PAN-AFRICAN UNIVERSITY

INSTITUTE FOR WATER AND ENERGY SCIENCES (including CLIMATE CHANGE)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in
WATER ENGINEERING

Presented by

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ASSESSING THE RESPONSE OF HYDROLOGICAL PROCESSES TO CLIMATE CHANGE IN THE PRA RIVER BASIN, GHANA

Defended on 15/11/2021 Before the Following Committee

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DECLARATION

I Collins Acheampong, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material, and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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ABSTRACT

The Pra River Basin (PRB), Ghana, provides significant agricultural productivity and ecosystem services to Ghana. The challenge in water management within the PRB is constantly becoming a topical issue owing to the influence of increased climate change. Also, recent scenarios in climate variability have resulted in changing temperature and rainfall pattern thereby threatening water resource in three dams that source its water from the river basin. This has also negatively impacted river flow attributable to high rate of pollution, increased runoff, and high evaporation. It is therefore important to have an understanding of the consequence of variation in climate change on current and future hydrologic regimes and hydrologic extreme events through modelling approach.

Hence, this research investigated the response of hydrological processes and hydrologic extremes in relation to climate change in the River Pra Basin by employing five (5) new Coupled Model Intercomparison Project (CMIP6) GCM for two time slices, near future (2030s) and mid future (2050s) under two emission SSP2-4.5 and SSP5-8.5 scenarios. Preliminary analysis revealed bias-corrected CNRM-CM6-1 (with linear scaling technique for precipitation and distribution mapping approach for temperature) as the best suitable climate model for climate change projection and further assessment of climate change impacts on streamflow and hydrologic extremes. SWAT model calibrated and validated data results compared with observed flow data were deemed satisfactory for future flow simulations over the Pra Basin.

The change in projected monthly CNRM-CM6-1 precipitation data show variable temporal trends ranging between 2.84-5.74 mm under both SSP2-4.5 and SSP5-8.5 and with a more seasonal variation in change in precipitation projected under SSP5-8.5. Also, a continuous increasing trend is observed for mean projected temperature under SSP2-4.5 and SSP5-8.5 scenarios. The mean flow by the end of the middle of 21st century was projected to decrease at about 20.8% under SSP2-4.5 and 28.2% under SSP5-8.5 relative to the baseline period. Also, all seasons showed a decrease in annual seasonal discharge for the period of 2045 to 2074. Finally, the analysis of hydrologic flow regimes for extreme streamflow assessment revealed that the variability and magnitude of floods may increase in the near future due to increase in Q1(13.5%) and Q5 (5.4%) under SSP5. Hence flood mitigation measures as well as proper water resources management strategies must be ensured by stakeholders through the implementation of the PRB IWRM plan to avoid any catastrophes downstream of the basin.

RÉSUMÉ

Le bassin de la rivière Pra (PRB), au Ghana, fournit une productivité agricole et des services écosystémiques importants au Ghana. Le défi de la gestion de l'eau au sein du bassin devient constamment une question d'actualité en raison de la prolifération des activités anthropiques. Par ailleurs, les récents scénarios de changement climatique exacerbés par les activités anthropiques ont entraîné une modification des températures et des précipitations, menaçant ainsi les ressources en eau de trois barrages qui puisent leur eau dans le bassin fluvial. Cette situation a également eu un impact négatif sur le débit des rivières en raison du taux élevé de pollution, de l'augmentation du ruissellement et de la forte évaporation. Il est donc important de comprendre les conséquences des variations du changement climatique sur les régimes hydrologiques actuels et futurs et sur les événements hydrologiques extrêmes par le biais d'une approche de modélisation.

La présente recherche a étudié la réponse des régimes et des extrêmes hydrologiques en relation avec le changement climatique dans le bassin de la rivière Pra en utilisant cinq (5) nouveaux modèles couplés de comparaison de modèles (CMIP6) GCM pour deux tranches de temps, un futur proche (2030) et un futur moyen (2050), sous deux scénarios d'émission SSP2-4.5 et SSP5-8.5. L'analyse préliminaire a révélé que le modèle CNRM-CM6-1 était le modèle climatique le mieux adapté à la projection du changement climatique et à une évaluation plus approfondie des impacts du changement climatique sur le débit et les extrêmes hydrologiques. Les résultats des données calibrées et validées du modèle SWAT, comparés aux données de débit observées, ont été jugés satisfaisants pour les futures simulations de débit sur le bassin.

Les changements dans les précipitations mensuelles CNRM-CM6-1 projetées montrent des tendances temporelles variables allant de 2,84 à 5,74 mm à la fois avec les scenarios SSP2-4,5 et SSP5-8,5, avec une variation saisonnière plus importante dans les changements de précipitations projetés dans le cadre du SSP5-8,5. De même, une tendance continue à la hausse a été observée pour la température moyenne dans les scénarios SSP2-4.5 et SSP5-8.5 pour la température projetée. Le débit moyen à la fin du milieu du XXIe siècle ont diminué d'environ 20,8 % dans le scénario SSP2-4.5 et de 28,2 % dans le scénario SSP5-8.5 par rapport à la période de référence. En outre, toutes les saisons ont montré une diminution du débit annuel saisonnier pour la période de 2045 à 2074. Enfin, l'analyse des régimes d'écoulement hydrologique basée sur la courbe de durée de fréquence d'écoulement pour l'évaluation des débits extrêmes a révélé que la variabilité et l'ampleur des crues pourraient augmenter dans un proche avenir en raison de l'augmentation de Q1 (13,5%) et Q5 (5,4%) sous SSP5. Par conséquent, des mesures d'atténuation des inondations ainsi que des stratégies appropriées de gestion des ressources en eau doivent être assurées pour éviter toute catastrophe en aval du bassin.

ACKNOWLEDGEMENT

I enjoyed the support, help and encouragement of many people and institutions within the 24 months programme and in conducting this research.

First and foremost, I thank my supervisor, Prof. Amos T. Kabo-bah, for his advice and thoughtful suggestions on the work. Your relentless support in conceptualizing the idea for this research is much appreciated.

I am highly indebted to African Union Commission for the scholarship award offered me to pursue this programme. I say thank you to AU and PAUWES for giving me these awards in support of my 24 months study for the Water Resources Engineering programme at the Institute for Water and Energy Sciences, Including Climate Change, University of Tlemcen.

I also thank Dr Enoch Bessah, for his encouragement and guidance were instrumental and helpful for data collection and analysis. I would also like to extend my appreciation to Mr Emmanuel Arthur and Mr Ming for their help during model calibration and validation phase.

My heart goes out to my dear family members for their love, care, support, prayers and encouragement all through this point. You form a great and unified group of which I am delighted to be part.

Finally, I say thanks to Lilian Aboagyewaa, and to my friends Prince Kwabena Boateng and Abdul Majid Is-Hak who offered me support and advice throughout the study and everyone who in diverse ways contributed to the success of this study.

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LIST OF ABBREVIATIONS

CC	Climate Change
CDD	consecutive dry days
CHIRPS	Climate Hazards Group Infrared Precipitation combined with Station data
CILLS	Comité Inter-états de Lutte contre la Sécheresse dans le Sahel
CMIP5/CMIP6	5th and 6th Coupled Model Inter-Comparison Projects
CWD	consecutive wet days
DEM	Digital Elevation Model
ESA CCI	European Space Agency Climate Change Initiative
ETCCDI	Climate Change Detection and Indices
FAO	Food and Agriculture Organization
FDC	Frequency Duration Curve
GCM	General Circulation Models
GEE	Google Earth Engine
HRU	Hydrologic Response Unit
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
LULC	Land-use/Landcover Change
PRB	Pra river basin
R20	Number of Heavy precipitation days >=20 mm
RCM	Regional Climate Models
RX1day	maximum 1-day precipitation
RX5day	maximum 5-day precipitation
SCN	Soil Conservation Service Number
SPI	Standardized Precipitation Index
SUFI-2	sequential uncertainty fitting Algorithm 2
SWAT	Soil and Water Assessment Tool
WRC	Water Resources Commission
WCRP	World Climate Research Programme

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CHAPTER I

1. INTRODUCTION

1.1. Background

Water remains and is continually considered to be among the useful resources found on earth vital for the sustenance of humans and ecosystems. Freshwater resource availability both in high quality and quantity is crucial for human survival. The Pra River Basin (PRB) provides an important ecological service, including municipal water supply, agriculture (irrigation), and water to small- and large-scale mining institutions. PRB also serves as an important tourism site in Ghana. Within the PRB, issues concerning pollution, quality deterioration and the depletion of these useful resources are perceived as one of the most interesting issues currently discussed. Hence, the setting up of River Pra Basin Management Board to ensure integrated and sustainable water-use and management within the catchments of Pra river. The Pra basin has significant agricultural activities with cash crops such as cocoa and oil palm plantation scattered within the basin. Moreover, agricultural activities dominate withdrawals of water from the river although the PRB provides potable water to about 4.2 million inhabitants. Also, more mining companies are located within this basin, especially along the Offin and Birim river sub-basins (Water Resources Commission, 2012). The Pra basin houses the most densely populated rural and urban settlements in Ghana (WRC, 2012). The population is expected to increase with more people expected to go into farming (due to the rich nature of the soil) and the recent surge in small-scale mining within the river basin. It is only in the event that an increasing population will eventually result in high water demand (Fujihara, Tanaka, Watanabe, Nagano, & Kojiri, 2008). Hence, putting pressure on existing water resources in a known locality or catchment, which may lead to water scarcity. Moreover, water scarcity may also occur under high irrigation water requirements if the existing agricultural practices with no soil conservation measures and the rate of irrigation schemes are applied to crops. The Water Resources Commission (2012), attributes an increased pollutant load, change in runoff and flow routing schemes to illegal timber logging, poor farming activities, industrial water withdrawal, and the recent increase in activities of small-scale illegal mining both on and along the river channel. The deterioration of lands in Ghana is also increasing at a faster pace due to recent rise in small-scale illegal mining activities together with poor agricultural practices and the high influx of population in urban centres (Water Resources Commssion, 2012). This has negatively impacted the existing water resources including rivers and streams due to high rate of pollution, increased runoff, and high evaporation. Hence, variable climate and change in land-use/landcover (LULC) patterns are often considered as the main responsive factors altering hydrological cycle at a certain catchment.

Climate variability significantly changes the hydrological events including precipitation, runoff, soil moisture content, and evapo-transpiration (Kabo-bah, Anornu, Ofosu, & Kamila, 2014; Shooshtari et al., 2017). These hydrological events become even more complex to forecast and model together while predicting the occurrence of floods, droughts, and or analysing baseflow events when the influence of LULC change also becomes more predominant together with climate variability (Yan, Cai, Li, Wang, & Liu, 2019). Also, previous research employing models to predict and understand the long-term effect of climate change on water availability or land use change on runoff processes do not always represent the general spatial and temporal trend and variation in the water resources availability. This is because, it has been observed in recent studies that, water availability and runoff process are both affected by anthropogenic activities and a variation in climate. Hence, it is sometimes more significant to predict both the synergistic impact and the individual impacts of climate change and human activities (especially LULC) on the hydrologic regimes of a watershed.

Several scientific debates and policies are addressing human activities and impact on the already stressed freshwater resources and which, also, is intensified due to climate change (CC). A change in streamflow pattern, volume, peak flow, and routing time of flow is usually attributable to a changing climate while change in LULC patterns results in altering runoffs, frequency of flood, baseflow, and river discharge (M. L. Tan, Ibrahim, Yusop, Duan, & Ling, 2015). LULC changes exacerbated by human activities influence water resources available to humans. They may even result in more severe degradation of lands due to water-driven soil erosion together with the depletion of nutrients available to plant in a given basin (CILSS, 2016).

Climate variability is known to be the main contributing factor affecting water availability and crop productivity around the world (Kang, Khan, & Ma, 2009). According to IPCC, (2007), the occurrence and frequency of extreme climate events are predicted to increase and may potentially have negative consequences on agricultural production and ecosystem health.

Usually, countries with weak ecosystem services, faced with water scarcity, poor soil structures or condition, and alteration in the hydrological cycle due to climate variability while LULC changes usually result in an increasing flood and drought-prone risk areas together with an increasing rate of soil erosion, sediment, and nutrient deposition (Op de Hipt et al., 2019). Also, to a certain extent, a temperature increase results in a high rate of evaporation which eventually results in droughts through drying of the land's surface at high spatio-temporal variability (Trenberth, 2005; Joorabian Shooshtari et al., 2017). This may in turn adversely affect crop health, crop yield, and agricultural productivity through damage to crops and lands (soil surface) and also altering streamflow. Globally, especially in Africa, climate change impacts on food security, water resources, hydropower, and the health of humans is well known (Magadza, 2000). It has also been predicted that Africa will be more susceptible to the significant effects of climate change on water resources, food security, and human health if sustainable and adaptation strategies are not implemented.

There is, therefore, the need to understand and predict climate change impacts on hydrology so that proper adaptation strategies can be developed. Hence, the hydrological modelling approach is growing in popularity to deal with climate change impacts. Usually, physically-based semi-distributed hydrologic models are employed in the predictions since their parameters give physical meaning with better estimation resulting in good simulation or predicted results (Pandey, Himanshu, Mishra, & Singh, 2016; Z. Tan, Leung, Li, & Tesfa, 2018).

This research, therefore, seeks to quantitatively assess and predict climate change effects on hydrologic processes and hydrologic extremes in the River Pra Basin, employing a scenario-based simulation approach using the Soil and Water Assessment Tool (SWAT). The results of this research, together with recommendations, will play a crucial role in developing proper adaptation strategies and preventative measures for meeting the challenge of probable future extreme events. It will serve as reference for the River Basin Management Authorities of the PRB to ensure decision-making processes that ensure sustainable management of water in the basin are put in place.

1.2. Research Problem

According to Kankam-Yeboah, et al. (2013), Ghana may experience water stress and may need to import water in 2025 due to a changing climate on hydrologic aspects and water resources. The Pra River Basin (PRB) provides significant agricultural productivity and ecosystem services to Ghana. Arthur et. al (2020), in their research on dam site suitability mapping, identified ten (10) areas within the PRB as suitable sites for mini-grid power projects. Also, there are currently seven dams with their intake from the river that supplies water to surrounding communities. Moreover, when the Kakum river supplying water to the Brimsu water treatment plant water level drops or dries up, water is pumped from the PRB to supplement the water for treatment and supply to most parts of Cape Coast Municipality. The Sekyere-Hemang Water treatment project which sources its raw water from the Pra River was constructed in 2013 to augment the shortage in water supply in the Cape Coast Municipality and most towns and villages located in the coastal areas of the Central region.

In dam siting and construction of storage reservoirs for water supply for municipal water use and irrigation, industrial and hydropower projects, water in large quantity is usually part of important factors considered. Usually, water planners assumed that, over the design life of the project covering for a long period of time, the trends in rainfall and temperature might not change much. However, recent scenarios in climate change exacerbated by anthropogenic climate forcing have resulted in a changing temperature and rainfall pattern threatening the available water resources. Hence, it is important to have some knowledge on the available water resources through modelling approach as well as understanding the consequence of climate variability coupled on water resources.

Several pieces of research have been conducted to evaluate the effect of climate variability and change in land cover or land-use patterns on hydrologic processes in many West-African river basins (Oti et al., 2020; Adjei, Adjei, Obuobie, & Odai, 2019; Anouar, Yebdri, & Errih, 2017; Awotwi, Kwame, & Quaye-ballard, 2017; Nyatuame, Amekudzi, & Agodzo, 2020; Op de Hipt et al., 2019). The upper catchment of the PRB has received much attention and with much research on climate and land-cover change impacts (Amu-Mensah, Amu-Mensah, Akrong, Addico, & Darko, 2019; Antwi-Agyei et al., 2019; E. Boakye, Odai, Adjei, & Annor, 2008; Domfeh, Anyemedu, Anornu, Adjei, & Odai, 2016; Osei et al., 2017; Osei, Amekudzi, et al., 2019; Osei, Ko, et al., 2019) due to the location of two important dams (Barekese dam and Owabi dam) which supplies potable water to the Kumasi Metropolitan areas. Water planners and managers have also contributed significant research to protect ecosystem services delivered by the Pra river basin.

The lower reaches of the basin, especially at Twifo-Praso community suffer from annual flooding due to high precipitation in the rainy months. In the Pra river basin, series of research have been conducted to either quantify the influence of climate variability (Bessah, Raji, Taiwo, Agodzo, & Ololade, 2020a; Kankam-Yeboah et al., 2013). However, researches conducted over the River Pra Basin to assess and quantify the response of hydrologic regimes due to the impact of climate change is limited (Awotwi, Kwame, Quaye-ballard, et al., 2017; Bessah, Raji, Taiwo, Agodzo, Ololade, et al., 2020). Also, research focusing on future climate change impact on water resources and hydrological extremes within the PRB ae limited (Awotwi et al., 2021; Osei et al., 2021). However, these studies focused on high flows relying on Coupled Model Intercomparison Project (CMIP5) climate data projections and regional climate models (RCMs). The new Coupled Model Intercomparison Project (CMIP6), 6th Phase ensembles (Eyring et al., 2016; Klutse et al., 2021) which comes with climate models of high spatial variability with some at even a more higher spatial scale than regionally downscaled CMIP5 models (example with some obtainable from Regional Climate Model (RCM) of Coordinated Regional Climate Downscaling Experiment (CORDEX) platform). Also, it is still unknown how the new CMIP6 models simulate hydrologic response to a changing climate over major West-Africa basins. Moreover, to the researchers knowledge, no research has been conducted on employing the new CMIP6 datasets to predict future climate change on hydrologic flow as well as hydrologic extremes over West-Africa basins including the Pra basin within the 21st century.

Therefore, this study aims to assess and quantify the effect of climate change on hydrologic regimes and their effect on the temporal variability of hydrological extremes within PRB. Also, the effect of future climate change on the frequency, extent and duration of hydro-meteorological extreme events (high or low flows) will be investigated within PRB by employing the CMIP6 model.

1.3. Research Objectives

The main objective of this research is to assess the response of hydrological regimes/processes and hydrologic extremes related to climate change in the River Pra Basin with more focus at the Lower Pra River basin, Ghana.

1.3.1. Specific objectives

The specific objectives of this research include;

1. To calibrate and validate the SWAT model by simulating long-term hydrologic data in the River Pra Basin
2. To quantitively assess the effect of climate change on hydrological process in the River Pra Basin
3. To predict and quantify the potential impact of variable temperature and precipitation on future streamflow.
4. To simulate the variations and trends in hydrological extreme events under future climate and suggest strategic recommendations for sustainable water management in the basin

1.4. Research questions

1. How can we adapt SWAT model to be used to accurately predict climate change on hydrologic processes and extremes in the Pra River Basin?
2. What is the effect of climate change on streamflow in the River Pra Basin?
3. How will a change in temperature and rainfall affect water availability in the basin?
4. How are future temperature and rainfall variations are related to extreme hydrological events (flood and drought)?

1.5. TENTATIVE THESIS CHAPTER OUTLINE

This research is structured into six chapters. The first Chapter is the introduction which include the research background. It also introduces the statement of problem, research objectives and the general thesis outline. The next chapter is the literature review (Chapter 2) which provides important information and background studies of related research done within the research topic and the area of research study. This throw highlights more on areas that have been widely covered and gaps that have been identified and needs to be filled. Chapter three introduces the study area description and chapter four introduces the methodology covers the data collection and datasets that were used in model building and processing. Also, the description of models used together with the method used in attaining the study objectives are described. Chapter five covers, the results and discussion of field measured datasets and results obtained through model simulations. Finally, chapter six presented the conclusion of results and recommendations which also highlight possible future research areas.

CHAPTER II

2. LITERATURE REVIEW

2.1. Climate variability and Land Use and Land Cover Change impact on Hydrological Processes

The competing needs and accessibility to water resources has been altered due to upscale of socio-hydro-economic global and regional developmental projects and further exacerbated by climate and LULC change impacts. Moreover, increasing population resulting in high food demand has also led to an intensive agricultural practice resulting in aggravated LULC change practices (Dibaba, Demissie, & Miegel, 2020b, 2020a). The intensification in LULC change practices may worsen not only within the local agricultural area but may result in a regional or global conundrum of destroying the biophysical resources or functioning properties of earth system (Luck, Landis, & Gassert, 2015). Climate change may further worsen the current impact scenarios of land-use change within the environment and or locality especially on access to water and availability.

In recent years, the focus of many researches has been geared towards the responsiveness of hydrological regimes to land-use and climate change. Hence, a lot of research have been conducted on the major contributing factors including land-use and anthropogenic climate change altering the hydrologic cycle. Recent trends in a changing climate and land-use patterns have caused an increased runoff resulting in flooding, erosion, nutrient and sediment deposition reduced reservoir in downstream areas and sometimes drought events due to low precipitation recorded. This usually results in low yield in crops and limited water resources accessible to the watershed inhabitants for consumption. Furthermore, more forested and grassed areas are being turned into pavement surfaces and cultivated lands and the high demand of land for construction and agricultural farming practices. Hence, reduced infiltration with decreasing baseflow that might have eventually contributed to recharge of surface and aquifer recharge and waterflow to springs. The surge in high population in urban zones and in most productive agricultural basin are the main responsive factors. Wu, Zhan, & Güneralp, (2014) also stated that, urbanization exerts pressure on the existing ecosystem due to increase land use/landcover change thereby affecting ecosystem health.

The River Pra Basin provides important ecological service. However, anthropogenic activities including agriculture, expansion real-estate and built-up areas, mining and increasing deforestation due to timber logging considered as the main factors contributing to change in land-use-land-cover (Ayivor & Gordon, 2012; Tsai et al., 2019). Moreover, Ayivor & Gordon, (2012) in their paper, argued that, the responsible factors of landuse change in most Ghanaian river basins result from local communities meeting their livelihoods especially their socio-economic needs. Another school of thought by other researches (Boakye, et al., 2008) also believe change in land-use are usually influenced by population growth, poverty and industrialization. Moreover, high influx of people in cities results in increased water demand putting pressure on the available water resources. Hence, the responsive factors for changing land-use or landcover pattern all impacts water resources within a particular basin and could eventually result in flooding, erosion, nutrient and sediment deposition which result in biodiversity loss and eutrophication of in-land surface water bodies.

Climate variability significantly alters hydrologic process including precipitation, runoff, infiltration, base flow, soil moisture content, and evapo-transpiration (Kabo-bah et al., 2014; Shooshtari et al., 2017) and significantly causing socio-economic problems to Sub-Saharan countries. Several researches have been conducted to assess consequences of variable climate and change in land cover or land-use patterns on hydrologic processes in many African river basins (Oti et al., 2020; Adjei, Adjei, Obuobie, & Odai, 2019; Nyatuame, Amekudzi, & Agodzo, 2020; Op de Hipt et al., 2019; Kwarteng, Gyamfi, Anyemedu, & Adjei, 2020). Oti et al., (2020) in their study over the River Densu Basin of Ghana with WEAP21 model coupled with climate models observed that, temperature is expected to increase while rainfall will likely decrease in future resulting in reduced streamflow between 2015-2080 over the Densu basin. Hence, they concluded, climate change may significantly stress water availability within the basin. Adjei et al., (2019) in their research also found that, increasing population and rapid developmental projects has resulted in most of the Densu River basin being coverted from forests to barelands and settlements (paved and non-paved surfaces) between 1986 -2018.

The PRB has received much research on climate and LULC change effects (Awotwi, Kwame, & Quaye-ballard, 2017; Antwi-Agyei et al., 2019; E. Boakye, Odai, Adjei, & Annor, 2008; Domfeh, Anyemedu, Anornu, Adjei, & Odai, 2016; Osei et al., 2017; Osei, Amekudzi, et al., 2019; Osei, Ko, et al., 2019). Awotwi et al., (2017) using linear regression model, found that, during the dry months, runoff was observed to have and increasing trend between 1970-2010 and attributed this to a variable rainfall and anthropogenic practices especially small-scale mining contributing to the total runoff over the Pra basin. They also observe that, lower part of PRB may experience future flooding events if the trend in climate and or changing land-use pattern continues.

2.2. Impact of climate change on hydro-climatic extremes

In recent decades, the frequency, extent and duration of hydro-meteorological extremes have had a massive impact on humans and natural resources especially water resources (IPCC, 2012).

The response of hydrological extremes specifically flooding resulting from anthropogenic induced climate and landuse activities can be severe. Hence, over the years, Scientist involved in weather and climate studies have observed a substantial change in temperature, and rainfall trends around the world as well as rise in sea levels in many coastal cities. The Intergovernmental Panel on Climate Change (IPCC, 2013) have projected that, by the close of 21^{st} century, the global earth surface will experience temperature increase by getting up to about 0.3 - 4.8 ^{o}C warmer than as currently experienced. However, global future precipitation trends will have a non-uniform pattern depending on the seasonal or regional of observed incidence or precipitation (Okwala, Shrestha, Ghimire, Mohanasundaram, & Datta, 2020).

The focus of many studies has been towards the responsiveness of hydrological regimes to a changing climate. Hence, more research has been conducted on the major attributed factors altering the hydrologic cycle including land-use and anthropogenic climate change. However, hydro-climatic extreme have also gain significant research attention due to their potential destruction capabilities (Chen et al., 2020). According to IPCC, (2007 & 2013) report, the occurrence and frequency of extreme climate events are predicted to increase in the 21^{st} century and may potentially have negative consequence on agricultural production and ecosystem health. Usually, this can be seen in recent trends in increase flood and droughts across the globe with West Africa not being an exception. The degree and occurrence of floods resulting from changing climate and or poor land use and management practices may result in flooding with different characteristic pattern which may in turn have an effect on water resources within certain localities or regions. Hence, the subject, global warming and the attended effects have been significant topic of interest among researchers and the media at large in recent years.

In recent times, there have been severe cases of rising temperature resulting in thermal expansion of atmospheric water vapour (Allen & Ingram, 2002; Wentz, Ricciardulli, Hilburn, & Mears, 2007). This increase in temperature is predicted by several climate scientists to still increase thereby intensifying the hydrological cycle because the atmospheric air is expected to hold more water vapour due to the thermal expansion of air in the atmosphere (Gu, Yu, Yang, & Ju, 2018; Hirabayashi et al., 2013).

The Pra river basin is one the major basins with many sites allocated and projected as suitable for small dam projects as well as for irrigation projects. However, extreme hydro-meteorological events including variability in extreme precipitation and temperature may hinder such developmental projects as they pose significant threat such as increase sedimentation, collapse of the dams, and increase risk of flash floods. In the event of the extreme temperature patterns, the risk to this water resources includes high rate of evaporation leading to prolonged drought in the smaller tributaries feeding the main river, hence, hindering irrigation and water supply projects.

In the interest of protecting downstream areas from flooding due to increase flows, rainfall and temperature patterns may need to be well studied and understood to predict the frequency and magnitude as well as the timing of occurrence of these events so that effective measures are put in place to curb any disaster that may occur (Budhathoki, Babel, Shrestha, & Meon, 2020) and the potential impact they may have on available water resources.

2.3. Hydrological modelling

Hydrological models coupled with climate models offer a means of predicting the current along with the future influence of climate impacts and LULC changes on hydrological regimes. Hydrological models also offer a means of quantitatively predicting the stand-alone as well as the combined impact of LULC and climate change on hydrology and hydrological regimes (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011; Tirupathi & Shashidhar, 2020). Usually, large uncertainties usually result during the prediction and modelling the availability of future water resources within a given watershed with hydro-climatic models. Also, uncertainties arise during the prediction and or simulating incidence of rainfall or how precipitation varies spatially. Therefore, the response of hydrological regimes and hydrologic extremes in river basins to climate and LULC change must be understood. Also, with the resulting outputs of hydrological and climate models, important recommendation can be prescribed to water managers to ensure sustainable and efficient water allocation and effective land-use management. Hydrological models of various types are already developed and are available for use (including empirical, conceptual, and physically-based models) in simulating hydrological process change as a response to LULC change and temperature rise. Model selection is dependent on various factors including identified problem to be solved, problem scale, availability of data, cost involved in computation and model robustness and uncertainty associated with model parameterization (Mendoza et al., 2015; Tirupathi & Shashidhar, 2020). The Soil-Water-Assessment-Tool (SWAT) is one of the well-known hydrologic models for the assessment of land-use and climate variability on water resources. SWAT is a continuous, semi-distributed physical-based model, that is used to model or simulate hydrologic response to change in land management and practices and also climate change as causal factor for hydrological regime change within a given catchment (Arnold, Srinivasan, Muttiah, & Williams, 1998). SWAT model was chosen for this study because it is widely opted for and the preferred choice for assessing large scale climate and LULC Change impacts on hydrology in many studies due to its ability in modelling the effects of climate and LULC Change in different environments at both local, regional and global scale (Arnold et al., 1998).

The model input parameters important for assessing hydrologic response and extreme hydrologic conditions include; rainfall, temperature, soil data, land-use/landcover map, digital elevation model map (DEM) and results of simulated water balance of the catchment. Osei, Amekudzi, et al., (2019), used SWAT to simulate hydrologic response of Owabi catchment to anthropogenic activities. They found acceptable model results in hydrologic parameter predictions. Kwarteng, et al., (2020) also found satisfactory results in using SWAT model coupled with bathymetric data to model and assess hydrologic parameters response to LULC on Brimsu reservoir catchment, Ghana.

CHAPTER III

3. DESCRIPTION OF STUDY AREA AND DATA SETS

3.1. Study Area

Pra river basin and its tributaries constitute the largest South-Western Basin in Ghana occupying about 20 % of the total land surface area of Ghana (Fig 1). The tributaries of Pra river are River Offin, Annum River, Oda and River Birim. The location of PRB is between latitude 5°0’ N - 7° 30’N and longitude 0° 30’W-2°30’W (Arthur et al., 2020), with an area of about of 23,188 km^2. And it is bordered by four regions in Ghana including the Ashanti, Western, Central and Eastern region. The source of recharge can be traced to the Kwahu-plateau mountainous area in the Eastern region of Ghana. The river with a main drainage channel length of 240 km and a mean annual discharge of 214 m3/s (Kusimi, Yiran, & Attua, 2015) empties into the Gulf of Guinea at Shama found in the Western Region of Ghana.

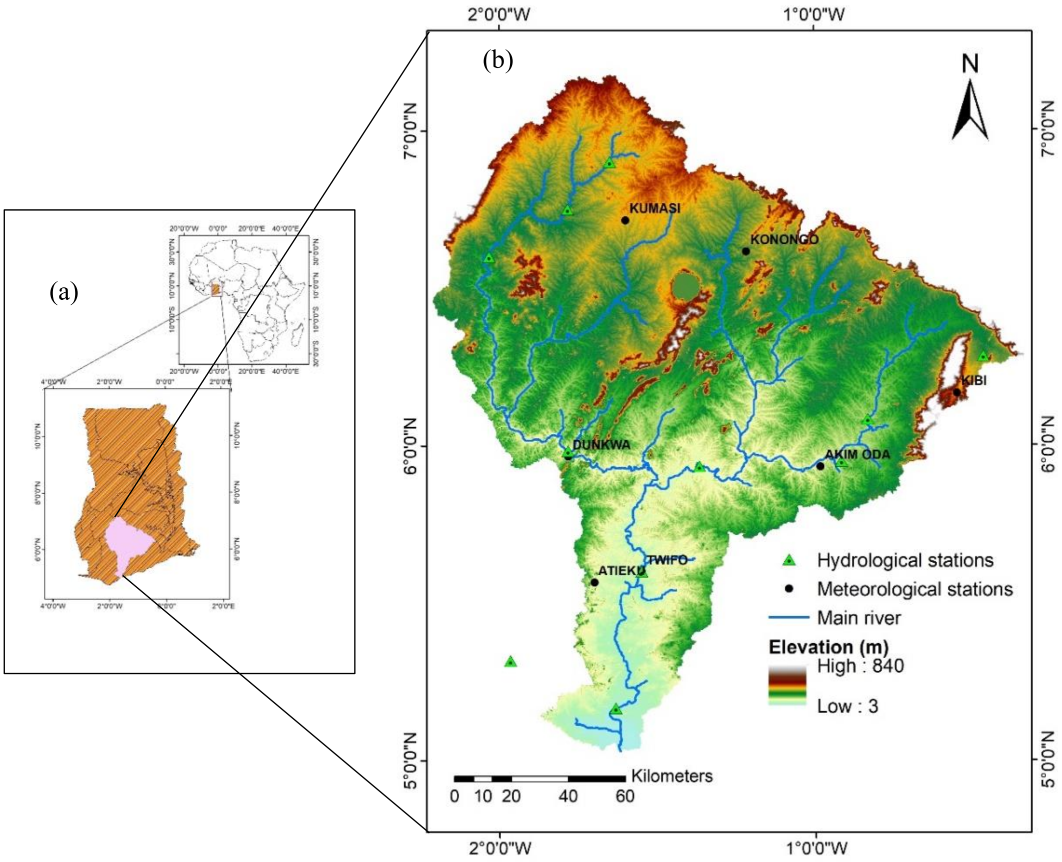


Figure 1: Map showing the Pra River basin, hydrological gauging stations, and meteorological stations: shaded area indicates study region

3.2. Geographical description of study area

The upper parts of the Pra river flow from the Kwahu mountains through Atewa forest reserve and it is characterised by geologic bedrock formation of Tarkwanian and Birimian origin (Ampadu, Chappell, & Tych, 2015). The land surface is mostly flat with few undulating topographies with an elevation averaging at about 450 m asl. The river Pra basin belongs to the wet sub-equatorial climatic belt characteristic by bi-modal rainfall pattern and the mean annual depth of precipitation ranges between 1500 mm and 1900 mm with runoff depth of about 4,174 Mm^3 (Awotwi et al., 2018). However, only about 12 % of the mean annual recorded precipitation contributes to streamflow in river Pra with more than 72% loss to evaporation. The bi-modal rainfall pattern recorded within the basin is shown in **Figure 2**. In the lower reaches (Twifo Praso and Daboase communities), the annual mean temperature lies between 21.74 °C and 32 °C. The soil cover of the drainage basin is classified into two soil types, Oxysols and Ochrosols (important for vegetation).

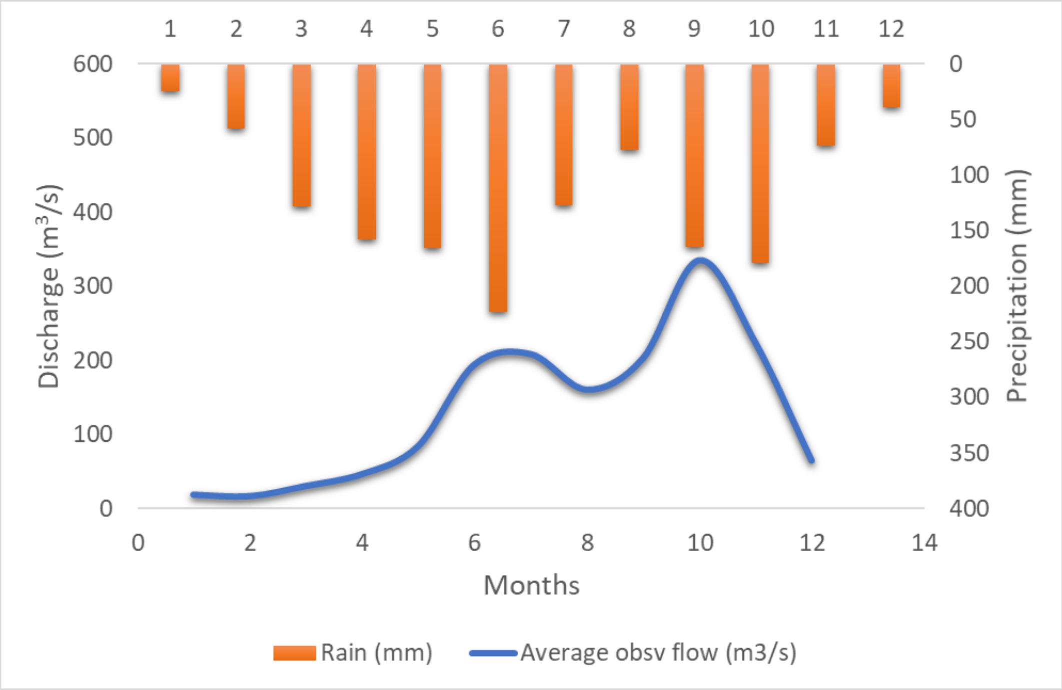


Figure 2: Trends in observed precipitation and discharge at the Pra basin

3.3. Data sets

3.3.1. Digital Elevation Model

SWAT model is very sensitive to the spatial datasets including Digital Elevation Model (DEM), soil and land-use data. For catchment delineation into smaller watersheds and subsequent HRU delineation by SWAT, the DEM data at 90m resolution was downloaded from http://srtm.csi.cgiar.org/ (Table 1). The DEM was further processed in ArcSWAT for watershed and sub-watershed delineation, flow direction and accumulation as well as generating the stream networks. Also, important basin and channel topographic properties including reach length, slope, and channel width where all created.

3.3.2. Soil data

Digital Soil Map of the World (ESRI raster format) was retrieved from the FAO soil database (http://www.fao.org/geonetwork/) at a resolution of 1: 5000000 as shown in Table 1. MWSWAT an extension of MapWindow version 488SR was used to import the FAO soil into SWAT database for subsequent ArcSWAT processing. After clipping the soil to the study area, 9 soil types are available withing the Pra basin (**Figure 3**). The dominant soil types in both the upper and lower basin are the Acrisols.

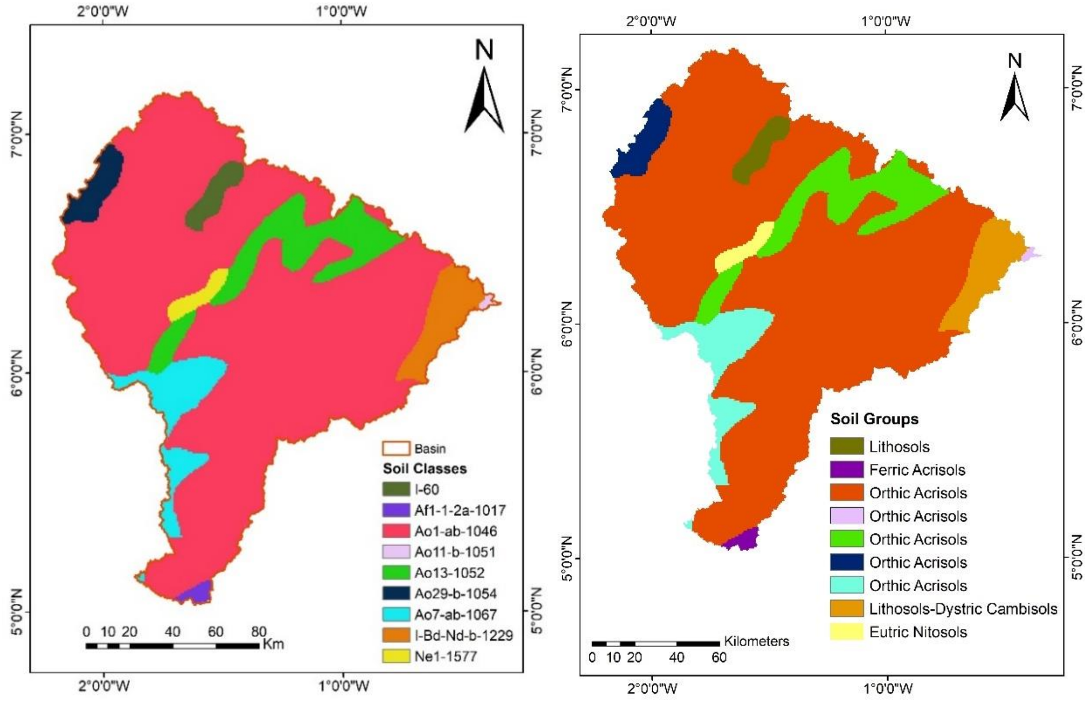


Figure 3: Map showing Soil groups of Pra Basin retrieved from FAO soil database

3.3.3. Land-cover data

For land cover maps, The European Space Agency (ESA) Climate Change Initiative (CCI) also provides global landcover maps at a resolution of 300 m. Landcover maps for the year 2010 was downloaded from ESA CCI website (http://www.esa-landcover-cci.org/) (Table 1). Rainfed-agricultural areas dominated land-use classes of the study basin (**Figure 4**).

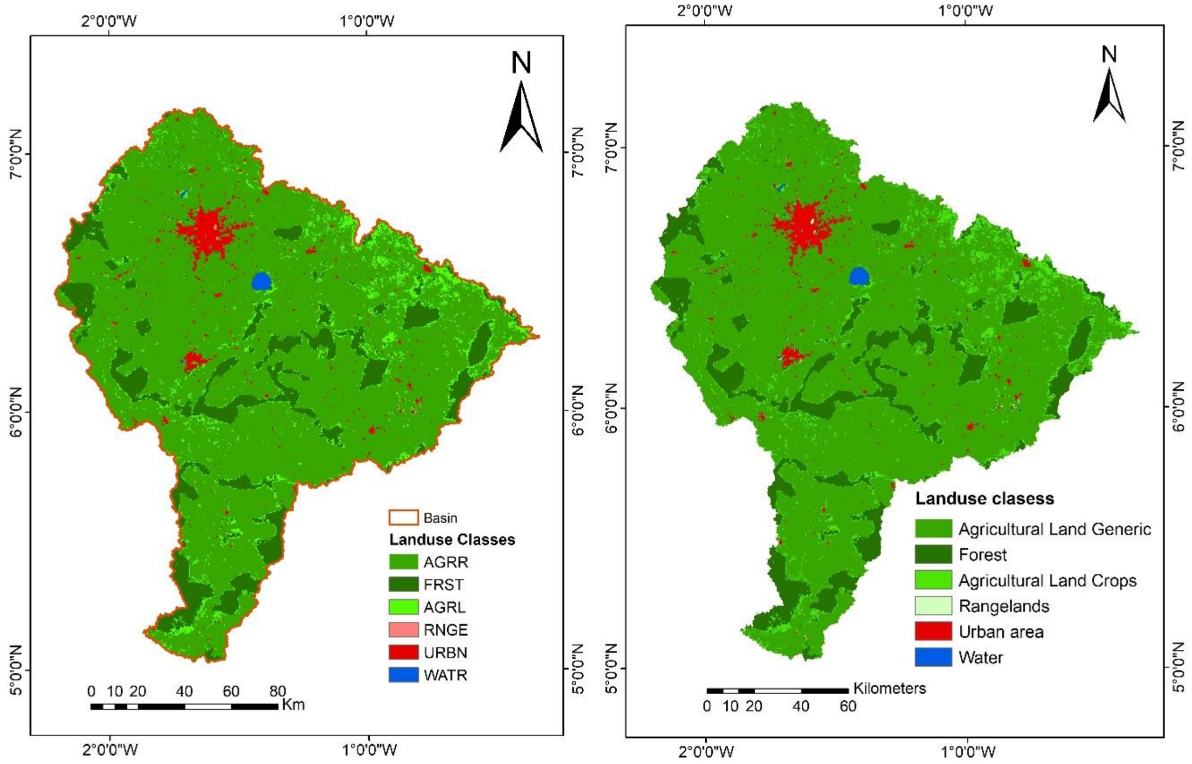


Figure 4: Maps showing Land use classes downloaded from ESA CCI

3.3.4. Climate Data

Ghana Meteorological Agency provides daily precipitation and temperature (minimum and maximum), data of some climate stations at daily and monthly scale. Climate data between the period of 1982 to 2015 from three climate stations (Kumasi, Twifo-Praso and Dunkwa on Offin) located within the basin was requested from Ghana Meteorological Agency and was used as part of the SWAT model setup and processing as seen in Table 1. These stations cover the upper, middle and lower part of the basin. Data quality and inconsistencies in obtained data was checked in excel, and missing rainfall data were direct filled using CHIRPS precipitation data at 5km spatial scale. This data has been found to be in good agreement with observe station point data (Atiah, Amekudzi, Aryee, Preko, & Danuor, 2020) and it has also been found to perform best when data gap filling missing or sparsely gauged basin in Ghana (Larbi et al., 2018). The Pra basin shapefile was first imported into Google Earth Engine (GEE) and the Climate Engine Application of GEE was used in the extraction of daily CHIRPS precipitation data in CSV format covering three (3) gridded stations.

For missing temperature data obtained, daily maximum and minimum temperature at 0.5^o resolution were obtained from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resource (NASA POWER) (https://power.larc.nasa.gov/data-access-viewer/) were used in filling missing data sets at the three climate stations.

3.3.5. Streamflow Data

Streamflow data measured in-situ are important for catchment inlet and outlet delineation in SWAT. Inlet definition of catchment helps in defining existing catchment processes and conditions while outlet definition is also important for the calibration and validation and performing sensitivity of hydrologic parameters for SWAT simulated hydrologic flow. In this research, stream gauge data at the downstream of the catchment located at Twifo-Praso was selected as basin outlet for SWAT modelling and the daily discharge data at this location was obtained from the Hydrological Service Department covering the period of 10 years (2000-2010) shown in Table 1.

Table 1: Datasets used in study

Dataset	Spatial resolution	Origin	year
Digital elevation model	90m	http://srtm.csi.cgiar.org/	NA
Land use data	300 m	ESA CCI	2010
Soil map		FAO soil database	NA
Weather data	daily	Ghana Meteorological Agency	1982-2015
Discharge data	Daily	Hydrological Service Department, Ghana	2000-2010

3.3.6. Future climate data

This research aims at assessing the combined impact of climate and land-use change on the availability of water resources in the Pra River Basin with a more focus on flow regimes including surface run-off, Baseflow and groundwater recharge, and evapotranspiration.

In this research 5 CMIP6 Global Climate Models (GCMs) with some at high resolution and others at a coarser scale were employed in the historical analysis (1985-2010) and for the projection of climate at the near future (2021-2050) under two climate emission and/or forcing scenarios of the Shared Socioeconomic Pathways (SSP2-RCP4.5 and SSP5-RCP 8.5). Moreover, these datasets were downloaded from CMIP6 database website (https://esgf-node.llnl.gov/search/cmip6).

Table 2: Description of CMIP6 GCMs used in research studies

No	Model	Responsible Organization	Horizontal Resolution (Longitude x Latitude)	Reference
1	HadGEM3-GC31 -MM	The UK Met Office Hadley Centre for Climate Change	0.83º x 0.54º	Ridley et al. (2019)
2 3	CNRM-CM6-1 CNRM-CM6-1-HR	French National Centre for Meteorological Research	1.41º × 1.41º 0.5º x 0.5º	Voldoire (2018)
4 5	ECMWF-IFS-LR ECMWF-IFS-HR	European Centre for Medium-Range Weather Forecasts	1 x 1 0.25º x 0.25º	-

CHAPTER IV

4. METHODOLOGY

4.1. Overview

This research is designed towards assessing climate impacts on water resources in the Pra river basin utilizing SWAT model data from CMIP6 GCM models under two climate forcing scenarios. The simulation of the hydrological aspects and hydrologic processes of the Pra river basin were implemented in Arcswat (SWAT interface extension in Arcgis) with Twifo Praso streamflow gauging station selected as the basin outlet. The general model setup and processing steps that were followed to achieve the research objectives are shown in **Figure 5** below;

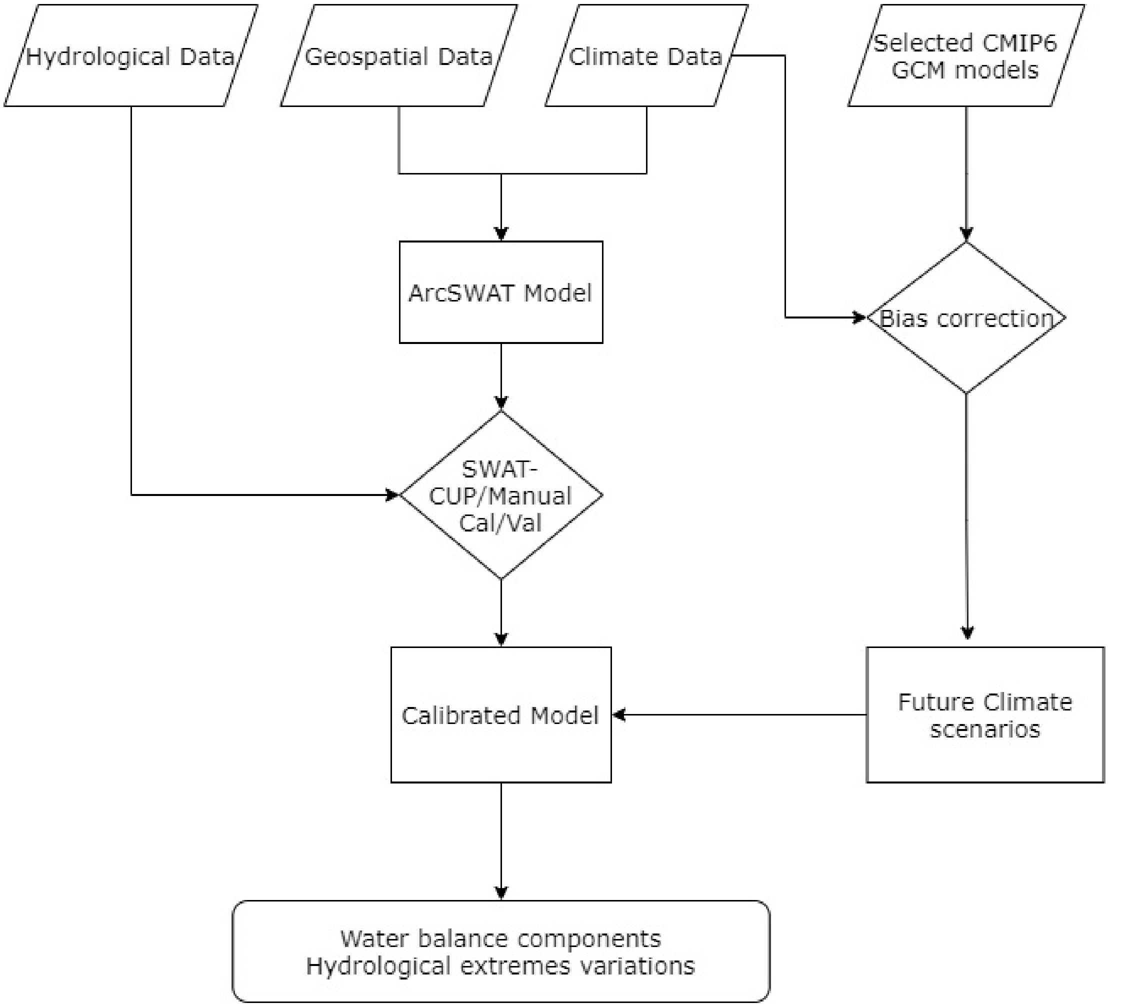


Figure 5: Methodological Flow chart for deriving water balance components and hydrological extremes

4.2. SWAT Model Description and setup

SWAT is a continuous, semi-distributed physical-based model, that is used to model or simulate hydrologic response to change in land management and practices and also climate change impacts on the hydrologic cycle within a given catchment (Arnold et al. 1998). SWAT has been widely used across the world in assessing hydro-dynamics and hydrologic processes of different watersheds. Most of these research papers can be accessed from SWAT literature database (https://www.card.iastate.edu/swat_articles/). The model input parameters important for assessing the hydrologic response and extreme hydrologic conditions include; rainfall, temperature, soil data, land-use map, digital elevation model map (DEM) and other important hydrologic parameters governing water flow out of the catchment.

In the SWAT model, smaller sub-basins are first generated from DEM and which are further developed into multiple hydrological response units (HRUs) based on land elevation, land-use type and the type of soil under research study area. Under each HRU, SWAT simulates the various hydrological components based on the water balance equation (M. L. Tan et al., 2015). Precipitation, surface runoff, evapotranspiration, infiltration, lateral flow and percolation are hydrologic processes that SWAT can simulate. Estimation of surface runoff by SWAT is based on modification of the well-known U.S. Soil Conservation Service Curve Number using daily rainfall values. The basin runoff is then derived using overland-flow and the confluence of the basin networks (Neitsch et al 2009). Getting good SWAT simulated outputs relies on these input parameters. Model input data are summarised in **Table 1**. SWAT models the hydrological processes at a daily time step; however, recent research have revealed that monthly time steps can also be accurately modelled (Yan et al., 2019). Hence, in this study, the hydrological water balance of the basin was modelled at a monthly time-step. Under each HRU, SWAT centres on soil-water balance equation to simulate the various hydrological components (Arnold et al., 2012) as shown as equation 1 below;

$$SW_t = SW_{t-1} + \sum_{i=1}^{t}(R_i - Q_i - ET_i - P_i - QR_i) \quad (1)$$

$Where;\ SW\ is\ the\ soil\ water\ content;\ i\ is\ the\ time\ of\ day\ for\ the\ simulation\ period;$ $and\ R, Q, ET, P\ and\ QR\ are\ daily\ precipitation, runoff, evapotranspiration\ and\ return$ $flow\ respectively.$

4.2.1. Hydrological model processing

After DEM processing, a total of 27 sub-basins were generated (**Figure 6**) based on streamflow networks, selected flow outlets and stream gauge points as well as water storage reservoirs with minimum sub-basin set at 5 km^2. In defining the HRU for the sub-watersheds, an overlap threshold of 5% for landuse and soil on landuse and 2% for slope on soil areas respectively were set. Slope classes based on DEM map used for the study area. HRU definition was set into 4 classes (at 0-5%, 5-12%, 12-85% and 85-9999). A total of 210 HRUs were generated by SWAT model SWAT v2012) for the Pra Basin.

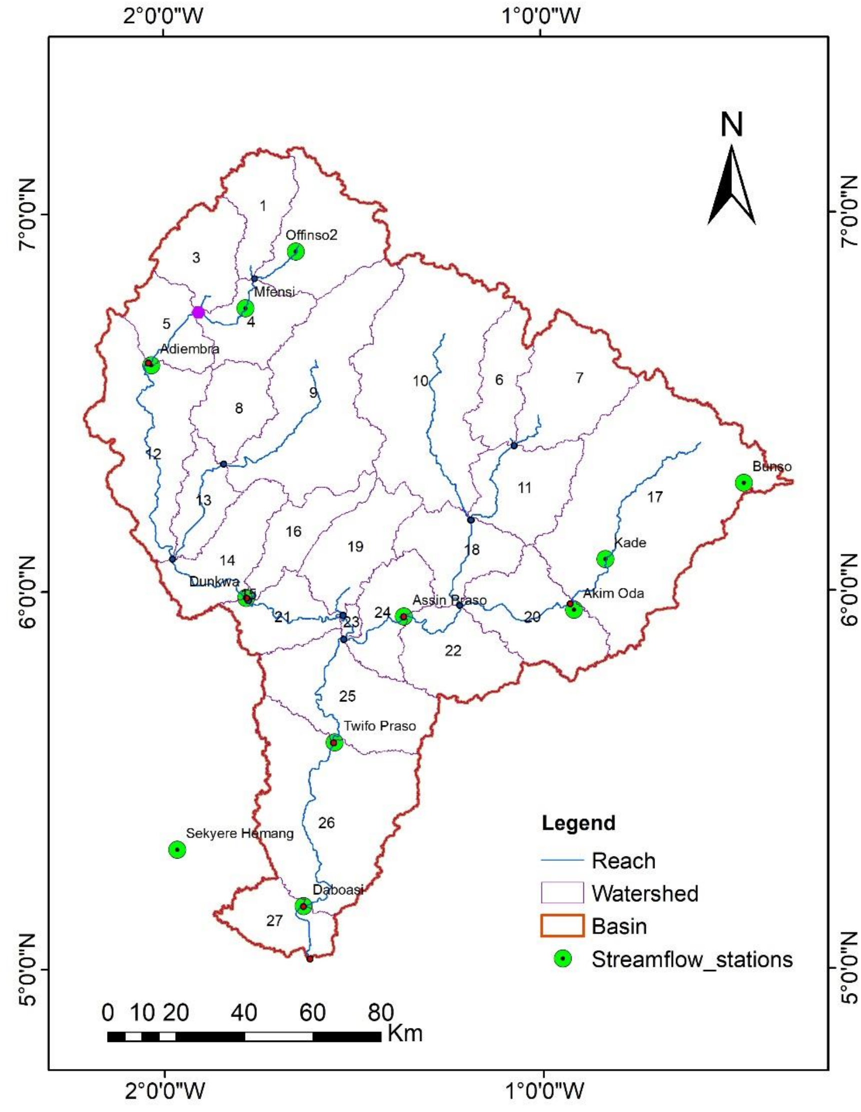


Figure 6: The delineated Pra River Basin and sub-catchments

SWAT weather input files including observed Rainfall data, with its coincident maximum and minimum temperature data at Twifo-praso, Dunkwa-On-Offin and Kumasi Airport station over the study area obtained from the Meteorological Agency were prepared in Microsoft excel and imported as text files into ArcSWAT and were utilized in simulating the run-off of the catchment by SWAT. However, relative humidity, wind speed and solar radiation were auto simulated by SWAT model. SWAT was run for a period of years (1982 -2015) with 3 years chosen as warm-up period for model getting accustomed to catchment hydrologic process and characteristic properties. Surface runoff estimation used by SWAT in this study was based on modification of the well-known U.S. Soil Conservation Service Curve Number (CN) using daily rainfall values while estimation of evapo-transpiration was based on the Penman-Monteith method.

4.2.2. Calibration and Validation

In this study, both manual and automatic calibration techniques were employed for model parameter calibration to reduce any uncertainty that may result and improve output of model simulations. The recorded streamflow data was divided into calibrated and validated data sets for model developments run-off simulation by selecting the sequential uncertainty fitting (SUFI-2) algorithm of SWAT-CUP. The purpose of SWAT-CUP is to obtain the best value of parameters which can significantly alter the model output (streamflow/sediment). In all, 10 years of streamflow data measured at the Twifo-Praso gauge station were used for calibration and validation excluding the 3 years (2000-2002) of warm up period. The warmup period (2000-2002) was important for SWAT model to get familiarized to the variability and pattern of period hydrometeorological observation. That is this warm-up period set the initial conditions of model run for model stabilization relying on input parameters.

First automatic calibration was performed by employing SWAT-CUP and SUFI-2 algorithm which are relatively known for calibrating and analyzing series of parameters. A research conducted by Khoi & Thom, (2015) on uncertainty analysis of four algorithms used for hydrologic model parameterization found SUFI-2 as the algorithm with small margin of uncertainty in simulation results compared with observed results. SUFI-2 algorithm accounts for all sources of error and or uncertainty in input parameters, driving forces or variables as well as errors resulting from model. This may include any uncertainty associated with input temperature and rainfall data, model input parameters and parameterization and field measured data. A review of literature of relevant works done on the catchment and basins with similar characteristics to study area was performed to select the most usual sensitive parameters. SWAT-CUP was run for 500 simulations for every set of inputs used during calibration until the best set of parameters with the best set of statistical metrics were obtained. After, automatic calibration, the best fit values of the parameters were manually adjusted to fit the observed run-off values using SWAT manual helper tool of ArcSWAT. In this study, using the observe flow at Twifo-Praso, the calibration and validation of the hydrological model was carried out at a monthly time-step.

4.2.3. Model Accuracy Assessment and Uncertainty Analysis

The performance of SWAT model was evaluated using the following statistical metrics: Nash–Sutcliffe efficiency (NSE), linear regression (determination coefficient (R^2)) and Percent bias (PBIAS) by comparing observed discharge measurements with simulated runoff values at selected river basin outlet using the second set of runoff data. Also, the 95% prediction uncertainty (95PPU) of SWAT-CUP was used in the quantification of uncertainties that were associated during the optimization of Calibrated input parameters that influence model performance. The measure of the uncertainties associated with model output or performance resulting from parameter optimization is realized through Latin Hypercube sampling expressed at 95PPU. This involves the estimation of 97.5% and 2.5% uncertainty levels of the cumulative distribution of model output variables (Karim C. Abbaspour et al., 2007; Arnold et al., 1998). Also, r-factor and p-factor were used to ascertain model fitness since only using the statistical tools such as RMSE, NSE, R^2, MAE etc., can be misleading (K.C. Abbaspour, 2021). In evaluating model performance, that is comparing simulated stream flow against observed discharge, a P factor > 0.7 shows that observed flow values are within 95 PPU and r values < 1.5 which describes the width of 95 PPU band over standard deviation observed parameters are recommended.

4.3. Climate change modelling

In this research, observed climate data comprising daily precipitation and temperature measurement covering 3 climate stations located within the basin were used as baseline simulation datasets. The climate observed datasets covered the period of 1985 to 2015 was obtained from Ghana Meteorological Agency. Global Climate Models (GCMs) are growing in popularity and use for climate impact assessment and decision-making tools. The new Coupled Model Intercomparison Project (CMIP6), 6th Phase ensembles (Eyring et al., 2016; Klutse et al., 2021) which comes with climate models of high spatial variability with some at even a more high spatial scale than regionally downscaled CMIP5 models (example with some downloadable from Regional Climate Model (RCM) of Coordinated Regional Climate Downscaling Experiment (CORDEX) platform). CMIP6 also comes with additional complex physical structures than their previously CMIP5 models (Klutse et al., 2021; Taylor, Stouffer, & Meehl, 2012). Also, within the CMIP6 ensemble project, it has seen an increase in the participating modelling groups, as well as future modelling scenarios and different experimental modelling conducts. Moreover, compared with the Representative Concentration Pathways (RCPs) 4.5 and 8.5 emission scenarios of CMIP5, CMIP6 comes with a newly updated emission scenarios called the socioeconomic pathways (SSPs) relying on five emission narratives that “defines alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development” (Alaminie et al., 2021).

The performance of CMIP5 and CMIP3 climate models in simulating precipitation and temperature across the globe and in Africa and at regional scales have been undertaken. Also, within Africa and West-Africa regional and its sub-regional basins, the capability of CMIP5 and CMIP3 in simulating climate extremes have been undertaken (Amisigo, Mccluskey, & Swanson, 2015; Ashaley, Anornu, Awotwi, Gyamfi, & Anim-Gyampo, 2020; Awotwi et al., 2021; Bessah, Raji, Taiwo, Agodzo, & Ololade, 2020b; Durodola & Mourad, 2020; Ibrahim, Wisser, Barry, Fowe, & Aduna, 2015; Osei et al., 2021; Oti et al., 2020; Tanteliniaina, Rahaman, & Zhai, 2021). However, there is limited research conducted with other climate models especially CMIP6 (Akinsanola, Ogunjobi, Abolude, & Salack, 2021; Akinsanola, Ongoma, & Kooperman, 2021; Alaminie et al., 2021; Ogega et al., 2021) to assess climate change impacts on water resources in Africa. Hence, utilizing this model (CMIP6) to assess climate impact on precipitation extremes and their subsequent impact on hydrologic processes will be important for research and for subsequent GCM model improvement.

In this research, 5 CMIP6 GCMs including CNRM-CM6-1, CNRM-CM6-1-HR, HadGEM-GC31-MM, ECMWF-IFS-LR, and ECMWF-IFS-HR) were downloaded from the World Climate Research Programme (WCRP) powered by Earth System Grid data portal (https://esgf-node.ipsl.upmc.fr/). Also, the SSPs under the medium forcing emission (SSP2-RCP4.5) and strong or business as usual emission scenario (SSP5-RCP8.5) were extracted and used in this study for climate forcing and future climate projection for 2030s (2015- 2044) and 2050s (2045-2074).

4.3.1. Bias correction of climate models

The GCM datasets were subjected to bias correction following the linear scaling (multiplicative) method, Distribution Mapping method and Power Transformation method for Precipitation datasets. And also Linear scaling (additive) method, Distribution mapping method and Variance scaling method were applied to the temperature datasets (Okwala, Shrestha, Ghimire, Mohanasundaram, & Datta, 2020) before the best bias-corrected CMIP6 GCM data was used for the hydrologic processes and extreme hydrologic prognosis as well as trend analysis of climate events. This step was important to ascertain which of the CMIP6 GCMs provides an accurate prediction of precipitation and temperature over the study area compared with ground observational measurements.

However, it was important first to check how the raw simulated historical CMIP6 GCMs compared with the observed precipitation and temperature measurements, hence the monthly mean of simulated CMIP6 models (CNRM-CM6-1, CNRM-CM6-1-HR, HadGEM-GC31-MM, ECMWF-IFS-LR, and ECMWF-IFS-HR). The CMhyd software algorithm developed by Rathjens, Bieger, Srinivasan, & Arnold, (2016) was utilized in implementing all the bias corrections methods mentioned in order to select the best CMIP6 model based on extensive statistical results between observed and bias-corrected climate data. Data obtained from Ghana Meteorological Agency which was gap filled with CHIRPS precipitation gridded data and NASA POWER Reanalysis Data for precipitation and temperature data respectively were used as baseline period and for bias correction of extracted GCM data. The performance of the climate was evaluated using the following statistical metrics: Mean Absolute error (MAE), mean absolute percentage error (MAPE), root mean squared error (RMSE) and determination coefficient (R^2) to compare how the different models predicted values compare with observed datasets and for best predictive model selection for subsequent use in hydrologic impact change analysis.

4.4. Extreme hydrological events

In this study, the extreme climate indices were computed based on 27 existing climate indices developed and defined by the Climate Change Detection and Indices (ETCCDI) and later adopted by World Meteorological Organisation Expert Team on Sector-specific Climate Indices (WMO/ET-SCI). To evaluate the extreme hydrological events and trends, six (6) extreme precipitation indicators out of the 27 extreme indices developed by a group of experts of Climate Change Detection and Indices (ETCCDI) (Chen et al., 2020) were employed and used for future hydrologic extreme trends analysis. The indices that were used include 6 precipitation indices with flood indicators and drought indices are shown in Table 3. The ETCCDI developed the RClimdex interface on R software which is also freely downloaded from (http://cccma.seos.uvic.ca/ETCCDMI/index.shtml), which can be used to compute the indices once the look-up-table has been correctly developed. Hence, in this research, the selected extreme climate indices were computed using CLIMPACT2 software build and written on the interface of R software. CLIMPACT2 which is freely available at (https://climpact-sci.org/) was developed based on Climdex.pcic R packages (Alexander & Herold, 2016). The trends in extreme indices estimated by CLIMPACT2 are based on Sen's slope, which is more useful in trend analysis.

Table 3: Extreme Precipitation indices

	Index	**Descriptive name**	**Definitions**	**Units**
Flood	Rx1day	Max 1-day precipitation amount	Annual maximum consecutive 1-day precipitation	mm
	RX5	Maximum consecutive 5-day rainfall	Annual maximum average consecutive 5-day precipitation	mm
	R20	Number of very heavy precipitation days	Annual count of days when PRCP>=20mm	days
	CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm	days
Drought	CDD	Consecutive dry days	Maximum number of consecutive days with daily rainfall (RR) <1mm	Days
	SPI	Standard precipitation index	Precipitation index	

CHAPTER V

5. RESULTS AND DISCUSSION

5.1. Model sensitivity results

The observe flow data at Twifo-Praso station from 2003-2008 were used for model calibration and 2009-2010 for validation utilizing SUFI-2 algorithm in SWAT-CUP. During the performing of sensitivity analysis, input parameters were first initially dummy setup and were run in SWAT-CUP to obtain the most sensitive parameters that need to be optimized and to ascertain if the simulated and observed flow follows a similar hydrological pattern. The criteria of ascertaining the most sensitive parameters were based on p-value and t-stat under the Global sensitivity analysis in SWAT-CUP. Parameters with p-value greater than 0.5 were assumed to be not sensitive to model parameter optimization and hence were excluded from subsequent SWAT-CUP Sufi-2 algorithm runs. Also, parameters with p-values less than 0.05 were selected and defined as the most sensitive parameters affecting discharge.

The identification of model parameters needed for model setup was first obtained through scouting literature of important similar research done within the basin of study and other catchments with similar hydrologic and topographic properties. This initial step of model parameter identification is important for trimming down and removing other parameters that may not or less likely affect model simulation and stabilization of model run during a matchup with observed with flow data. Also, most of the initial parameter values were obtained from the SWAT-2012 user manual (Abbaspour, 2015). A total of sixteen (16) model input parameters were used in this study and four (4) parameters (including CN2, ESCO, ALPHA_BF, and RCHRG_DP) were found to be the most sensitive and needed to be optimized for flow simulation in SWAT. Model calibration and sensitivity results showed SCS runoff curve number (CN2), Soil evaporation compensation factor (ESCO) and Baseflow alpha factor (ALPHA_BF) to be the most sensitive parameters within the modelled watershed. These three sensitive parameters have great impact and are also important for hydrological processes occurring within the given watersheds (Deng, Zhang, Li, & Pan, 2015). These parameters are also sensitive to peak discharges especially CN2 due to its spatial variability at the basin and HRU levels. Model input optimization parameters used in this study are listed in **Table 4**.

Table 4: SWAT input parameters used in study with rankings of most sensitive parameters

Parameter (SWAT code)	Parameter description	Min value	Max value	Fitted Value	Rank
r__CN2.mgt	SCS runoff curve number	-0.2	0.2	-0.198	1
v__ESCO.hru	Soil evaporation compensation factor	-0.25	0.25	0.799	2
v__ALPHA_BF.gw	Baseflow alpha factor (days)	0	1	0.187	3
a__RCHRG_DP.gw	Deep aquifer percolation fraction (-)	0	1	0.029	4
v__CANMX.hru	Maximum canopy storage	0	20	5.931	5
v__GWQMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	0	1500	1486.661	6
v__CH_K2.rte	Effective hydraulic conductivity in main channel (mm/hr)	0	200	133.045	7
v__GW_DELAY.gw	Groundwater delay (days)	0	450	111.250	8
v__CH_N2.rte	Manning’s “n” value for the main channel	0	0.3	0.037	9
v__EPCO.bsn	Plant uptake compensation factor	0	1	1.098	10
r__SOL_AWC().sol	Available water capacity of the soil layer (mm H2O/mm soil)	-0.25	0.25	0.083	11
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	0	500	209.782	12
r__SOL_Z().sol	Soil depth of layers (mm)	-0.25	0.25	0.129	13
r__SURLAG.bsn	Surface runoff lag coefficien	-5	5	0.248	14
v__GW_REVAP.gw	Groundwater “revap” coefficien	0.02	0.2	0.192	15
r__SOL_K().sol	Saturated hydraulic conductivity (mm/hr)	-0.25	0.25	0.071	16

5.2. Calibration and Validation

The model's calibration and validation results of graphical representation are shown in **Figure 7.** The overall model simulated streamflow results can be deemed as satisfactory with the model’s ability to capture most of the peak flow periods. However, at some periods, a mismatch between peak rainfall and peak discharge was observed. This may be due to long periods of drought or very low rainfall, hence, dams located within the catchment must be filled up before overflow takes place. Also, soil moisture conditions may need to be satisfied before runoff takes place hence the resulting discharge shape. During model calibration in SWAT-CUP, the objective function considered for model performance were the Nash Sutcliffe Coefficient (NSE), coefficient of determination (R^2) and Percent bias (PBIAS). Positive PBIAS value obtained shows an underestimation by the model while negative PBIAS values shows overestimation by model. For the calibration, data run values obtained were 0.69, 0.71 and -2.0% while for the validation data sets, 0.64, 0.65 and 3.6% were obtain for NSE, R^2 and PBIAS respectively (**Table 5**).

Table 5: Statistical summary results

	Statistical parameter				
	R2	**NSE**	**PBIAS**	**p-factor**	**r-factor**
Calibration	0.71	0.69	-2.0	0.78	1.72
Validation	0.65	0.64	3.6	0.71	1.14

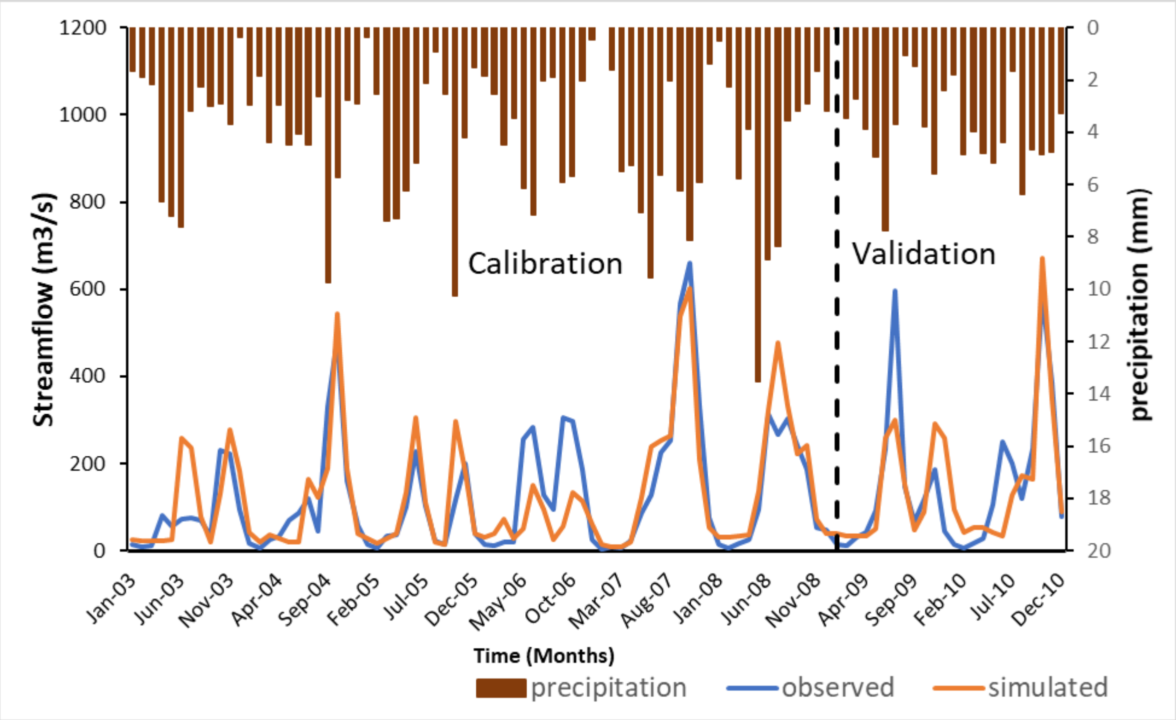


Figure 7: Graph of model calibration and validation

Also, p-factor values of 0.78 and r-factor value of 1.72 obtained for calibration set model run and 0.71 and 1.14 for p-factor and r-factor respectively for validation run. The obtained statistical summary results for monthly calibration were deemed good with R^2 and NSE greater than 0.6 while PBIAS < ±25% according to (Moriasi et al., 2007; M. L. Tan, Gassman, Srinivasan, Arnold, & Yang, 2019). However, the model was not able to estimate some peak flows. Similar observations have been made by other researchers regarding SWAT incapability of simulating peak flows. Also, the model's overall performance with validation results lower than calibration datasets may indicate input date may not be of very high quality. However, the validation results within the acceptable range make the model deemed good and fit for the Pra basins hydrological basins assessment. Hence, the model's good performance can further be used for subsequent investigations of climate impacts on hydrologic processes and climate extremes impact on stream flow for the study area.

5.3. Water Balance for Baseline Scenario

In the assessment and quantification of the availability of water resources within a certain catchment or basin, it is important to understand the varied hydrological processes that govern the flow. Also, in predicting the future impact of climate or land-use change on water resources, it is important to know the current or historical hydrological aspects and hydrological regimes that is controlling or might have the potential of affecting flow and water availability. Usually, a representative water balance component is needed for the prediction and flow quantification. However, not all these parameters are measurable, and one may have to resort to mathematical modelling techniques together with recently developed remote sensing data.

In this study, a physically-based model, SWAT that has been calibrated, was used to estimate the various water balance components of the Pra basin. The annual monthly average of water balance components is shown in **Table 6**.

Table 6: Average monthly water balance components values (2003-2010) for the Pra basin

Months	PRECIP (mm)	SURQ (mm)	LATQ (mm)	WYLD (mm)	AET (mm)	PET (mm)
Jan	26.07	2.36	0.57	3.40	24.96	156.03
Feb	67.50	5.68	0.61	6.40	51.48	151.59
Mar	111.39	4.11	0.80	5.31	162.99	209.49
Apr	143.31	2.44	1.03	3.69	138.53	190.95
May	187.82	19.70	1.75	20.27	71.84	171.96
Jun	203.66	42.16	2.75	44.96	71.87	157.56
Jul	128.98	26.91	2.41	29.87	65.61	178.86
Aug	81.18	9.89	1.36	12.64	54.70	170.06
Sep	179.38	31.78	2.32	34.09	60.79	131.47
Oct	177.04	27.89	3.08	32.18	67.90	122.40
Nov	82.49	8.49	2.02	11.29	55.57	138.51
Dec	45.58	4.46	1.05	5.89	38.65	153.04
TOTAL	**1434.40**	**185.85**	**19.73**	**209.99**	**864.88**	**1931.92**

The result of the annual hydrologic aspects shows evapotranspiration estimated as 864.88 mm (about 60%) followed by surface runoff value of 185.85mm (representing about 13%) as the predominant factor responsible for water loss within the catchment. There have been reported cases of water treatment abstraction structures located within the basin being closed down due to the high deposition of sediments into the reservoir. Surface runoff been the major contributor to water yield may be attributed to being the main responsible factor for the high turbidity of the Pra river. However, the estimated value of surface runoff may be considered too low to be the main contributing factor responsible for sediment deposition and erosion cases recorded at the watershed level. This can be due to the increasingly small-scale illegal mining activities leading to loss of vegetative covers within the catchment. The conversion of forested areas to agricultural land might also be responsible for the high evapotranspiration recorded. From **Figure 8,** the major precipitation peaks follow a bimodal rainfall pattern influenced by the movement of the Inter-tropical Convergence Zone (Obahoundje, Ofosu, Akpoti, & Kabo-bah, 2017). This follows similar observations by Mul et al., (2015). Moreover, surface runoff contributed most to water yield measured at the designated outlet of the basin.

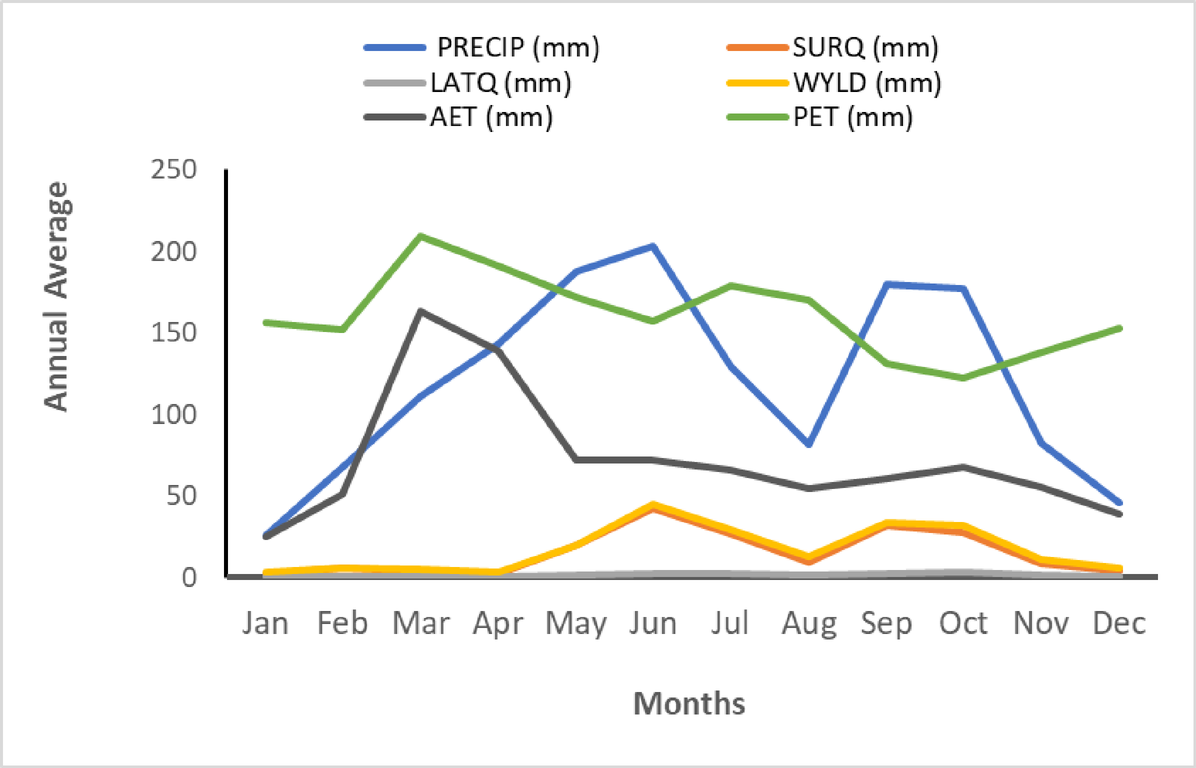


Figure 8: Average annual water balance components of Pra basin water balance components

5.4. Future Climate Variability

In this research, all the bias correction methods employed performed satisfactorily in removing biases between observed precipitation and temperature measurements and simulated results from the CMIP6 models. The bias corrections techniques used includes the linear scaling (multiplicative) method, Distribution Mapping method and Power Transformation method for Precipitation datasets. And also, Linear scaling (additive) method, Distribution mapping method and Variance scaling method for temperature datasets. All the models were able to accurately predict the shape of the observed rainfall and temperature patterns at all three stations with little or no degree of biasness in all datasets. However, in this study, the linear scaling (multiplicative) method was selected for bias-correcting modelled precipitation datasets while Distribution Mapping method was used for correcting the CMIP6 GCM temperature datasets over the Pra basin since the gave the least degree of unbiases and uncertainties between the observed and bias-corrected measurements. Although the linear scaling method was best for correcting biasness in precipitation measurements in our study, the results obtained with the distribution mapping were equally good. This result is similar to observations obtained by (Awotwi et al., 2021). They found the Distribution Mapping method to be the best-biased corrector for CMIP5 precipitation and temperature compared with observed data over the Pra basin.

5.4.1. Bias-correction of CMIP6 Climate Model data

5.4.2. Precipitation data

Ghana is of tropical climate influenced by the West-African monsoon and the movement of the Inter-tropical Convergence Zone (Kayaga et al., 2021), where rainy seasons are seen in the summer months and dry season in winter. **Figure 9** represents the hydro-climatical observation of annual monthly mean of observed precipitation and temperature data compared with the raw uncorrected CMIP6 models (CNRM-CM6-1, CNRM-CM6-1-HR, HadGEM-GC31-MM, ECMWF-IFS-LR, and ECMWF-IFS-HR) respectively spanning the period between 1985-2014 over the Pra river basin. It can be inferred from **Figure 9** that, most the GCMs captures the observed precipitation pattern except for HadGEM-GC31-MM, which underestimated the observed precipitation. This result is in agreement with research findings by (Wang et al., 2021) where it was found that CMIP6 models to better capture or simulate precipitation trends over areas influenced by global monsoon than the previously developed CMIP5 models. Also, there was a shift of simulated peak rainfall and observed rainfall for almost all of the models except the high resolution CNRM-CM6-1. The uncorrected ECMWF-IFS-HR was able to capture the observed precipitation pattern at almost all of the three meteorological stations datasets used in this study. Also, the other raw and uncorrected GCM models showed a shift in peak rainfall between observed and simulated rainfall at all gauging stations while also underestimating all precipitation measurements. Similar observation were made by Awotwi et al., (2021) over the Pra river basin using CMIP5 models and M. L. Tan et al., (2021) in Malaysia, over the Kelantan river basin utilizing HighResMIP CMIP 6 models. The high performance of ECMWF in simulating the precipitation are in agreement with similar results obtained by (Ajibola, Zhou, Gnitou, & Onyejuruwa, 2020). However, it underestimated low rainfall and over-estimated peak rainfall at the Twifo-Praso station while under-estimating all rainfall values at Kumasi Airport and Dunkwa-On-Offin meteorological station. Hence, CNRM-CM6-1 simulated precipitation was selected in this study for assessing the climate impacts on future streamflow over the Pra basin.

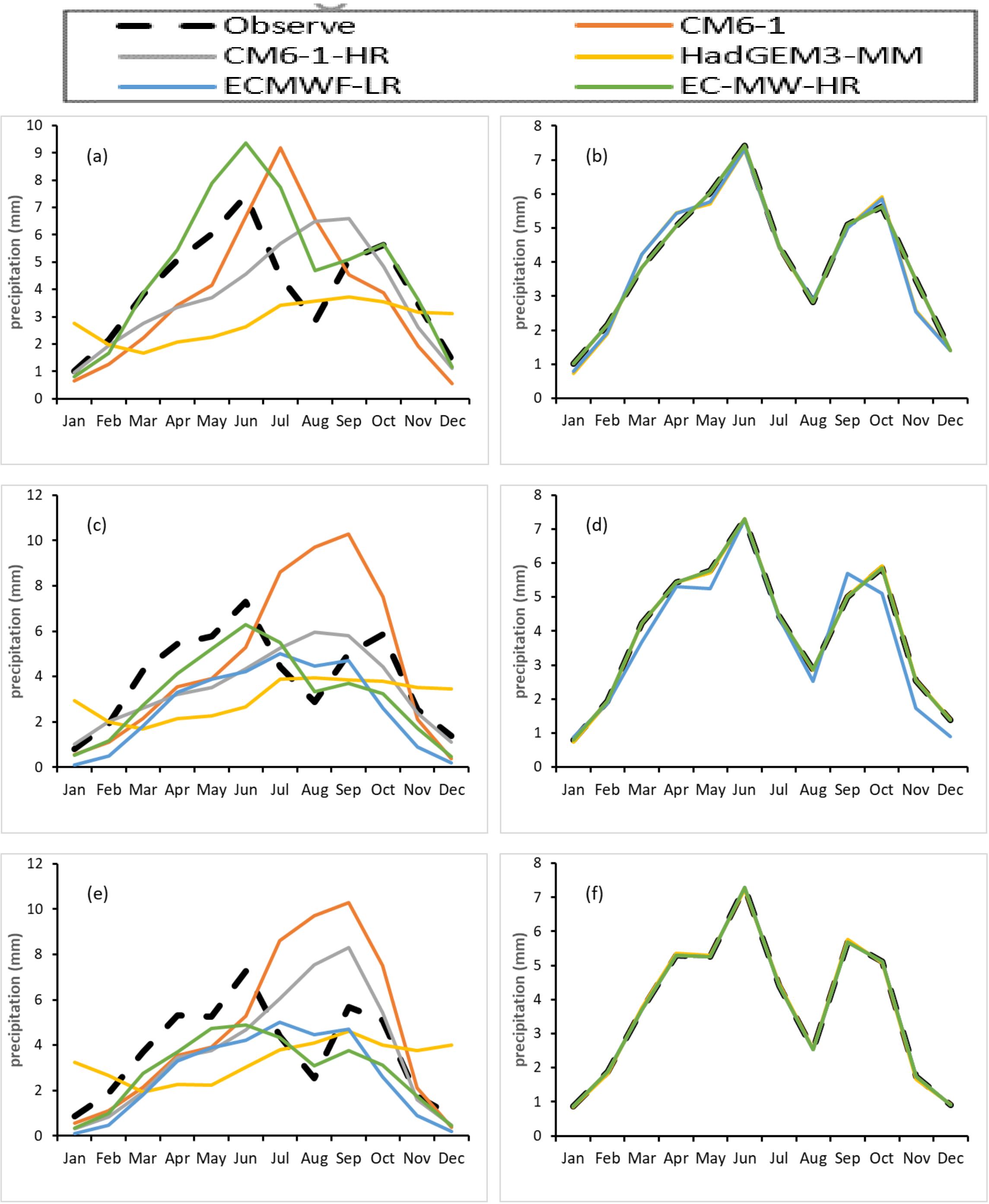


Figure 9: Annual mean monthly observed and five (5) CMIP6 simulated amount of precipitation for Twifo Praso (a, b) Dunkwa-On-Offin (c, d) and Kumasi MET station (e, f); col 1(a- e) for Raw GCM data and col 2 (b-f) for bias-corrected for the historical period of 1985 – 2014 for the Pra River Basin.

5.4.3. Temperature data

From **Figure 10**, the raw GCM models showed underestimation as well as overestimation for the monthly averaged observed temperature measurements over the Pra basin. Most of the models where able to capture both the scale and shape of the observed temperature except for HadGEM3-MM which showed a reverse order for both maximum and minimum temperature. In all, the raw ECMWF-HR, ECMWF-LR and CM6-1-HR simulated temperature datasets accurately captures the observed temperature with small error. Moreover, CNRM-CM6-1 showed an underestimation and over-estimation for maximum and minimum temperature respectively.

In all, CMIP6 models performance improved after bias correction by applying the Linear scaling and Distribution Mapping method for precipitation and temperature data respectively. There was reasonable shape and scale of resemblance between bias-corrected CMIP6 GCM and the observed data. All models showed much improvement. Also, the raw the HR CMIP6 better captured the observed precipitation and temperature measurements. showed However, ECMWF-LR showed some form of deviation from the observed datasets for the precipitation measurements. Moreover, the results of bias-corrected precipitation and temperature shows that CMIP6 GCMs adequately reproduce the observe precipitation and temperature patters within the Pra river basin. This observation is similar to results obtained by Ogega et al., (2021) over lake victoria basin and M. L. Tan et al., (2021) over Kelantan River Basin.

The bias-corrected CM6-1 and ECMWF-LR and EC-MWF-HR showed much improvement with little to no error from the observed precipitation and temperature measurements. Similar observation were made by (Ajibola et al., 2020) for research conducted on the performance of HighResMIP CMIP6 models on precipitation simulation over West-Africa. However, ECMWF-LR and EC-MWF-HR have no future scenarios and hence could not be adopted for use in assessing future climate scenarios. Hence, CNRM-CM6-1 was selected in this study for assessing the climate impacts on future streamflow over the Pra basin.

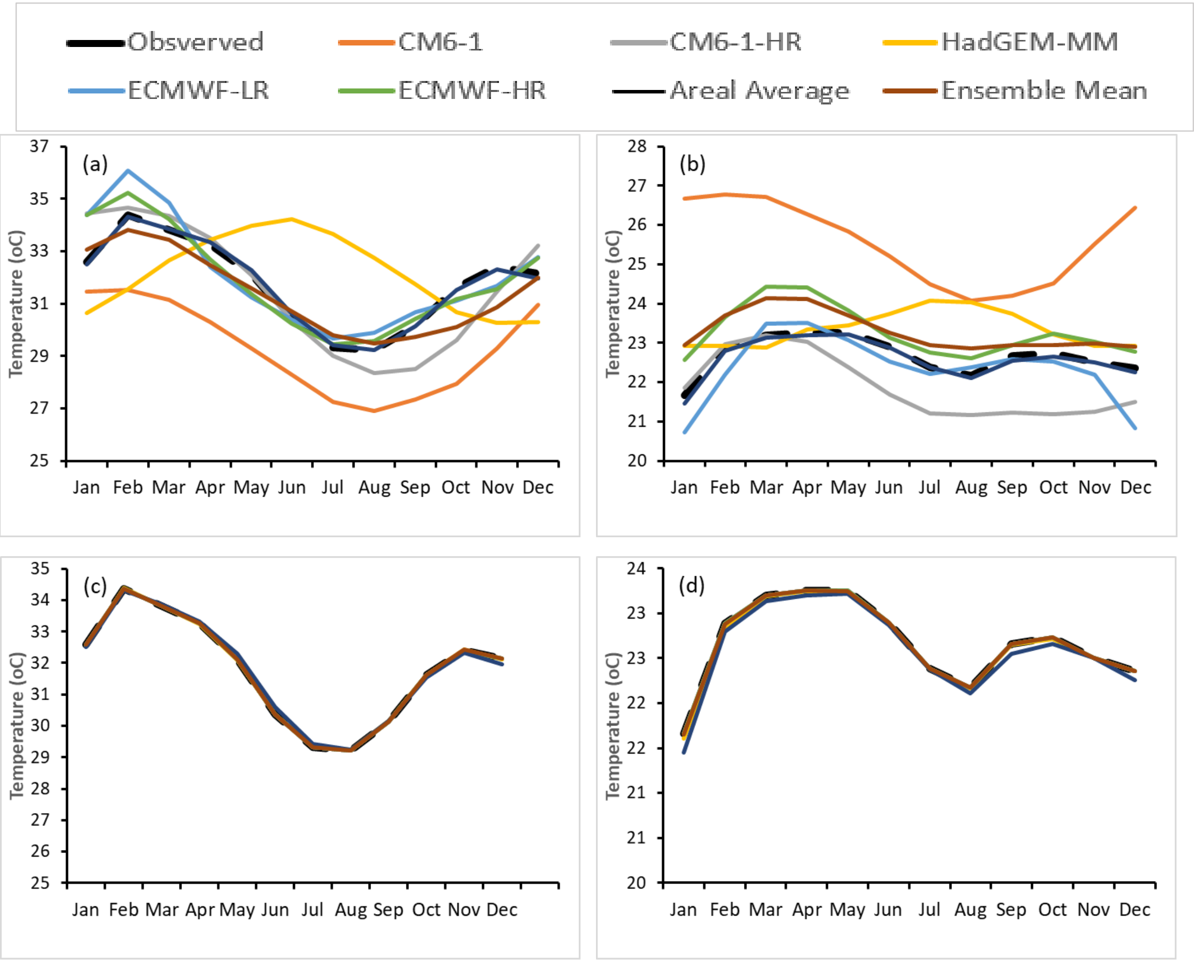


Figure10: Annual mean monthly CMIP6 simulated temperature for selected basin outlet at Twifo-Praso station with maximum temperature (a, c) and minimum temperature (b, d); and row 1 (a, b) Raw GCM data and row 2 (c, d) for bias-corrected for the historical period of 1985 – 2014 compared with observed maximum and minimum temperature for the Pra River Basin.

5.5. Predicted annual and seasonal change in precipitation

Figure 11 shows the predicted inter-annual mean changes of precipitation for the historical periods and the future years over the Pra basin spanning from 1985-2100 with best bias-corrected CMIP6 model, CNRM-CM6-1 under SSP2-4.5 and SSP5-8.5 in relation to the baseline period. It can be seen from the historical analysis that, the annual mean precipitation at the gauging station showed temporal variation with high and low precipitation events ranging between 3.05 - 5.19 mm. Similar observations were made from the mean areal precipitation covering the three climate stations used in this study. For the variation in precipitation under SSP2-4.5, precipitation is projected to also show variable temporal trends ranging between 2.84-5.74 mm. A similar prediction with CNRM-CM6-1 is made for precipitation change under the SSP5-8.5 scenarios. This result is in agreement with research by (Almazroui et al., 2020) for projected precipitation change over West Africa using CMIP6 and gridded precipitation dataset. From the precipitation projection, precipitation showed a decreasing trend under SSP2-4.5 and SSP5-8.5 at the latter part of 21st century specifically within the period of 2091-2100. However, for precipitation projection with CM6-1 under SSP5-8.5 showed more seasonal variation. Also, from the predicted analysis under both scenarios, precipitation is expected to decrease between the period of 2040 to 2060.

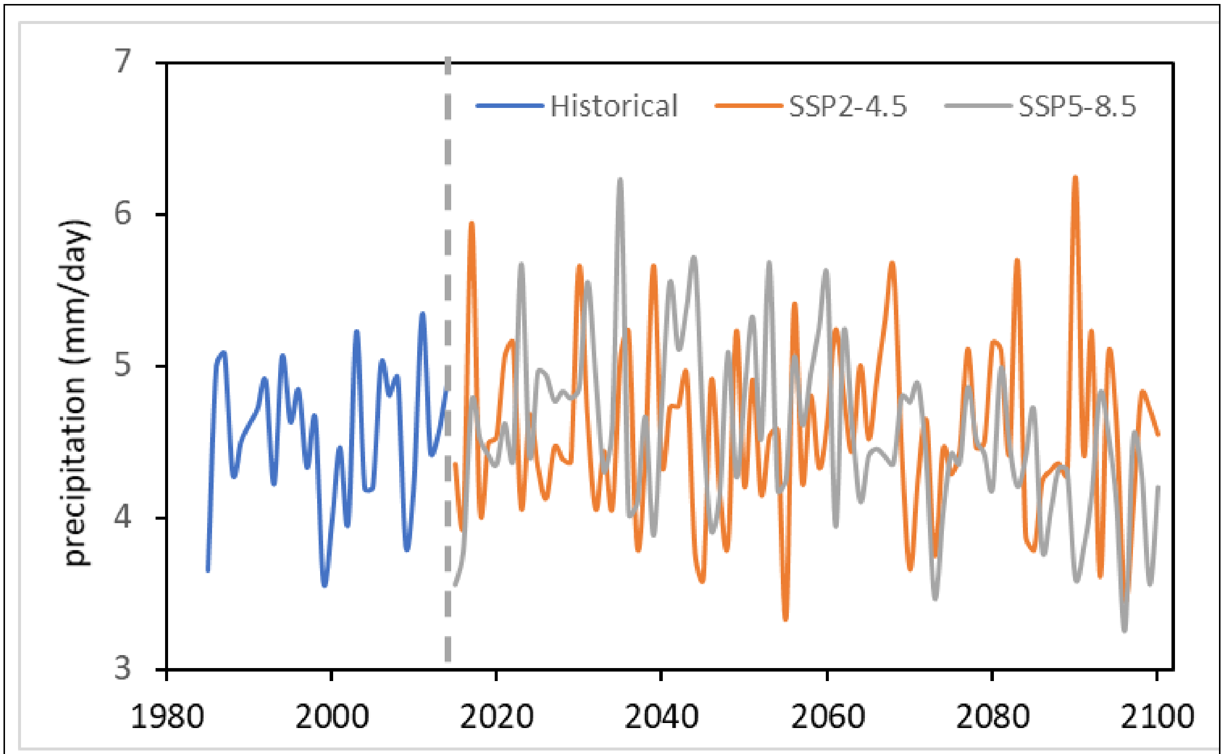


Figure11: The annual precipitation for the historical period (1985–2014) and future climate (2015–2100) under SSP2-4.5 and SSP5-8.5 scenarios

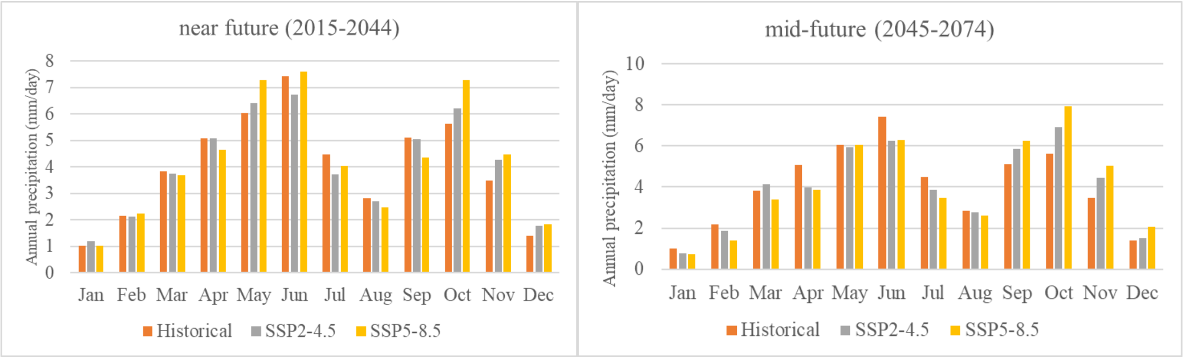


Figure 12: Seasonal variation between simulated CNRM-CM6-1 precipitation (2015-2100) under SSP2-4.5 and SSP5-8.5 scenarios and the historical period (1985-2014) at the Pra basin selected outlet

The temporal seasonal distribution of change in precipitation for the study region under two emission scenarios (SSP2 and 5) are shown in **Figure 12.** A 30 year each of historical (1985-2014) and simulated precipitation covering the near-future (2015-2044) and mid-future (2045-2074) were used in assessing the seasonal trends in future precipitation. The distribution of precipitation follows the normal rainfall distribution pattern of Ghana where maximum rainfall is usually recorded within the mid-months of May, June July and latter months October and November whereas low amount of rainfall is normally seen in the month December, January, and February (DJF) and sometimes in August. The capability of the CNRM-CM6-1 models to capture this rainfall patterns shows its robustness for simulating future precipitation within the West African basins, including our study area. However, the models under both SSPs showed an increase in rainfall for the SOND period (September, October, November, December), indicating, more rainfall is likely to occur in future within these months. In this research, seasonal precipitation prediction for the study area for the first six months (January-June) shows high prediction values under SSP2-4.5 while the last six months have larger precipitation changes by the model predicted under SSP5-8.5. In climate change analysis, relying solely on the mean of simulated precipitation and temperature over a given area or basin may not reveal other important aspects of the climate change. That is whether the climate data predicted by the model is sufficient enough for use in climate change impacts on hydrological analysis (Ajibola et al., 2020). Especially, if the simulated climate may likely increase or decrease within a specified climate period. Hence, performing relative change analysis on the modelled climate data is important.

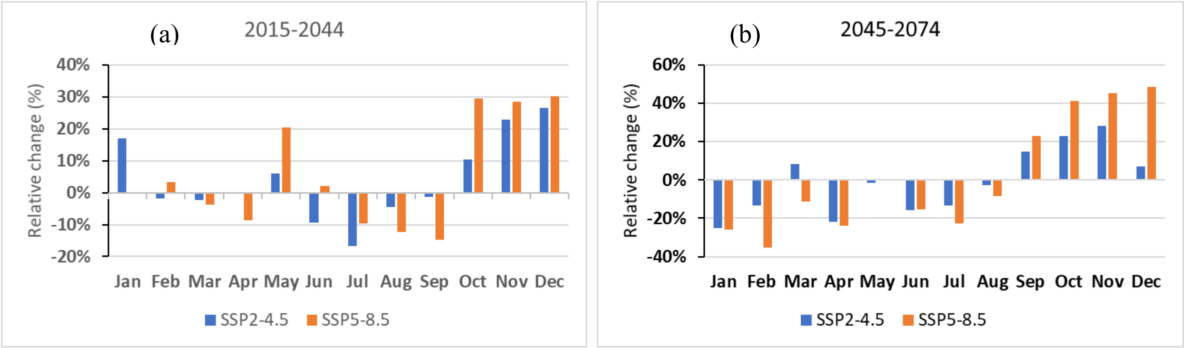


Figure 13:Change in seasonal precipitation for the (a) near-future and (b) mid-future period in relation to the historical period

Figure 13 shows the high temporal variability in projected change in precipitation in relation to the baseline period over the study area. This confirms the result of (Almazroui et al., 2020) when they found large seasonal precipitation variation and dependency of 21 century projected precipitation over Africa.

The high temporal change in precipitation in expected in the near-future (2030s) with a 1.1% and 5.1% of change in precipitation for ssp2-4.5 and SSP5-8.5 scenarios respectively (**Figure 14**). However, in the mid-future (2050s), precipitation showed a decreasing change at -0.2% under SSP2-4.5. On the other hand, the model predicted a decrease in percent precipitation change between January and August due to the annual seasonal variation. However, an increasing change in precipitation is simulated between September to December for both change scenarios, SSP2-4.5 and SSP5-8.5. The decreasing trend in projected precipitation over the Pra basin was also observed by (Gyamfi, Tindan, & Kifanyi, 2021) utilizing the ensemble mean of multi-Regional Climate Models of CORDEX Africa.

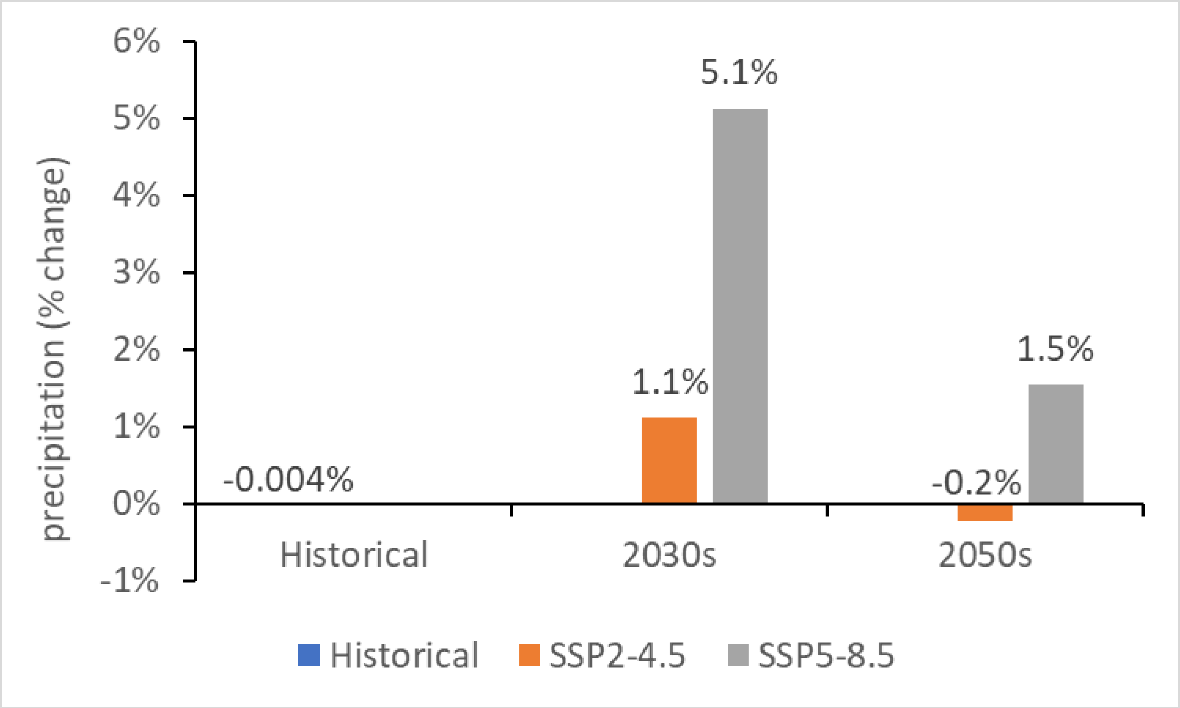


Figure14: Annual change in average precipitation for future scenarios in relation to the baseline period

5.6. Predicted annual and seasonal change in temperature

Figure 15 depicts the time series of annual mean maximum and minimum baseline and simulated temperature of CNRM-CM6-1 of CMIP6 GCM under SSP2-4.5 and SSP5-8.5, that was historically bias-corrected utilizing the Distribution mapping method implemented in CMhyd software. The historically bias-corrected temperature covers the periods of 1985-2015 while the projected temperature covers the period between 2015-2100. The resulting temperature (max and min) showed diverse variation for the historical period (1985-2014). Generally, continuous increasing trend could be observed for mean temperature under SSP2-4.5 and SSP5-8.5 scenarios for the projected temperature. This is consistent with Almazroui et al. (2020) results where they projected climate over West Africa utilizing CMIP6 models. However, temperature projections under SSP5-8.5 over the entire simulation period were higher than projections under the SSP2-4.5 emission scenarios. Similar results were obtained with CMIP6 multi-model ensembles under SSP2-4.5 and SSP5-8.5 by Supharatid & Nafung, (2021) over South-East Asia. Moreover, a similar trend could be observed in both scenarios for projected maximum **(Figure 15.a)** and minimum temperature **(Figure 15.b)** during the near-future period between 2015-2044. However, a distinction in projected temperature can be seen from the mid-century till the latter period which spans from 2045-2074 and 2075-2100 respectively.

The 30-year simulations periods under study in this research for the annual mean temperature (maximum (minimum)) is predicted to increase by 1.34 ^{o}C (1.56 ^{o}C) and 1.36 ^{o}C (1.61 ^{o}C) for the 2030s while a change of 2.45 ^{o}C (2.98 ^{o}C) and 3.43 ^{o}C (4.12 ^{o}C) for the 2050s under SSP2-4.5 and SSP5-8.5 scenarios respectively relative to the baseline.

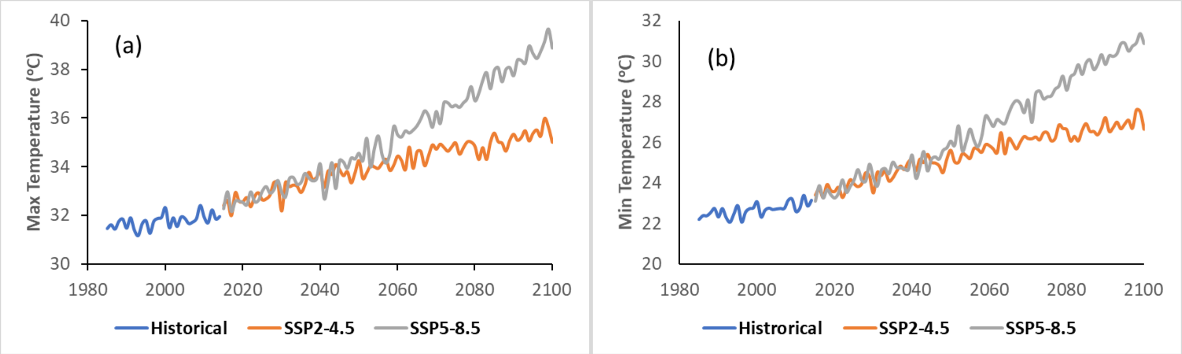


Figure 15: The annual temperature trend in historical period (1985–2014) and projected period (2015–2100) under SSP2-4.5 and SSP5-8.5 scenarios for (a) maximum temperature and (b) minimum temperature.

The seasonal changes in mean temperature for the baseline period and projected are shown in **Table 7**. Temperature in the Pra basin is projected to increase during the 2030s and 2050s period as positive relative changes were observed under both SSP2-4.5 and SSP5-8.5 scenarios for the different seasons. The average maximum temperature between 2015-2044 is projected to increase between 3.45 – 4.78% while the minimum temperature is predicted to increase between 4.78 – 11.98 % under SSP2-4.5. A high change in maximum temperature is projected under SSP5 during the mid-century ranging between 12.59% in MAM to 28.15% in December, January and February (DJF) season. Similar to results in Figure 15, the mean annual seasonal change in projected temperature under the emission scenarios in 2030s do not differ most. Moreover, they are showing a reduction in mean temperature for all seasons under study. Seasonal increase in projected minimum temperature under both scenarios and maximum temperature under SSP5-8.5 were higher in the DJF season. The minimum temperature during the dry season or winter months (DJF) will see an increase of 4.69 ^{o}C and 6.25 ^{o}C under SSP2-

4.5 and SSP-5-8.5 respectively relative to the historical period. Similar results were found for the maximum temperature in the winter months.

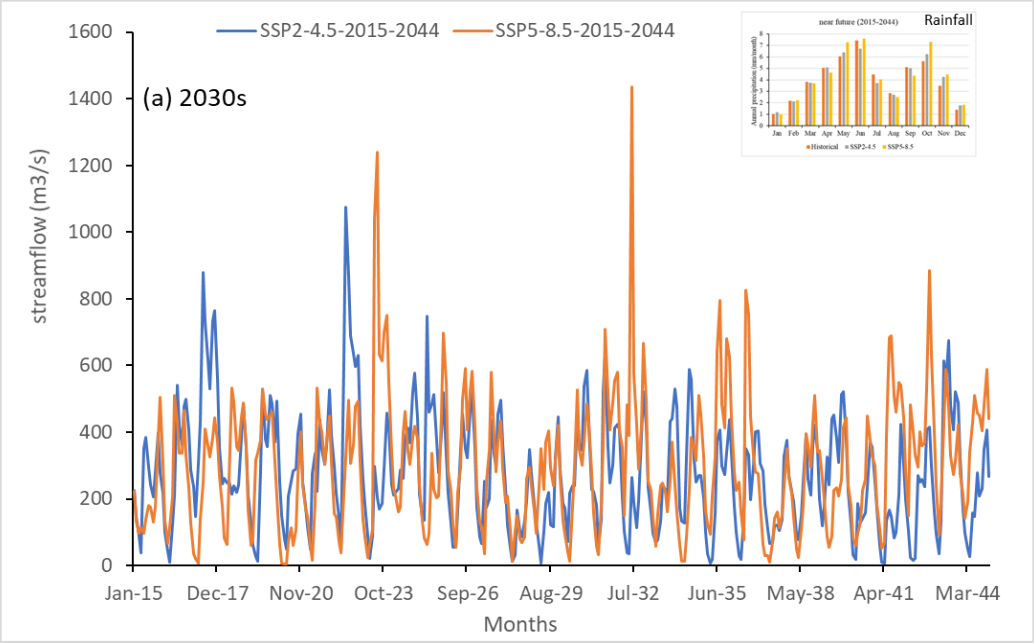
Also, a projected increase in maximum and minimum temperature at 3.43 ^{O}C and 4.12 ^{O}C under SSP5-8.5 at the end of the mid-century stipulates a warming effect. This increase in the average temperature is projected to increase until the end of the 21st century over Africa, showing a critical warming trend. This result is consistent with previous studies by (Coffey, Benham, Krometis, Wolfe, & Cummins, 2014; Tanteliniaina et al., 2021). They found a change in the annual and seasonal temperature to increase in the 21st century. Moreover, changes in projected temperature in 2060s under SSP-5-8.5 were high for all seasons. The mean change in temperature of 7.17% (4.09%) for 2030s while 7.74% (13.23%) for 2050s under SSP2-4.5 is projected for maximum and minimum temperature respectively. Likewise, under SSP5-8.5, the mean change of relative temperature is predicted for the 2030s at 4.09% (7.13%), and for 2050s at 18.25% (10.29%) maximum and minimum mean temperature, respectively to the baseline period.

Table 7: Projected changes in seasonal temperature for the historical period (1985–2014) and future period (2015–2100) under SSP2-4.5 and SSP5-8.5 scenarios for maximum temperature and minimum temperature; where; DJF-December-January; MAM- March-May: JJA-June-August; SON- September-November

		Maximum Temperature (%)				**Minimum Temperature (%)**			
		DJF	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**
Baseline (^{O}C)		33.03	33.07	29.65	31.39	22.30	23.24	22.49	22.63
2030s	ssp2-4.5	3.45	3.90	4.78	4.22	11.98	4.46	6.45	5.78
	ssp5-8.5	3.67	3.79	4.30	4.62	11.74	4.39	6.12	6.27
2060s	ssp2-4.5	6.69	7.45	8.89	7.92	21.15	8.68	12.2	10.9
	ssp5-8.5	28.15	12.59	17.01	15.25	14.62	7.85	10.23	8.45

5.7. Effects of climate change on discharge

The change in streamflow under SSP2-4.5 and SSP5-8.5 for the two simulation periods (2030s and 2050s) are discussed in this section. The calibrated SWAT model was used to assess further the impact of climate on the water availability, hydrological aspects, and streamflow dynamics within the Pra Basin. The best model predictor (CNRM-CM6-1) for historical climate and projected CNRM-CM6-1 climatology under SSP2-4.5 and SSP5-8.5 over the Pra Basin was chosen to assess the characteristic future impacts. However, in this research land-use map for the year 2010 (baseline map) was used in the future prediction because landcover change impacts was not considered. The projected streamflow of the Pra basin resulting from the effect of climate change under two emission scenarios (ssp2 and ssp5) are shown in **Figure 16**. The simulated streamflow showed a variable pattern for the given months and within the given time slices. However, the average monthly simulated streamflow, follows the trends influence by African Monsoon with high rain in summer and low rain in winter. High amount of discharge was projected in the rainy seasons (JJA) and low projected discharge in the dry season (DJF). The high projected discharges can be seen in the high peaks of **Figure 16** for both time slices under study. The projected large increment in discharges also corresponds with high rainfall recorded within the MAM, JJA and SON season over the basin.



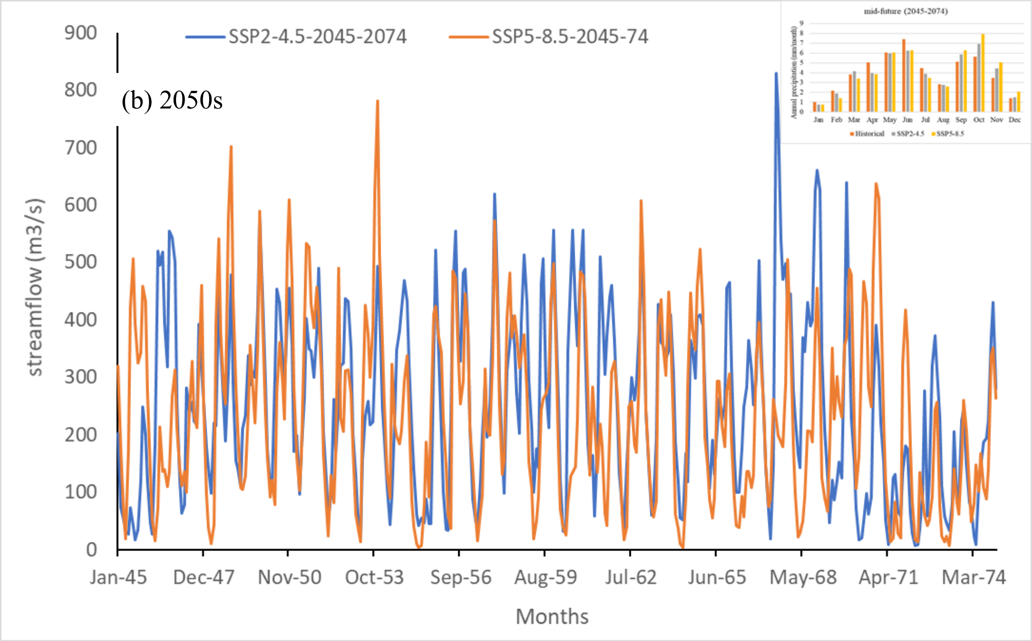


Figure 16: Projected streamflow dynamics compared in (a) 2015-2044 period (the near future) and (b) 2045-2074 period (mid-century) during the changes under SSP2-4.5 and SSP5-8.5 emission scenarios within the Pra Basin.

5.7.1. Seasonal changes in stream flow

In climate change effect on future streamflow analysis, judgement with only the mean of simulated discharge at the basin outlet may not reveal all the important aspects of the climate change effects as well as the different characteristics of the hydrologic flow regimes, including low flow and high flows as well probability of occurrence of hydrologic extreme events. Hence, it is vital to understand and evaluate whether the calibrated model (SWAT model) can simulate the future flow regime of the river basin under study. That is, if the simulated flow may likely increase or decrease within a specified future flow period. Hence, performing relative change analysis on the modelled future discharge is significant. **Figure 17** shows the seasonal trend in change in projected streamflow for the time slices (2030s and 2050s) under study relative to the historical period.

Figure 17: Change in seasonal streamflow for the (a) near-future (2015-2044) and (b) mid-future (2045-2074) period in relation to the historical period (1985-2014) over the Pra basin.

Figure 17 (a & b) shows that the major peaks of projected streamflow under the two emission scenarios and two different time slices follow a bimodal flow pattern influenced by the movement of the Inter-tropical Convergence Zone on rainfall and West African monsoon. Similar observations were also made for projected precipitation under the two emission scenarios following similar results by Mul et al., (2015).

Overall, a bias-corrected CMIP6 model mean of streamflow by the end of the 21st century is projected to decrease at about 20.8% under SSP2-4.5 and 28.2% under SSP5-8.5 and with a range between -32.7% to -7.4% and -39.6% to -10% under SSP2-4.5 SSP5-8.5 scenario respectively for the CNRM-CM6-1. Also, a decrease in mean annual discharge was also projected for the different time slices under study. For the near future (2030s), the mean of the relative change in projected streamflow was estimated at -10.1% and -3.8 % under SSP2-4.5 and SSP5-8.5 scenarios respectively. The change in projected streamflow, ranged between – 20.7 % to 2.9 % and -14.3 % to 8.6% under SSP2-4.5 and SSP5-8.5 for the near future time slice. Also, the annual mean in projected streamflow for the mid-future (2050s) was estimated at -19.6% and -25.54% under SSP2-4.5 and SSP5-8.5 scenarios while the mean of annual monthly of change in projected streamflow ranged between -34.4% to -3.8% and -38.6 % to -3.6% under the two emission scenarios (SSP2-4.5 and SSP5-8.5) respectively. The result of a decrease in mean annual change in projected streamflow is consistent with results of (Kankam-Yeboah et al., 2013), where they simulated climate change impacts over the Pra Basin utilizing ensemble of two global climate models over similar time frame (2006-2035 and 2036-2075). Moreover, a decreasing trend in the mean projected streamflow was obtained by (Osei et al., 2017; Osei, Amekudzi, et al., 2019; Sarah, 2019) over the Offin river basin, which is a sub-basin at the upper part of the Pra river basin. Furthermore, (Bessah, Raji, Taiwo, Agodzo, Ololade, et al., 2020) over the Pra basin with INVEST model and ensemble mean of five climate models projected a decreasing trend in seasonal water yield. In contrast, (Awotwi el. al 2021), observed an increasing trend for precipitation with an ensemble of CMIP5 GCMs. Similar observations were also made by (Bessah et. al 2020), but by applying their best bias-corrected model. However, (Oti et al., 2020) observed a decreasing trend in projected streamflow and average rainfall over the Densu river basin in Ghana which has similar hydro-climatological characteristics to that of the Pra basin. Therefore, the obtained results of a decreasing trends in projected streamflow calls for management and adaptations strategies to cope with the future menace as a result of increased temperature and reduced flow on people and the ecosystem functions of the basin.

In all the time slices, the higher change in projected streamflow was observed in the rainy season while the least change of projected streamflow was observed during the dry months (DJF). Moreover, the decrement in streamflow resulting from a decrease in seasonal precipitation was not significant than a precipitation decrease due to the linearity of the relative change in streamflow against a change in rainfall (Gu et al., 2018). Moreover, annual seasonal change in discharge was more temporally varied during the near future (2015-2044) than in the mid-century (2045-2074). Also, for the time slice of 2015 to 2044, only the month of June exhibited an increment in streamflow under SSP5-8.5 scenario and January for the SSP2-4.5 scenarios in relation to the historical period. However, all seasons showed a decrease in annual seasonal discharge for the period of 2045 to 2074, stipulating that, annual discharge measured at the Pra basin outlet may likely reduce getting to the end of 21st century. The large decrement in projected streamflow for the 2045 to 2074 stipulates large uncertainties of model projection of future streamflow.

5.8. Hydrological extreme events assessment

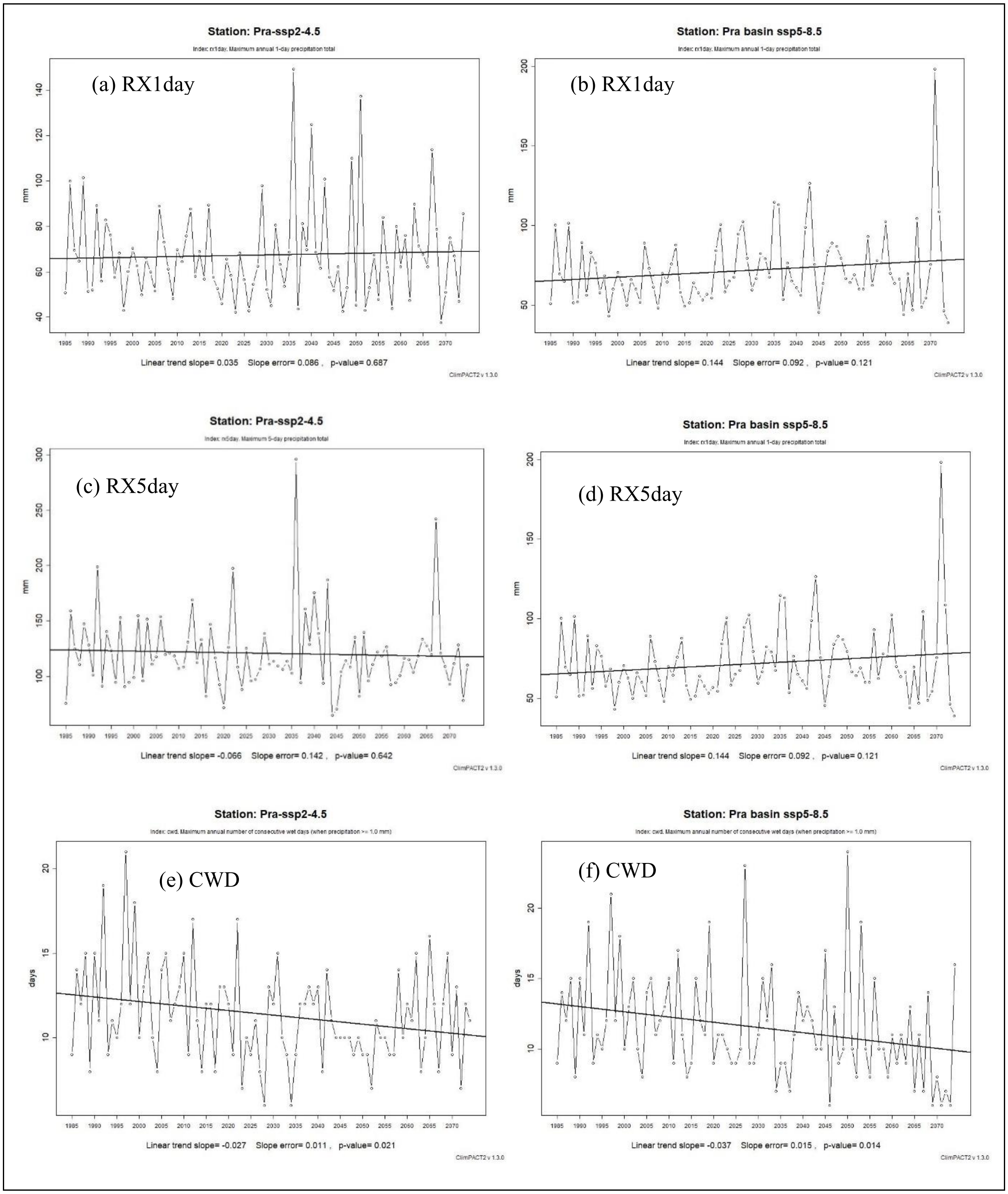
In climate change impact assessment, the most important tool developed primarily for the future impacts are the General Circulation Models (GCMs). The models simulates the response of climate to an increasing or decreasing greenhouse gas emissions (GHG) through climatic variable projections (Taye, Willems, & Block, 2015). There is a huge disparity in research assessing climate change impacts on extreme streamflow and extreme precipitation events within the West-African sub-basins. The focus of many researchers has been concentrated on future climate change impacts on precipitation while later attributing this change in precipitation to streamflow. Usually, this does not give a clear understanding on how a changing climate may affect future stream flow and reservoir volumes. Hence in recent years, other researchers have developed their own streamflow indices based on climate change impacts to assess the effects.

5.8.1. Climate change influence on extreme precipitation events

In this study, in order to quantify the effect of climate change on future precipitation, the annual Max 1-day precipitation amount (RX1day), Maximum consecutive 5-day rainfall (RX5day), Number of very heavy precipitation days (R20), Consecutive wet days (CWD), Consecutive dry days (CDD), and standardized precipitation index (SPI) were employed for the extreme precipitations events while flow duration curve is employed for extreme streamflow characteristics events within the basin. **Figure 18** shows the result of six precipitation indicators at the lower reaches of the gauge station located at the basin selected outlet.

Overall, the annual maximum 1-day (RX1day) and consecutive 5-day (RX5day) precipitation under both SSP-2-4.5 and SSP5-8.5 did not show any statically significant increasing or decreasing trend. RX1day over the Pra river by the end of the mid-century increased by 0.59 mm and 7.07 mm under SSP-2-4.5 and SSP5-8.5 respectively. However, RX5day will see an increase in precipitation under SSP5-8.55 by 10.98 mm while recording a decrease in annual consecutive 5-day precipitation by -4.0 mm. Also, consecutive wet days were projected to significantly decrease under both emission scenarios by about 1.5 days. On the other hand, consecutive dry weather conditions (CDD) were projected to increase by 1.5 and 2 days under SSP2-4.5 and SSP5-8.5 emission scenarios. Hence, confirming the results observed for the

CWD over the Pra basin. Also, the annual number of very heavy precipitation days (R20mm) is predicted to significantly increase. In all, the largest increase in precipitation was observed for RX1days and RX5days under SSP5-8.5, although these values were not significant statically due to high variability in projected precipitation under SSP5-8.5. However, incidence of flash floods is still plausible due to recorded cases of very heavy precipitation at certain periods.



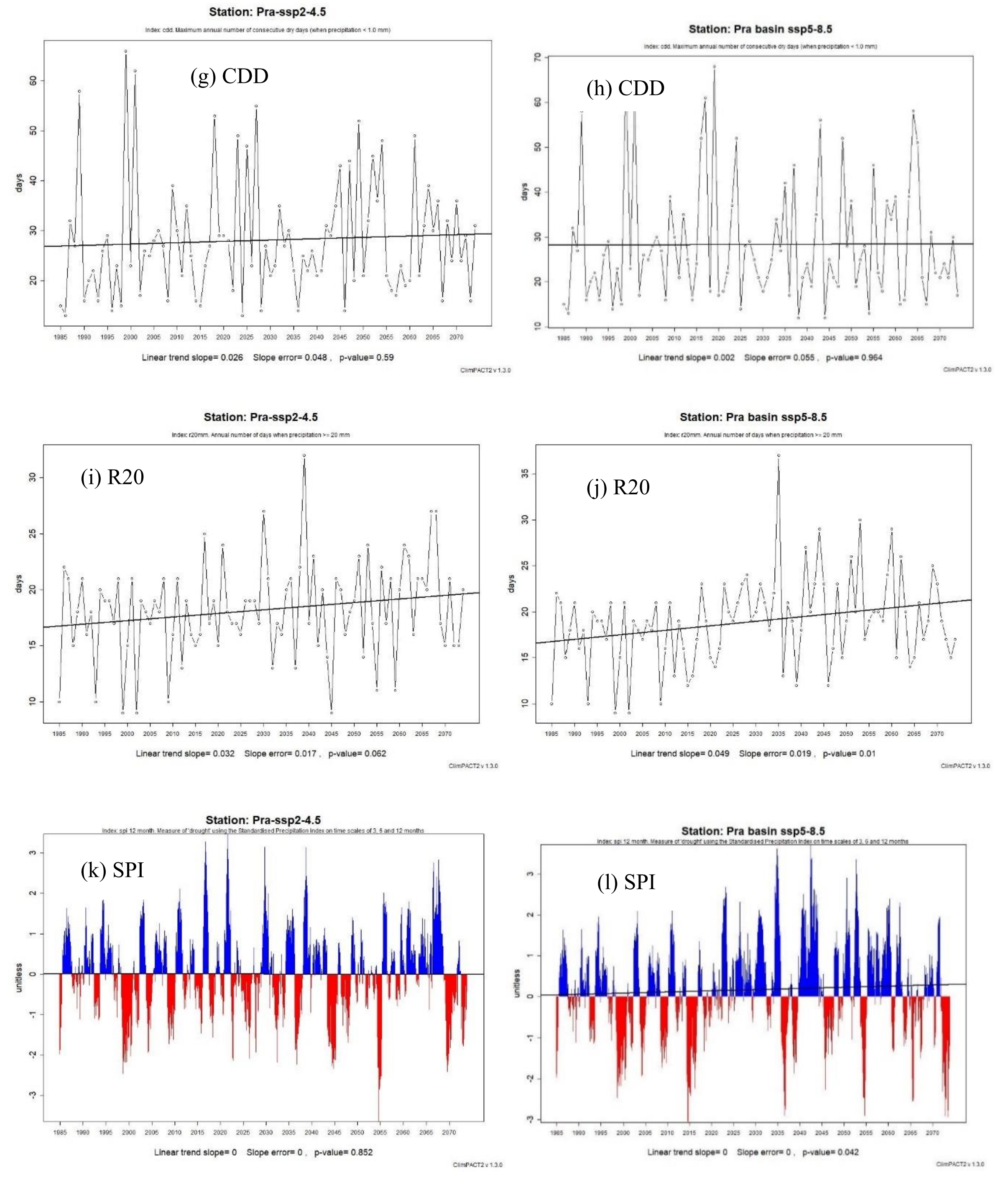


Figure 18: The observed spatial and temporal variations of extreme indices from 2015-2100.

5.8.2. Extreme streamflow assessment under future climate change

In this study, the impact of projected climate changes on the variation of future streamflow over the Pra basin was analysed through plotting of flow duration curve (FDC). Flow duration curves have had numerous applications in hydrological assessment for investigating dependable flows, which has its application in irrigation planning projects, hydro-power dams' structures or projects, and initializing of water resource developmental activities and projects (Tirupathi & Shashidhar, 2020). The FDC were plotted by utilizing the monthly simulated future streamflow at the selected basin outlet. Hence, the predicted daily streamflow was plotted with the corresponding probability of flow exceedance (See Appendix). In water developmental projects such as mini-hydro dams or reservoirs for irrigation, hydropower and water supply projects, 60 to 75% dependable yield is usually recommended for the reservoir simulation (Juharsyah, 2002). In water supply projects, India's Water Dispute Tribunal- II recommends a 65% (Q65) dependable flow (Tirupathi & Shashidhar, 2020). Also, for mini-hydropower plants for small scale irrigation projects, a 50% (Q50) dependable flow has been recommended in Indonesia (Zukhrufiyati, Triyono, Ginting, & Irianto, 2019). These dependable flow values help in the design as well as putting in place, protective measures against any odd catastrophic damages due to unexpected heavy precipitation resulting in flash floods.

The Pra river basin, is currently engulfed with water supply dams, mini-irrigation storage reservoirs and a proposed mini-hydropower projects at selected flow path destinations of the river basin. Hence, estimating the dependable flow will be important for the water managers and water-use stakeholders in future developmental, abstraction and use scenarios. The U.S Environmental Protection Agency (EPA, 2007) has proposed five (5) zonal intervals of streamflow duration curve to assess flow exceedance probability. The five zones developed by USEPA include "one representing high flows (0-10%), another for moist conditions (10- 40%), one covering mid-range flows (40-60%), another for dry conditions (60-90%), and one representing low flows (90-100%)". This approach was also adopted by (Tirupathi & Shashidhar, 2020) to assess climate impacts on extreme flows over the Krishan river basin. In this method, the 5th percentile corresponds to the middle range of high flows (0-10%) while the moist condition is centred at the 25th quartile. The normal or mid-range flows, dry weather flow conditions and very low flows are also placed at the 50th, 75th and 95th percentiles midpoints respectively (EPA, 2007).

The summary of important flow duration curve probability of exceedance values (**Figure 19**) together with projected annual, monthly, and daily streamflow are listed in **Table 8**. These parameters are mostly important for hydraulic structure designs, including flows with 95%, 50%, and 5% probability of exceedance. In all, the projected annual max/min, monthly max/min and daily max/min showed an increase during the mid-future under SSP5-8.5, while projection for the different periods under the other SSPs tends to decrease in future with respect to the historical period. In this study, a simple flood definition technique used by (Sharma & Shakya, 2005) and also employed by (Devkota & Gyawali, 2015; WEC, 2011) was first employed in this study to define flood events before the frequency and magnitude of floods were analysed. The researchers define flood the daily flow in which the maximum peak of flow is greater than the long-term of the mean daily flow added to the standard deviation given as (Qavg + Stdev) in **Table 8.** Hence, at the extremely high flow events, any mean daily extreme flow (Q10, 5, and Q1) greater than 510.57 mm, may be assumed to be of high probability to cause floods within the catchment if all other conditions remains the same.

From the **Table 8** and **Figure 19**, the probability of the magnitude and variability of very high flows (Q1 and Q5) could increase during the Near-future (2015-2044) and but will see a reduction in the Mid-future (2045-2074). This increase in high streamflow during the NF was estimated at 3.4 m3/s (0.58%) and 31.7 m^3/s (5.4%) for Q5 under both scenarios (ssp2 and ssp5) respectively. Also, projected increase in high streamflow for Q1 is estimated to increase at about 78.82 m3/s (10.56%) under SSP2 and 13.47 m3/s (13.47%) under SSP5 w.r.t the baseline period. However, projected changes in low flows under all SSPs will see a decrease. Hence, these changes in projected high flow and the FDC predicts that the variability and magnitude of floods may increase in the near future due to increase in Q1 and Q5 under SSP5. Also, very extreme dry flow, including Q98, Q95 and Q90 decreasing, signifies the probability of drought in future is plausible as it was shown by an increasing CDD and decreasing CWD during the extreme indices analysis.

Table 8: Comparison of Annual, Monthly and Daily flow statistics of historical and projected flow

Flow Variable	observed	Projected CNRM-CM6-1			
	1985-2014	2015-2044		2045-2074	
	Baseline	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Annual maximum	424.3	519.4	507.1	388.4	374.1
Annual minimum	132.4	146.7	129.4	93.5	93.0
Monthly maximum	865.4	1075.0	1436.0	829.1	780.7
Monthly minimum	4.301	6.1	4.4	7.4	4.0
Daily maximum	4846	3513	8903	3214	3238
Daily minimum	3.4	3.2	2.6	2.8	2.9
Qdavg	307.8	276.72	298.97	251.78	232.98
Qavg + Stdev	510.57				
Q98	21.8	12.6	10.3	15.5	8.7
Q95	42.7	25.1	27.7	27.9	16.1
Q90	75.5	58.2	60.1	46.7	37.4
Q65	214.5	186.0	202.0	163.1	136.3
Q60	245.6	209.7	226.0	189.5	160.5
Q50	304.0	250.9	279.3	233.5	212.8
Q10	539.4	504.9	536.6	471.4	455.0
Q5	586.2	589.6	617.9	528.7	518.5
Q1	746.7	825.5	847.3	652.5	662.0
Q0.1	1839.5	1524.6	3271.4	1487.7	911.1

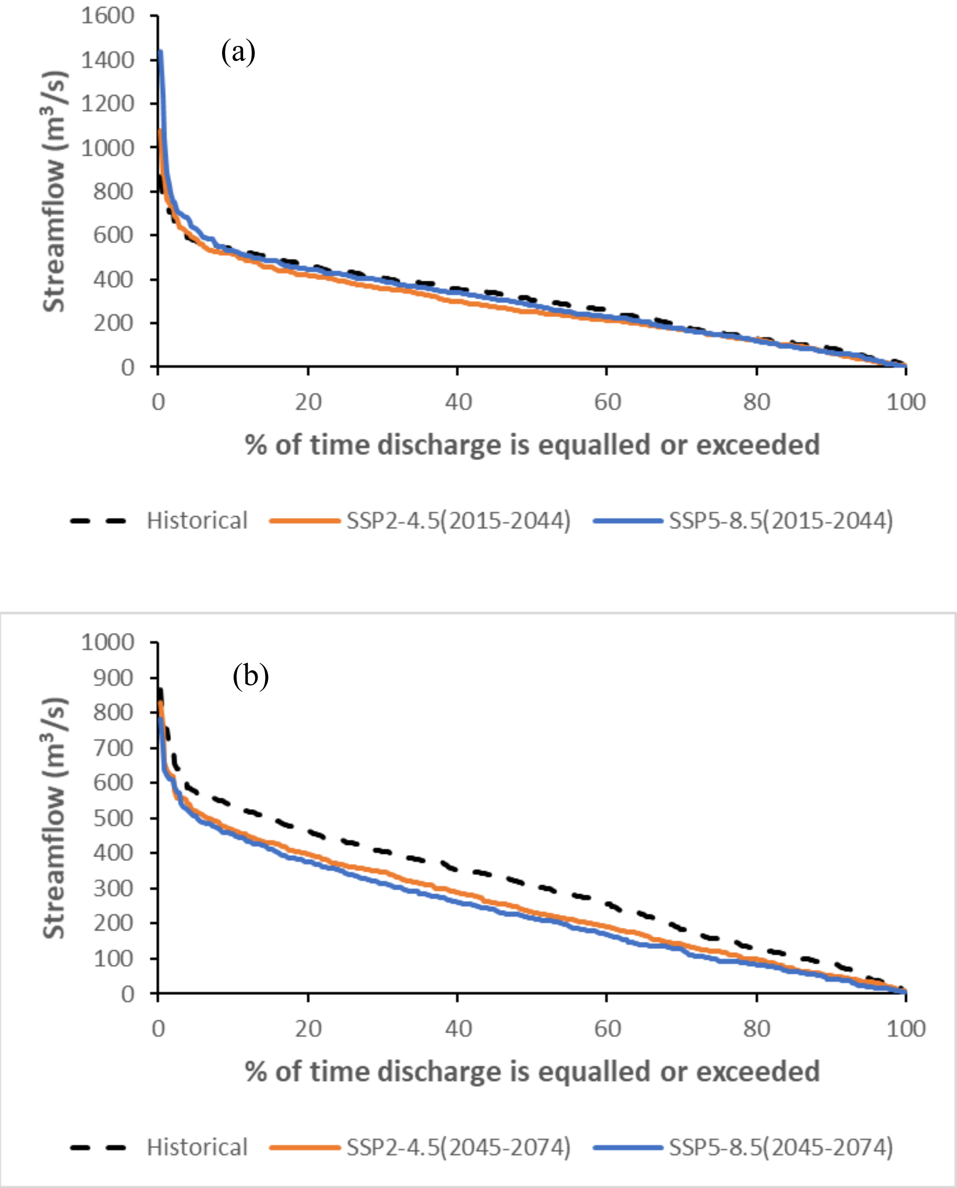


Figure 19: Flow duration curve of the Pra river basin under present and future scenarios at the outlet

5.8.3. Quantifying the difference in extreme discharge simulated under the two climate scenarios

In this research, to further quantify the period in which the annual maxima extreme discharge events (low and high flows) in relation to the baseline period are likely to reoccur, the extreme value type I distribution was employed and used. Under both SPPs, an increase streamflow corresponds to a higher return period (**Figure 20**). Hence, it is projected that in future, the magnitude of flood events will increase and may even increase more in relation to high return periods. For a 100-year return period, flooding events are reinforced due to an increasing discharge volume at about 1.3 and 1.4 times under SSP2 and 1.1 and 1.0 times under SSP5 resulting from increased precipitation at the same return period projected for the Near-future and Mid-future respectively. Hence, the design of hydraulic structures downstream of the river basin for flood protection and the management of the water resource may be affected

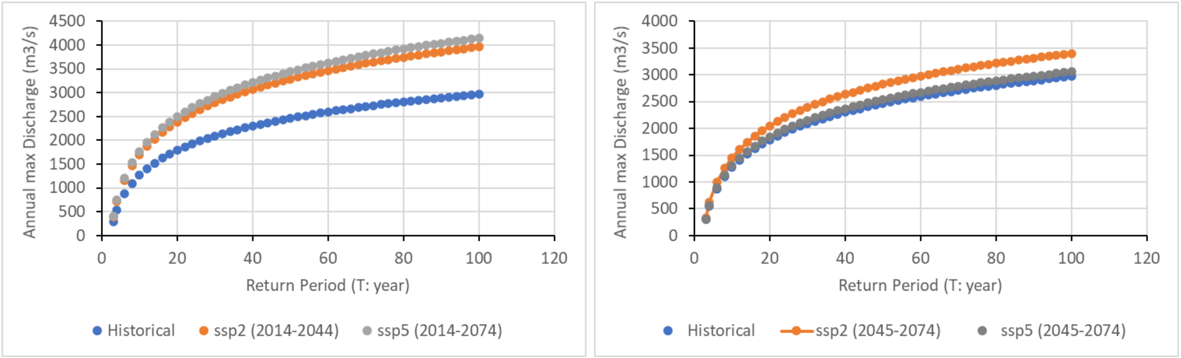


Figure 20: Different return periods by type I EVI for Historical and Projected streamflow under SSP2-4.5 and SSP5-8.5 emission scenarios

CHAPTER VI

6. CONCLUSION AND RECOMMENDATIONS

This research investigated the response of hydrological regimes and hydrologic extremes in relation to climate change in the River Pra Basin by employing five (5) new Coupled Model Intercomparison Project (CMIP6) GCM under two emission SSP2-4.5 and SSP5-8.5 scenarios. The selection of CMIP6 for climate change projection and impact assessment is because it comes with climate models of high spatial variability with some at even a higher spatial scale than regionally downscaled CMIP5 models especially the HighResMIP GCMs. Although, most of the CMIP6 climate used in this study comes with high resolution there have been reported cases of biasness between GCM simulated climate data and hydro-climatic observed data. In this study, the climate models used (CM6-1-HR, ECMWF-LR, CM6-1, HadGEM3-MM and EC-MW-HR) either showed overestimation or underestimation while others showed a shift in peak between simulated and the observed precipitation and temperature data. Hence, GCM simulated precipitation data was subjected to Linear scaling correction technique (multiplicative) while distribution mapping bias correction technique was used for bias-correcting maximum and minimum simulated temperature data over the Pra basin by employing CMhyd software. CNRM-CM6-1 climate model with the best bias correction statistical measures was selected and used for the climate change impacts on hydrology within the Pra basin. Also, SWAT model was employed for use in the hydrological simulation of future streamflow over the Pra basin. The SWAT model input parameters important for assessing hydrologic response and extreme hydrologic conditions include; rainfall, temperature, soil data, land-use/landcover map, digital elevation model map (DEM). Rain and Temperature data were obtained from responsible Authorities in Ghana while the others were downloadable online. In assessing the hydrological extreme events variation in Pra river basin, extreme indices including RX1DAY, RX5day, R20, CWD and CDD were employed. Also, flow duration curves and return period estimation were done by employing extreme value type I distribution for analysing extreme streamflow events.

6.1. CONCLUSION

In this research we investigated the response of hydrological processes and hydrologic extremes in relation to climate change in the River Pra Basin by employing the new Coupled Model Intercomparison Project (CMIP6) GCM for two time slices, near future (2030s) and mid future (2050s) under two emission scenarios SSP2-4.5 and SSP5-8.5.

SWAT model was calibrated in a monthly time step and the obtained statistical summary results for monthly calibration between simulated and observed flow were deemed good with R^2 and NSE greater than 0.6 while PBIAS < ±25%. For the calibration data run, values obtained were 0.69, 0.71 and -2.0% while for the validation data sets, 0.64, 0.65 and 3.6% were obtain for NSE, R^2 and PBIAS respectively. Hence, model was deemed satisfactory for future flow simulations over the Pra Basin. The result of the annual hydrologic aspects simulation by the calibrated SWAT model shows that, the predominant factors responsible for water loss within the Pra basin were evapotranspiration and surface runoff estimated as 864.88 mm (60%) and 185.85mm (13%) respectively. It was also found that the major peaks of precipitation follow a bimodal rainfall pattern influenced by the Inter-tropical Convergence Zone. However, surface runoff contributed most to water yield measured at the designated Pra basin outlet.

Moreover, the effect of climate change on discharge was also analysed. The mean flow by the end of the 21st century was projected to decrease at about 20.8% under SSP2-4.5 and 28.2% under SSP5-8.5 respectively for the CNRM-CM6-1 bias-corrected simulated climate data. Also, the major peaks of projected streamflow under the two emission scenarios and two different time slices (2030s and 2050s) follow a bimodal flow pattern influenced by the Inter-tropical Convergence Zone on rainfall. Also, all seasons showed a decrease in annual seasonal discharge for the period of 2045 to 2074, stipulating that, annual discharge measured at the Pra basin outlet may likely reduce getting to the end of 21st century.

The result of the potential impact of climate change on the variation in temperature and precipitation was assessed. It was found that, a continuous increasing trend was observed for mean temperature under SSP2-4.5 and SSP5-8.5 scenarios for the projected temperature. The average maximum temperature between the period of 2015-2044 is projected to increase between 3.45 – 4.78% while minimum temperature is predicted to increase between 4.78 – 11.98 % under SSP2-4.5. A high change in maximum temperature was projected under SSP5 during the mid-century ranging between 12.59% in MAM to 28.15% in DJF season. In all, a high increase in minimum temperature was projected compared to increase in maximum temperature. Furthermore, the effect of climate change on precipitation revealed that, a change in projected monthly precipitation show variable temporal trends ranging between 2.84-5.74 mm under both SSP2-4.5 and SSP5-8.5 and with more seasonal variation in change in precipitation projected under SSP5-8.5. Also, precipitation showed a decreasing trend especially at the end of the 21st century. In contrast, more precipitation is likely to occur in future within these SON season since model prediction under both SSPs shown an increase in precipitation. Hence a uni-modal rainfall pattern as opposed to the bi-modal pattern is expected in future over the basin. In all, a high temporal change in precipitation in expected in the near-future (2030s) with a 1.1% and 5.1% of change in precipitation for SSP2-4.5 and SSP5-8.5 scenarios respectively while in 2050s, SSP5 projected an increase in change in precipitation at about 1.5 % under SSP5 while a decrease under SSP2-4.5 at about -0.2% relative to the baseline period. Hence, although a decreasing trend is observed in projected precipitation, the annual projected change in precipitation may increase under both SSPs for the 21st century except for projection under SSP2 for the late 21st century.

Finally, all the extreme precipitation indices used in this study did not show any statically significant increasing or decreasing trend. A decrease in CWD but an increase in CDD confirms the decreasing trend in precipitation at the gauge station. However, an increase in R20 mm signifies potential of heavy precipitation and likelihood of flash flood being recorded although precipitation may be decreasing during the near and mid-fututre. Furthermore, the analysis of hydrologic flow regimes based on flow frequency duration curve for extreme streamflow assessment revealed that the variability and magnitude of floods may increase in the near future due to increase in Q1(13.5%) and Q5 (5.4%) under SSP5. On the other hand, projected changes in low flows under all SSPs may see a decrease, hence the magnitude of drought may also likely increase at certain periods in future. Finally, for a 100-year return period, flooding events are reinforced due to an increasing discharge volume for the 2030s (at about 1.3 and 1.4 times) and 2050s (1.1 and 1.0 times) resulting from increased precipitation at the same return period projected under SSP2-4.5 and SSP5-8.5 respectively. Hence flood mitigation measures as well as proper water resources management strategies must be ensured to avoid any catastrophes downstream of the basin as well as the implementation of Pra River Basin Integrated Water Resources Management Plan IWRM).

6.2. RECOMMENDATIONS

The following recommendation have been drawn in relation to the study results for future works and measures that ensure effective basin management.

1. The approach is simulating climate impact on hydrologic processes and streamflow based on only one GCM, hence an ensemble of different climate models could be used in the prediction to ascertain the CMIP6 models performance in the study area and for subsequent usage in other watersheds.

2. The use of only climate variables (temperature and precipitation) are not the only responsive factors on hydrological extremes. Land-use change as well as other human interferences on basin management also plays significant impact. Hence, incorporating this as well as conservation practices in future models will help assess their affect together with climate variables on hydrologic regimes, future stream flows and hydrologic extremes.

3. It can be understood from the activities ongoing within the catchment that watershed management alone would not be able to keep the reservoirs sustainable, however a combination of reservoir sediment management and watershed management can help preserve reservoir capacities.

4. There is a need to embark on regular educational programmes focused at sensitizing local communities on good environmental practices to protect further land use change and sustain good ecosystem. Other regulatory bodies and agencies should make bold attempts to enforce environmental regulations at the local level to protect the reservoirs.

5. In all, this research proposes putting in place flood mitigation measures as well as ensuring proper water resources management strategies and plans to avoid any catastrophes downstream of the basin through proper and accurate selection of structural and non-structural measures for climate impact mitigation in water resources system.

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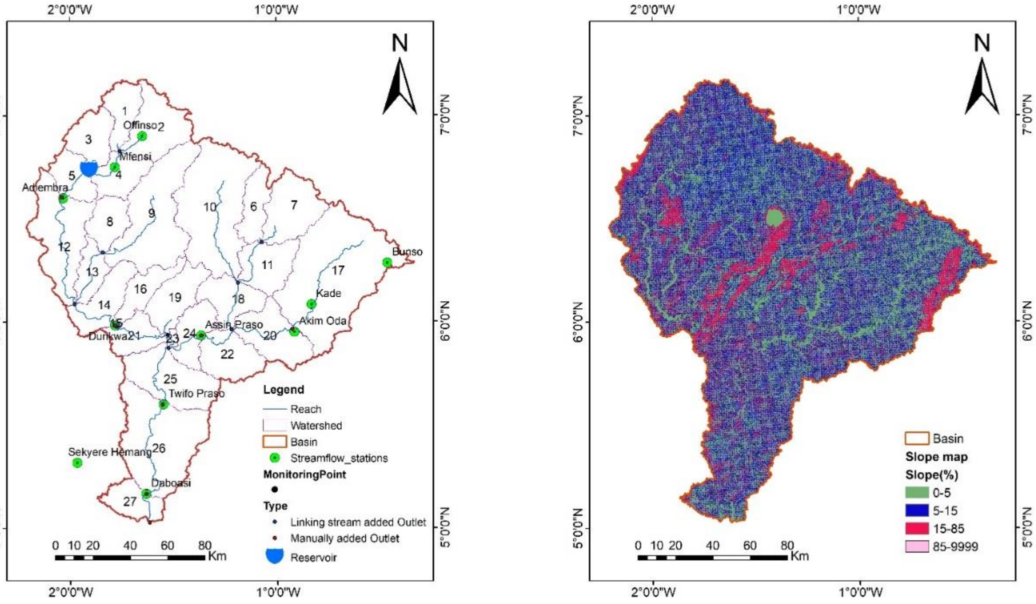
APPENDIX



Figures Showing sub-basins with dam and Slope of Pra Basin

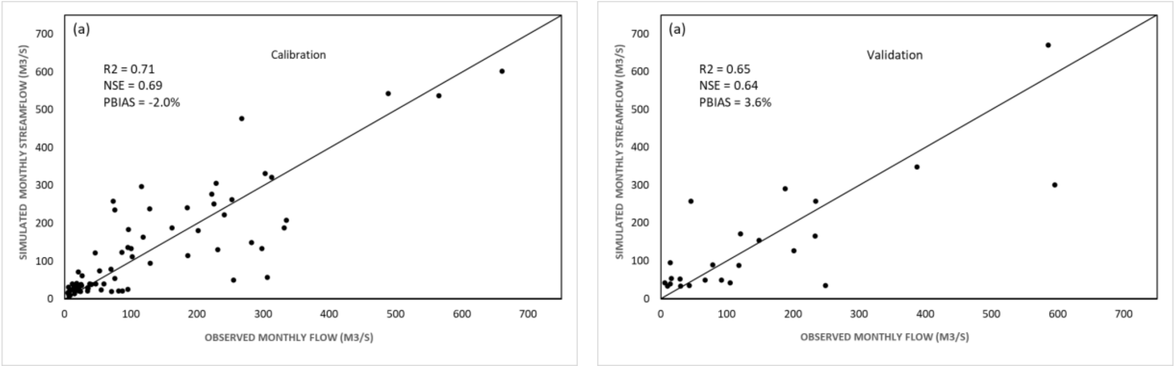


Figure showing Statistical summary of model (a) Calibration (b) Validation

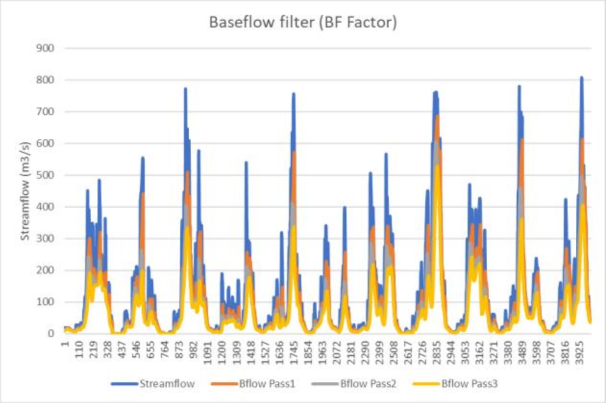


Figure showing baseline filter separation factor

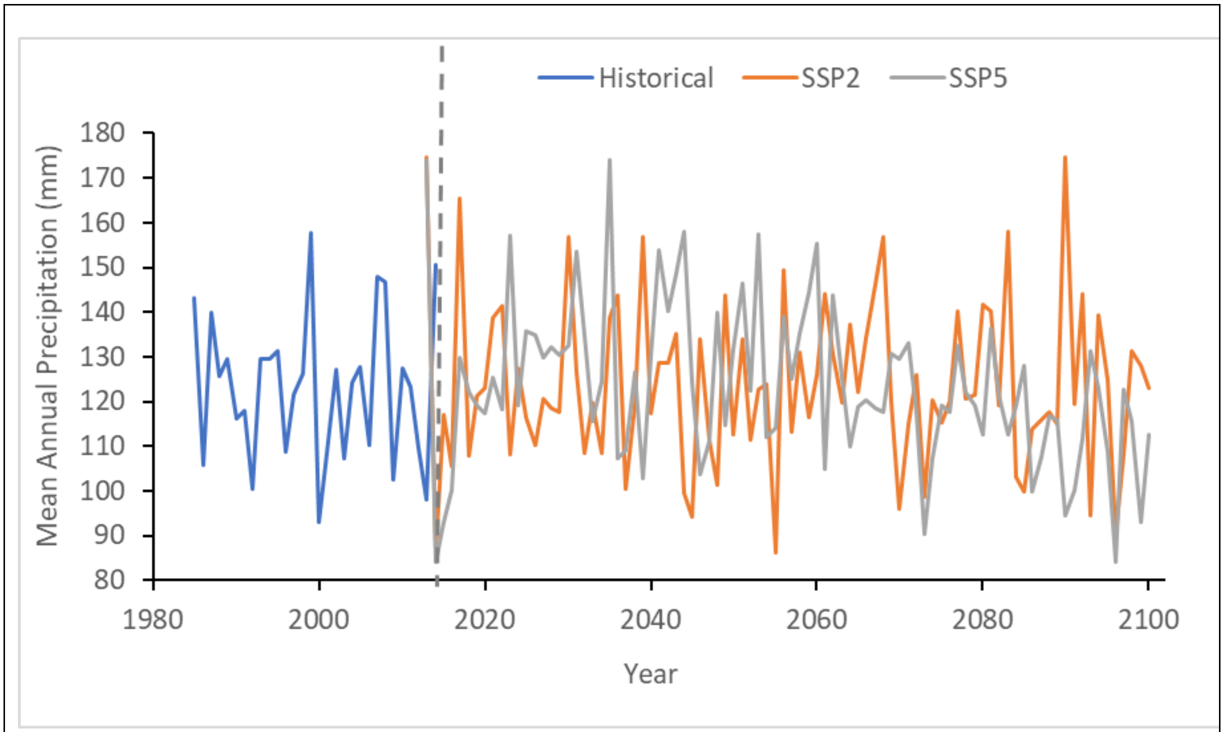


Figure showing historical and predicted trend of Mean Annual Precipitation

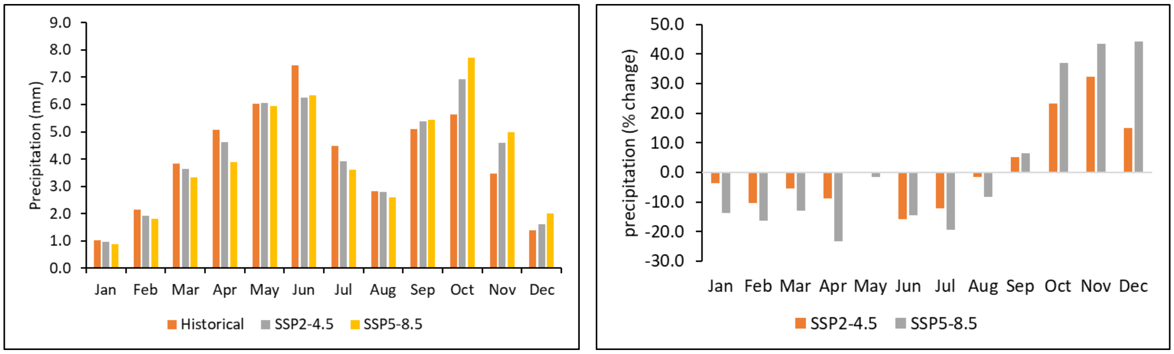
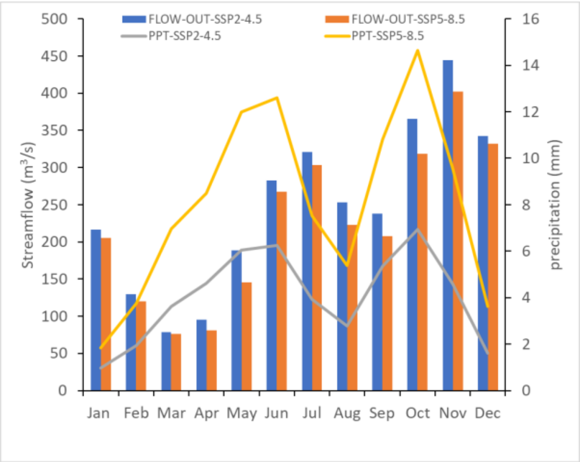
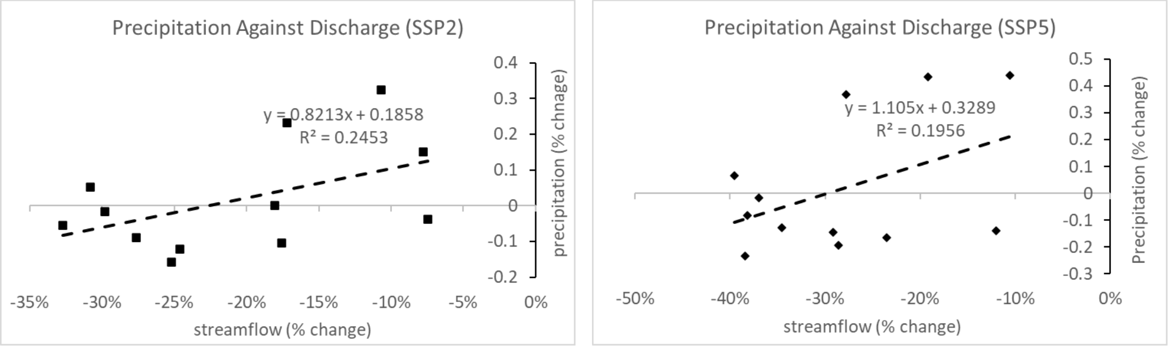


Figure showing seasonal trends in (a) projected precipitation (2015 – 2100) and (b) the relative change in precipitation w.r.t Historical period (1985 - 2014)



Figures show mean seasonal variation in streamflow and precipitation for the period between 2015 - 2100



Figures showing change in streamflow plotted against precipitation over the Pra river basin covering the period between 2015 to 2100 under SSP2-4.5 and SSP5-8.5 scenarios.

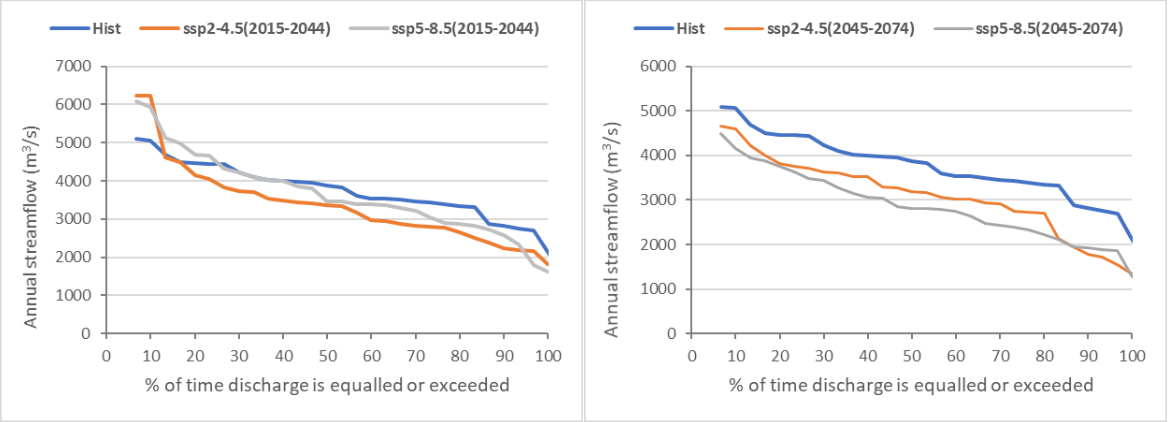


Figure showing maximum Annual flow duration curve and probability of exceedance

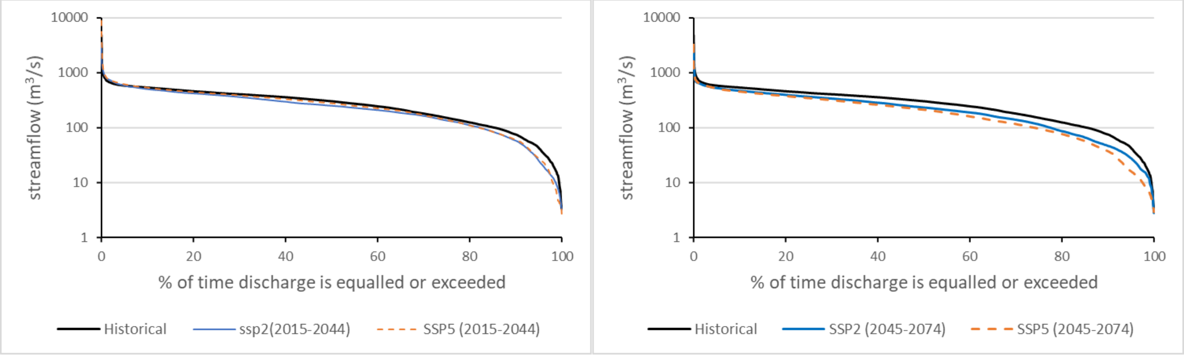


Figure showing maximum daily flow duration curve and probability of exceedance

SIGNATURES

Amos T. Kabo-bah, Ph.D.	Collins Acheampong
October 20 , 2021	October 20, 2021
Supervisor	Student