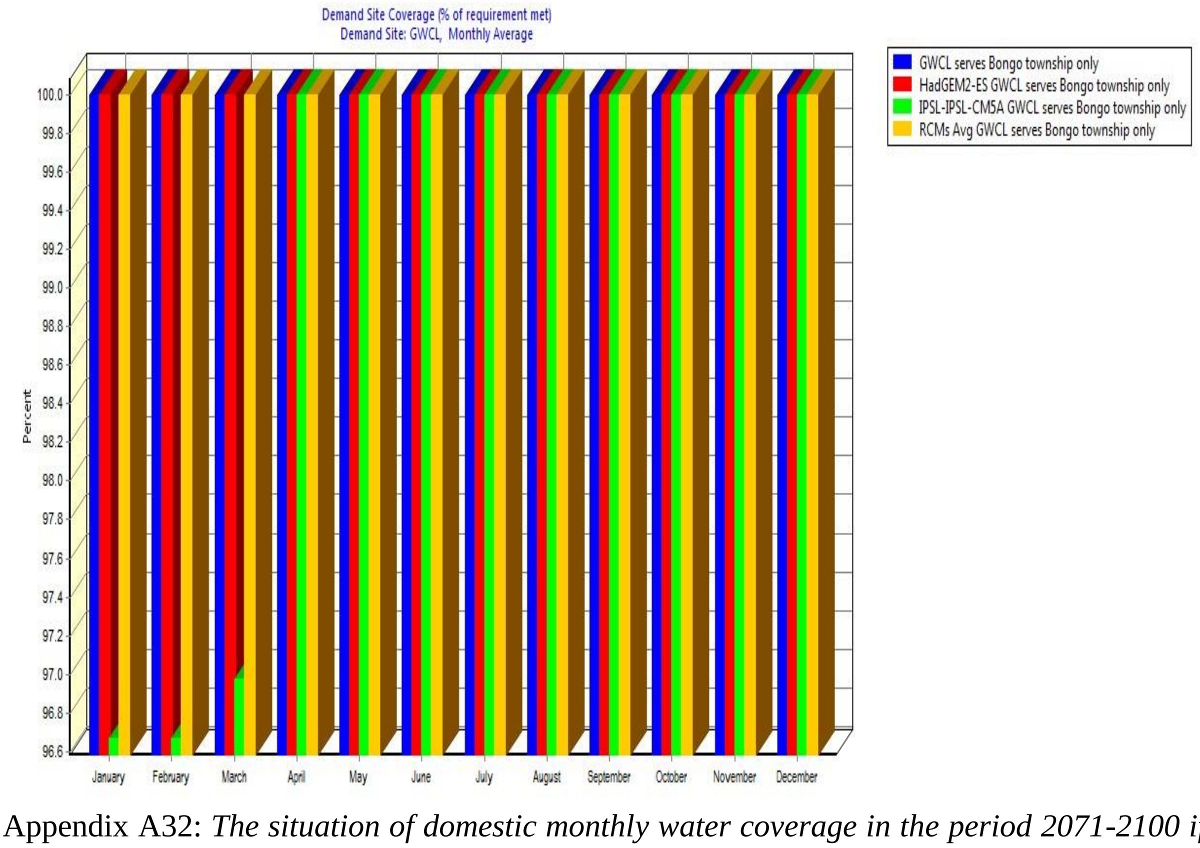
Appendix A29: *The situation of domestic monthly water coverage in the period 2021-2050 if Vea irrigation reservoir serves domestic water supply to Bongo District and its environs*



Appendix A30: *The situation of domestic monthly water coverage in the period 2021-2050 if Vea irrigation reservoir serves domestic water supply to only Bongo Township*



Appendix A31: *The situation of domestic monthly water coverage in the period 2071-2100 if Vea irrigation reservoir serves domestic water supply to Bongo District and its environs*



Appendix A32: *The situation of domestic monthly water coverage in the period 2071-2100 if Vea irrigation reservoir serves domestic water supply to only Bongo Township*

APPENDIX B: SURVEY QUESTIONNAIRE

GRADUATE RESEARCH PROGRAM, CLIMATE CHANGE AND WATER RESOURCES
UNIVERSITY OF ABOMEY-CALAVI, BENIN

FARMERS' HOUSEHOLD SURVEY QUESTIONNAIRE

PERCEPTION OF FARMERS ON CLIMATE CHANGE, ADAPTATION OPTIONS AND BARRIERS TO ADAPTATION

This research survey questionnaire is purely for academic purposes with the objective of **'Assessing and comparing farmers' perceptions on climate change and variability with statistical analyses of observed climatic data, their adaptation practices and barriers to adaptation, as part of a broader research that assesses the impacts of climate and land use changes on water availability in the Vea Catchment for irrigation'.** You are assured of confidentiality of any view expressed in relation to this research. I therefore entreat you to provide information as accurate as possible for true results. Thank you for your kind co-operation.

Questionnaire number:			
Name of interviewer:			
Date of interview:	D	M	Y
Name of respondent:			
House number of respondent:			
District:			
Community:			

SECTION-A
DEMOGRAPHIC

1a. Sex: 1: Male 2: Female
2a. Age of Respondent: 1: 50–59yrs, 2: 60–69yrs, 3: 70yrs+
3a. Originality/Nativity: 1: Born and raised in the community, 2: Migrant,
4a. Number of years stayed in the community: 1: 30–39yrs, 2: 40–49yrs, 3: 50yrs+
5a. Do you have any social responsibility (social position) in the community? 1: Yes ☐, 2: No ☐
6a. Respondent's level of education: 1: Basic/Middle school, 2: Secondary/Vocational, 3: Tertiary(specify)………… 4: Non-formal 5: None
7a. Marital status: 1: Married, 2: Single, 3: Widow/Widower, 4: Divorce/Separated
8a. Respondent's household (HH) size: 1: 1-5, 2: 6-10, 3: 11-15, 4: 16-20, 5: 21-25, 6: 26-30, 7: 31+
9a. Occupation: 1: Crop farming, 2: Livestock farming, 3: Fish farming, 4: Crop & livestock farming, 5: Fish & livestock farming, 6: Crop, livestock & fish farming
10a. Years in Occupation: 1: 30–39 yrs, 2: 40–49 yrs, 3: 50yrs+, 4: Other (specify):………..........................
11a. Where is your farm location? **KEY:** 1: Near river, 2: On hills, 3: Low land, 4: Near river and on hills, 5: Near river and low land, 6: Other (specify):………………………
12a. Which type of agriculture do you practice? 1: Rainfed only☐, 2: Irrigation only☐, 3: Rainfed & irrigation ☐, 4: Other (specify):………………………
13a. Religion of Respondent: 1: Christianity, 2: Traditional, 3: Islam, 4: Other...

SECTION-B
PERCEPTION OF FARMERS ON CLIMATE CHANGE

1b. Have you observed any long-term changes in the mean of climate variables (particularly temperature and rainfall) over the last 30 years? 1: Yes ☐, 2: No ☐
2b. If yes, indicate (√) what have been the changes.

S/N	2b. Long-term changes in mean climate variables	Selected factors (√)
2.1b	Increased temperature	
2.2b	Decreased temperature	
2.3b	Increased in rainfall duration	

2.4b	Increased in number of rainfall events	
2.5b	Increased in rainfall intensity	
2.6b	Decreased in rainfall duration	
2.7b	Decreased in number of rainfall events	
2.8b	Decreased in rainfall intensity	

3b. To what extent are these changes? 1: Extreme changes; 2: Many changes; 3: Some changes; 4: Limited changes; 5: Few changes; 6: I don't know

4b. What have you observed to be the main effects/impacts (negative) of these long-term changes in the mean of climate variables over the last 30 years? [Indicate (√)]

RANK: *On a scale of 1 to 7, where 1= Extremely severe (Disastrous), 2= Very severe (critical), 3= Severe, 4= Significant, 5= Somewhat significant, 6= Irrelevant, 7= I don't know.*

4b Effect (Negative impact)	**Selected factors (√)**	**RANK (order of severity)**
4.1b Changed timing of rains		
4.2b Abrupt change in season/ changes in growing season		
4.3b Reduced cropping (growing) season		
4.4b Increased frequency of drought & crop failure		
4.5b Increased frequency of floods & farms destructions		
4.6b Postharvest losses		
4.7b Pests invasion		
4.8b Prevalence of disease		
4.9b Poverty & food shortages		
4.10b Lack of potable water		
4.11b Erosions		
4.12b Extinction of some crops & crop varieties		
4.13b Extinction of fishes & aquatic life		
4.14b Death of livestock		
4.15b Rising cost of farming/ fishing		
4.16b Destruction of farm roads & homes		
4.17b Rural-urban migration		
4.18b Siltation of water bodies		
4.19b Disappearance of vegetation cover		

5b. To what extent can you describe these effects/impacts? 1: Extreme effects; 2: Multiple effects; 3: Manageable effects; 4: Limited effects; 5: Little effects; 6: I don't know

6b. How do you consider the vulnerability and risky level of your farm activities/livelihood to the incidence of the following climatic related factors?

RANK (VULNERABILITY): *On a scale of 1 to 6, where 1= Extremely vulnerable, 2= Very vulnerable, 3= Vulnerable, 4= Somewhat vulnerable, 5= Not vulnerable, 6= I don't know.*

RANK (RISK): *on a scale of 1 to 6, where 1 = Very certain (Very serious), 2 = Certain (Serious), 3 = near certain, 4 = Very likely, 5 = Frequent, 6 = Seldom*

S/N	**Incidence**	**Vulnerability (Code)**	**Risk (Code)**
6.1b	Increased temperature		
6.2b	Decreased rainfall & poor distribution during cropping season		
6.3b	Floods		
6.4b	Droughts (during cropping season)		
6.5b	Changed timing of rains		
6.6b	Abrupt change in season/changes in onset of planting season		

Other issues on 6b (specify):..
....

Key for 6b: *Vulnerability = livelihood exposure or state of being easily affected by these climate related incidences (lack of adaptive capacity); Risk level = Effect/impact severity x Likelihood of occurrence*

7b. What have you observed to be the main opportunities (positive impacts) of these long-term changes in the mean of climate variables over the last 30 years? 1: Flood water harvest for irrigation, 2: Improved groundwater yields, 3: Floods increase fish harvest, 4: Other (specify):………………………

8b. How will you capitalize on these opportunities or positive effects in future for better farm productivity? 1: adopt irrigation practice ☐, 2: irrigate more ☐, 3: shift to fish farming ☐, 4: Other (specify):………………………

9b. Have you seen changes in:

9.1b. the vegetation cover over the last 30 years? 1: Yes ☐, 2: No ☐

9.2b. the vegetation type over the last 30 years? 1: Yes ☐, 2: No ☐

10b. If **yes**, what have you noticed about the changes in:

10.1b. the vegetation cover over the last 30 years? 1: decreased ☐, 2: increased ☐, 3: Other (specify):………………………

10.2b. the vegetation type over the last 30 years? 1: decreased ☐, 2: increased ☐, 3: Other (specify):……………………….....................

SECTION C
FARMERS' ADAPTATION OPTIONS

1c. Have you made any changes/adjustments in your farming ways in response to climate change and variability (shifts in climate variables) over the last 10 years? 1:Yes ☐, 2: No ☐

2c. What adjustments in your farming ways have you made to these long-term shifts in temperature? 1: Use different varieties and crop types, 2: Mulching, 3: Sold livestock, 4: Farm near rivers and in low lands, 5: Mixed cropping, 6: Cover cropping, 7: Put trees for shading, 8: Crop rotation, 9: Other (specify):………………………

3c. What adjustments in your farming practices have you made to these long-term shifts in rainfall? 1: Fertilizer application, 2: Pesticide/herbicide application, 3: Farm near rivers and in low lands, 4: Near river and on hills, 5: Farm on hills, 6: Use different varieties and crop types, 7: Cover cropping, 8: Mixed cropping, 9: Crop rotation, 10: Other (specify):………………………

4c. Check the answers for **2c** and **3c** and then ask for the ones not yet listed there: What additional measures would you consider in the future?

4.1c Future additional measures (List in space below)	
4.1.1c	
4.1.2c	
4.1.3c	
4.1.4c	
4.1.5c	
4.2c Why did you not	**4.3c Reason (key)**
4.2.1c Use different varieties and crop types	
4.2.2c Move to different sites	
4.2.3c Implement soil conservation techniques	
4.2.4c Buy insurance	
4.2.5c Put trees for shading	
4.2.6c Build a water-harvesting scheme	
4.2.7c Irrigate more	
4.2.8c Change from crop to livestock	
4.2.9c Reduce number of livestock	
4.2.10c Migrate to urban area	
4.2.11c Find off-farm job	
4.2.12c Lease your land	

Key for 4.3c: 1: lack of money/credit facility, 2: lack of information, 3: shortage of labour, 4: Other [write into the lines provided above]

5c. If you do apply fertilizer and pesticide/herbicide, how often do you practice this? 1: once a year ☐, 2: twice a year ☐, 3: once every two years ☐, 4: once every three years ☐, 5: Other ☐ (specify)............

SECTION D
SUPPORT FOR FARMERS' ADAPTATION MEASURES

1d. Do you receive any external support for your adaptation measures? 1:Yes ☐, 2:No ☐

2d. If **yes**, in what form does the support come? 1: Financial support ☐, 2: Material support ☐, 3: Extension services ☐, 4: Subsidized farm inputs ☐, 5: Other (specify)…..

3d. Is this support free? 1:Yes ☐, 2:No ☐, 3: Other (specify)..

4d. If **no**, what are the conditions attached? 1: Loan to be paid back ☐, 2: to buy farm machinery on credit; 3: to buy improved farm inputs (seeds/animals, fertilizers, pesticides) on subsidized prices ☐, 4: provision of buffer stock ☐, 5: Other ☐ (specify)…………………..

5d. How long has this support been in existence? 1:1-5 yrs ☐, 2: 6-10yrs ☐, 3: 11-15yrs ☐, 4:16-20yrs ☐, 5: Other ☐ (specify)..............................

6d. How often do you receive this support? 1: once a year ☐, 2: twice a year ☐, 3: once every two years ☐, 4: once every three years ☐, 5: Other ☐ (specify).............................

7d. Which Organisation offers this support? 1: Government Agency ☐, 2: Agriculture research station ☐, 3: NGO ☐, 4: Other (specify)..................................

8d. Is this type of support beneficial? 1:Yes ☐, 2:No ☐

9d. If **yes**, how has it benefited you? 1: I got capital to expand my farm ☐, 2: reduced postharvest lost; 3: improved yield ☐, 4: reduced hunger ☐, 5: took another wife, 6: sent child to school, 7: purchase additional farm machinery, 8: Other ☐ (specify)………………….

10d. Do extension officers provide regular information on expected rainfall and temperature? 1:Yes ☐, 2:No ☐

11d. Apart from official extension workers, where else do you receive the necessary information and technical assistance? 1: Television; 2: Radio; 3: Neighbouring farmer, 4: Shopkeepers in village; 5: Community leaders, 6: Relatives, 7: None, 8: Others (please specify)..

12d. What five most needed services, investments, or developments would you want the government, the community, NGOs, or the private sector to do for you in your efforts to adapt to changes in mean temperature and rainfall? Please rank them in the order of importance [1st is most important, 5th is least important]

12.1d Issue (key)	**12.2d Who (key)**	**12.3d Ranking**
12.1.1d	12.2.1d	12.3.1d
12.1.2d	12.2.2d	12.3.2d
12.1.3d	12.2.3d	12.3.3d
12.1.4d	12.2.4d	12.3.4d
12.1.5d	12.2.5d	12.3.5d

Key for 12.1 - Issues: 1: irrigation development; 2: climatic information services; 3: provision of credit facilities; 4: review of land tenure system; 5: health services; 6: agriculture mechanization; 7: other (specify…………………………….)

Key for 12.2 - Who: 1: central government, 2: local government, 3: local community, 4: private sector; 5: other (specify...)

SECTION E
BARRIERS TO ADAPTATION

1e. What were/are the main constraints/difficulties in changing your farming ways? Check the answers in the table below and then fill in the ones not yet listed there:

1e. Difficulty	**Rank(order of severity)**	**Suggestion/solution**
1.1e Educational level		
1.2e No access to information		
1.3e Lack of Extension services		
1.4e Incompatibility with societal norms and values		
1.5e Inadequate capital		
1.6e No access to credit		
1.7e Sustainability		
1.8e Length of time required to see results		
1.9e Old age		
1.10e Land Tenure		
1.11e Topography of the land		
1.12e Physical characteristics of the land		

1.13e Infertile soil		
1.14e Labour intensive/non availability of labour		
1.15e No access to water for irrigation		
1.16e		
1.17e		
1.18e		
1.19e		

APPENDIX C: INTERVIEW GUIDE FOR FOCUS GROUP DISCUSSION

GRADUATE RESEARCH PROGRAM, CLIMATE CHANGE AND WATER RESOURCES
UNIVERSITY OF ABOMEY-CALAVI
ABOMEY-CALAVI, BENIN

<u>INTERVIEW GUIDE FOR FOCUS GROUP DISCUSSION WITH FARMERS</u>

PERCEPTION OF FARMERS ON CLIMATE CHANGE, ADAPTATION OPTIONS AND BARRIERS TO ADAPTATION

This research interview is purely for academic purposes with the objective of **'Assessing and comparing farmers' perceptions on climate change and variability with statistical analyses of observed climatic data, their adaptation practices and barriers to adaptation, as part of a broader research that assesses the impacts of climate and land use changes on water availability in the Vea Catchment for irrigation'.** You are assured of confidentiality of any view expressed in relation to this research. I therefore entreat you to provide information as accurate as possible for true results. Thank you for your kind co-operation.

Record number:			
Name of interviewer:			
Group type :			
Date of interview:	D	M	Y
District:			
Community:			

1. Have you noticed any long-term changes in the mean temperature over the last 30 years? *If too difficult: Has the number of hot days stayed the same, increased, declined, or fluctuated over the last 30 years?*
2. Have you noticed any long-term changes in the mean rainfall over the last 30 years? *If too difficult: Has the number of rainfall days stayed the same, increased, declined, or fluctuated over the last 30 years?*
3. Generally what is your account of monthly and seasonal temperature and rainfall patterns in this area over the last 30 years? Stayed the same, increasing, declining, or fluctuating over the years?
4. What has brought about these long-term changes in the mean temperature and rainfall in your view?
5. What are some farming/fishing practices you engage in that you think can lead to these climatic changes and affect the environment and the water resources?
6. Is there much awareness on these climatic changes?
7. How do its impacts affect your livelihood?
8. What have you seen to be the main effects of these long-term shifts in temperature and rainfall over the last 30 years?
9. What have been the opportunities or positive effects of these long-term shifts in temperature and rainfall over the last 30 years?
10. What do you foresee to be the main risks of similar long-term shifts in temperature and rainfall in future (in the next 30 years)?
11. What do you foresee to be the opportunities or positive effects of similar long-term shifts in temperature and rainfall in future (in the next 30 years)?
12. How will you capitalize on these opportunities or positive effects in future for better farm productivity?
13. Have you seen changes in the vegetation cover and vegetation type over the last 30 years?
14. What adjustments in your farming practices have you made to these long-term shifts in temperature?
15. What adjustments in your farming practices have you made to these long-term shifts in rainfall?
16. How are these adjustments improving your occupational conditions?
17. What additional adaptation measures would you consider in the future?
18. What were/are the main constraints/difficulties in changing your farming ways?
19. Do you get support for your adaptation measures?
20. Where does this support come from?
21. In what form is the support?
22. How has it benefited you?
23. What other support would you need in enhancing your occupation?

APPENDIX D: INTERVIEW GUIDE FOR INTERVIEWING INSTITUTIONS

GRADUATE RESEARCH PROGRAM, CLIMATE CHANGE AND WATER RESOURCES
UNIVERSITY OF ABOMEY-CALAVI
ABOMEY-CALAVI, BENIN

INTERVIEW GUIDE FOR INTERVIEWING INSTITUTIONS

(ICOUR, GWCL, AGRIC EXTENSION SERVICE, ETC)

PERCEPTION OF FARMERS ON CLIMATE CHANGE, ADAPTATION OPTIONS AND BARRIERS TO ADAPTATION

This research interview is purely for academic purposes with the objective of **'Assessing and comparing farmers' perceptions on climate change and variability with statistical analyses of observed climatic data, their adaptation practices and barriers to adaptation, as part of a broader research that assesses the impacts of climate and land use changes on water availability in the Vea Catchment for irrigation'.** You are assured of confidentiality of any view expressed in relation to this research. I therefore entreat you to provide information as accurate as possible for true results. Thank you for your kind co-operation.

Name of interviewer:	Interviewee's Position:		
Name of institution/organization:			
Date of interview:	D	M	Y
District:			
Community:			

1. Have you noticed any long-term changes in the mean temperature over the last 30 years?
2. Have you noticed any long-term changes in the mean rainfall over the last 30 years?
3. What has brought about these long-term changes in the mean temperature and rainfall in your view?
4. What are some activities/practices by the communities that you think can lead to these climatic changes and affect the environment and the water resources?
5. Is there much awareness on these climatic changes?
6. How do its impacts affect the water resources in the catchment and livelihoods/lives of the populace from your Organizational point of view?
7. How do its impacts affect the operations of your Organization now and in the future?
8. What are the main risks of these long-term shifts in temperature and rainfall presently and in the future (in the next 30 years)?
9. What are the opportunities or positive effects of these long-term shifts in temperature and rainfall presently and in the future (in the next 30 years)?
10. How will you capitalize on these opportunities or positive effects in future for better productivity?
11. What strategies/measures have you made to adapt to these long-term shifts and variability in climatic variables?
12. How are these adaptation measures improving the operations and productivity of your Organization?
13. What additional adaptation measures would you consider in the future?
14. What are the main constraints/difficulties in executing these adaptation measures?
15. Do you get support for your adaptation measures?
16. Where does this support come from?
17. In what form is the support?
18. How has it benefited you?
19. What other support would you need in enhancing the operations and productivity of your Organization?

Candidate biography

Andrew Manoba Limantol received his secondary education at Notre Dame Minor Seminary (Senior High School) in Navrongo, Upper East Region of Ghana, where he obtained Senior Secondary School Examination Certificate (SSSCE) in 1995. He also received training as a professional teacher at St. John Bosco Teacher Training College in Navrongo, Ghana, where he obtained Teacher's Certificate 'A' in 2000.

He holds BSc. Physics (Computer Option) and MSc. Soil and Water Engineering from Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana.

He taught integrated science and mathematics at St. Charles Lwanga Junior High School (JHS) and St. Joseph Technical School (Senior High School), both in Saboba in the Northern Region of Ghana. He served as a head of department and a senior house master at St. Joseph Technical School.

Currently, he is the District Resource Person (DRP) at the Binduri District of the Upper East Region of Ghana for Water, Sanitation and Hygiene (WASH) partnership project by the Government of Ghana (GoG) and United Nations Children's Fund (UNICEF).

***Abstract* :**

Vea catchment hosts one of the two major irrigation schemes in the Upper East Region of Ghana, inhabited by many rural farming communities and offers opportunity for all-year-round agricultural production for these communities. The catchment will continue to experience irrigation expansion and upsurge in domestic water demands due to population growth and urbanisation. Any adverse effects of climate change (CC) will be an add-on pressure on the catchment water resources and will be detrimental to the entire population in the area. This study assessed the influence of CC on future water resources availability in the catchment for irrigation and also examined land use/cover changes in the area. Water mass balance method was used to estimate historical streamflow for the catchment with the bathymetry data and the storage-area-height relationship (function) at the irrigation reservoir site. The IHACRES rainfall-runoff model was successfully calibrated and validated for future flow prediction using outputs from all the Regional Climate Models (RCMs) of Coordinated Regional Downscaling Experiment (CORDEX) that provided data for the Africa domain based on the highest emission scenario (RCP8.5). Based on socioeconomic scenarios drawn from survey data gathered through household and institutional interviews, focus group discussions and review of national policies on CC, the water allocation and planning model, WEAP, was successfully configured and used to assess future water availability situation in the catchment in two future periods, 2021-2050 and 2071-2100. Climatic data for the period 1972-2012 from four stations were additionally analysed. Landsat satellite imagery was also analysed to assess land use/cover changes in the catchment. The results indicate a rising trend in temperature and potential evapotranspiration over the past 41 years and projected rising trend in the next decades. No long-term trend and no variability changes in rainfall data were evident. With the lowest streamflow derived from RCMs simulated conditions and the current irrigation rate of 1.1%, the catchment will experience average annual water supply deficit (AWSD) of about 1.3×10^6 m^3 and 1.8×10^6 m^3 in the periods 2021-2050 and 2071-2100 respectively. If the potential irrigable area (1400 ha) of the catchment is developed under the current practices, both lowest and highest streamflow derived from RCMs simulated conditions indicate that in the period 2071-2100 the catchment will experience AWSD of about 3.3×10^6 m^3 and 0.7×10^6 m^3 respectively. Closed and open savanna woodland cover in the catchment decreased by about 55.7% and 44.2% respectively between 1990-2010 while grass/herbaceous cover and bare surface/built-up area increased by about 168.5% and 203.0% over the same period. The study indicates a projected considerable shortfall in water availability for irrigation in the coming decades due to CC coupled with population growth and associated water demand. Government and stakeholder organisations need to assist farmers by providing alternative irrigation facilities with improved irrigation efficiency in order to sustain livelihoods of farmers on the long run. This should go along with the introduction of new improved seeds and drought resistant crops to farmers. Land cover restoration programmes that includes incentives for protection of forest reserves be introduced to curtail the high pace depletion of the vegetation cover in the area.

***Key words* :** Climate change, impact, land use/cover changes, water resources, irrigation, Vea catchment

PhD

Andrew Manoba LIMANTOL

IMPACTS OF CLIMATE AND LAND USE CHANGES ON VEA CATCHMENT AND IRRIGATION SCHEME IN UPPER EAST REGION OF GHANA

GRP/CCWR/INE/WASCAL – UAC January, 2017