



Research article

Hydrologic response to climate change in the Densu River Basin in Ghana

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ABSTRACT

Climate change continues to pose a threat to the sustainability of water resources. Global warming can have several effects on the water resources and water demands in the Densu River Basin especially household water use and agriculture use among several others. However, the extents to which the hydrology of the Densu River Basin is will be altered in the future remains unknown. In this research, the Water Evaluation and Planning (WEAP21) system was used to study the impacts of future climate change on water resources in the Densu River Basin. Future climate data (rainfall and temperature) for the period 2051–2080 was generated from the Swedish Meteorological and Hydrological Institute's climate models (ICHEC-EC-EARTH and RCA4) for RCP4.5 scenario under CORDEX experiment. The results of the study indicate that the Densu River Basin will experience a temperature increase by 8.23% and a 17% reduction in rainfall resulting in 58.3% reduction in water resources in the area. The climate change impact analysis indicates a reduction in the river streamflow due to decrease in rainfall. It is recommended that future research on climate change adaptation for water management in the Densu River Basin should be conducted.

1. Introduction

Climate and water are connected in a complex way through several variables such as precipitation, temperature, and solar radiation, however, these conditions differ from region to region. The impacts of a change in any of these variables alter the hydrological cycle by increasing runoff, the intensity of rainfall and evaporation rate (Kabo-bah et al., 2014; Huang et al., 2014). These will be manifested in floods, drying-up of rivers, lakes, and water bodies, change in rainfall patterns and the occurrence of droughts (Faramarzi et al., 2013). The changing climate will increase strongly from decades with higher temperatures and extreme precipitation, resulting in declined water supplies, water quality and increased water demand (IPCC, 2014) with a severe impact on the Northern-Saharan communities. One of the key components of water resources is runoff and it will be highly impacted by climate change. Runoff is affected by changing of temperature and precipitation (Beyene et al., 2010). Due to importance of runoff for water supply a lot of research has been conducted to quantify the effects of climate change on runoff.

The impact of climate change and variability on water resources is evident across the globe (Seager et al., 2007; Bates et al., 2008; Lettenmaier et al., 2008; Pham et al., 2017) and this is expected to be worse on

the African continent (Niang et al., 2014). Africa is reported to experience future decrease in water availability resulting from range of drivers including climate change especially in the Northern and Southern Africa (Niang et al., 2014). The UNFCCC has reported increasing water stress for many countries within the African continent. The United Nation's report projects drying up and desertification especially in the Sahel and the Southern Africa (UNFCCC, 2007; UNESCO & UN Water, 2020). However, change in rainfall patterns in West Africa has affected runoff in the past years (Nicholson and Grist, 2001). The river discharge in West Africa is strongly influenced by variations in rainfall: there is three times reduction in runoff whenever there is a unit decline in rainfall (Mahe et al., 2013). The West African region is projected to experience an increase in temperature by the end of the 21st century, however, that of rainfall is uncertain (Niang et al., 2014; Roudier et al., 2014). The uncertainty of the rainfall events will have several effects on the water resources and water demands especially household water use, agriculture use and hydropower generation among several others (Peterson and Keller, 1990). The rise of the surface temperature and changes in patterns of rainfall will result in severe extreme weather events, including higher intensity rainfall events, increased/decreased streamflow conditions as well as increase in extreme high sea levels (UNFCCC, 2007; IPCC, 2014). These

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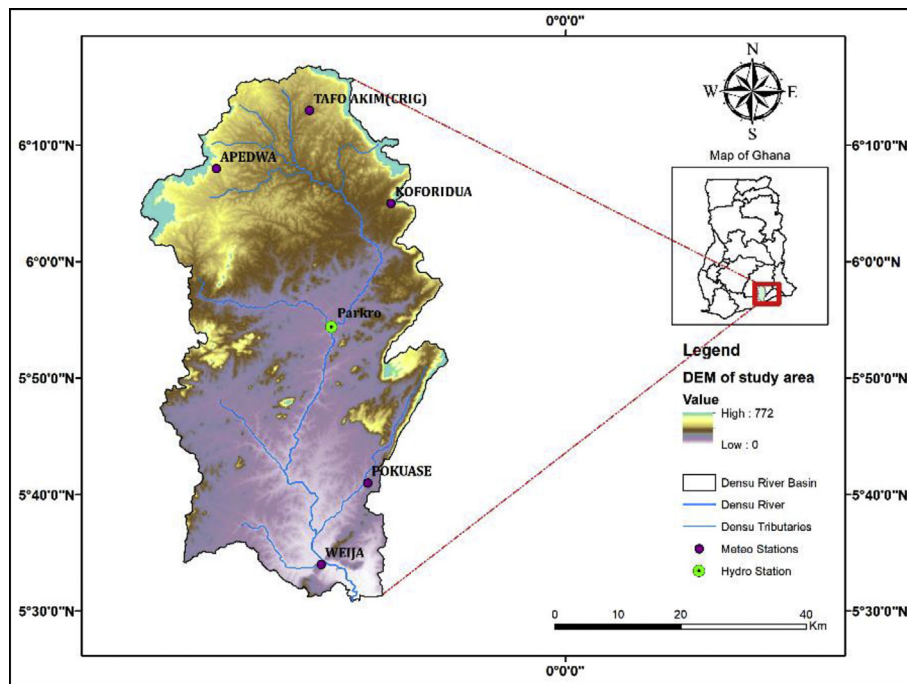


Figure 1. Map of the study area showing the DEM and river channels.

changes could affect the hydrological cycle, and it could have significant impacts on the availability (both quantity and quality) (IPCC, 2014; Hrdinka et al., 2015; Arsisoa et al., 2017) and distribution of water resources especially in Ghana (Gyau-Boakye and Tumbulto, 2006).

A study in the Volta Basin (McCartney et al., 2012) in Ghana showed significant decrease in annual rainfall by the middle of the twenty-first century. The same study observed a reduction in river discharges and mean groundwater recharge on major tributaries of the Volta River. In a research on some river basins in Ghana, the projection revealed an increase in temperature and decrease in rainfall for the 2020s and 2050s respectively in the White Volta and Pra basins. As a consequence, the mean annual streamflow in the White Volta and Pra basins were estimated to decrease by more than 20% for the 2020s and 2050s (Kankam-Yeboah et al., 2013). As the availability of fresh water is vital to the economic and social development of Ghana, it is very important to understand the relationship between climate change and water resources and how it will impact the water resources in order to design suitable policies to adapt.

This study, therefore, seeks to assess the impact of projected climate change on the river flows in the Densu River Basin of Ghana.

2. Materials and methods

2.1. Study area description

The research is carried out in the Densu River Basin in Ghana, West Africa (Figure 1). The Densu River Basin covers an area of about 2600km² located at the South Eastern part of Ghana and it lies within longitudes 0° 10'W – 0° 37'W and latitudes 5° 30' – 6° 17'N (Water Resources Commission, 2007). It spans through 12 Local Government Assemblies in the Central, Eastern and the Greater Accra region. The main Densu River takes its source from Atewa Range near Kibi and flows for 116 km into the Weija Reservoir before entering the Gulf of Guinea. With Odaw and Volta Basins to the east and north of the Densu River, it also shares its catchment boundary with the Birim in the northwest and the Ayensu and Okrudu in the west (Water Resources Commission, 2018). The main economic activities in the catchment are agriculture which includes the cultivation of crops and the raising of livestock and

fishing. Some crops cultivated in the area includes cocoa, maize, vegetables, pineapples, and cocoyam (Figures 1 and 2).

The Densu Basin has two distinct climatic zones: the relatively dry equatorial and the wet semi-equatorial climate. The dry climate is of the

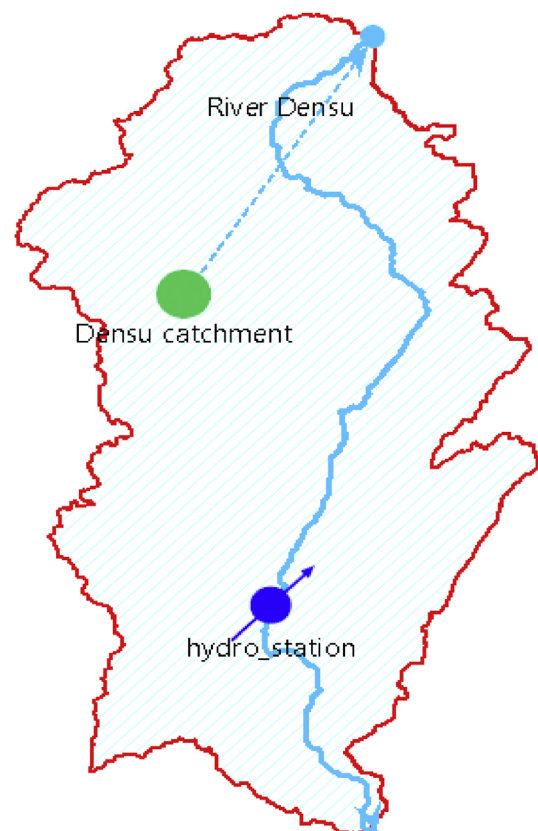


Figure 2. Schematic of WEAP model of the Densu river basin.

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

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

2.2. WEAP (Water Evaluation and Planning system) model

WEAP is developed by the Stockholm Environment Institute (SEI). WEAP is an easy-to-use model used to assist in water resources management. WEAP was developed to assess water demand and to evaluate water resource development projects, climate change impacts and water management scenarios (Seiber and Purkey, 2015). WEAP can be employed in different scales including agricultural systems, municipal systems as well as single catchments or complex transboundary river systems. It is one of the most used models for integrated water resources management. WEAP model is widely used to assess the impact of climate change in the future possible climate (Rosenzweig et al., 2004; Purkey et al., 2007; Alemayehu et al., 2010; Mehta et al., 2013; Santikayasa et al., 2015) and adaptation scenarios on water resources (Joyce et al., 2011). It has a user-friendly graphical user interface (GUI) which makes it easier to work around. It is straightforward, easy to use and can be downloaded at www.weap21.org.

WEAP can be used to simulate both hydrological processes and the effect of anthropogenic activities on water resources. WEAP calculates the hydrological cycle components by simulating the rainfall-runoff process on the catchment surface. The WEAP model contains four methods for simulating catchment processes. The methods include Irrigation Demands Only Method, Rainfall Runoff Method (Simplified Coefficient Method), Rainfall Runoff Method (Soil Moisture Method), and MABIA Method. These methods range from simple to complex and the choice of the method depends on the data availability and the purpose of the analysis. However, in this research, the Soil Moisture method was

used to assess the hydrological response of the Densu River Basin to the changing climate.

2.3. Soil moisture method

In the soil moisture method, the catchment is divided into two soil layers (control volumes) called buckets: an upper soil layer known as a shallow water capacity and a and a lower soil layer which represents deep water capacity (Figure 3). For a catchment which is sub-divided into several sub-catchments based on different fractional land use and/or soil type areas, a water balance is computed for each fraction area *j* for the first layer, assuming the climate is constant within each sub-catchment. The equation of the water balance is specified below (Seiber and Purkey, 2015).

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

where Z_{1j} is relative storage, based on the total effective storage of the root zone; Rd_j is the soil holding capacity of the land cover fraction *j* (mm); PET term is calculated using the modified Penman-Monteith reference crop potential evapotranspiration with the crop/plant coefficient ($k_{c,j}$) for each fractional land cover; P_e is the effective precipitation and RRF_j is the Runoff Resistance Factor of the land cover. Low and high values of RRF_j may cause more or less surface runoff respectively. $P_e(t)Z_{1j}^{RRF_j}$ is the surface runoff; $f_j k_{s,j} Z_{1j}^2$ is the interflow from the first layer; the term $k_{s,j}$ denotes the root zone saturated conductivity (mm/time) estimate and f_j is the partitioning coefficient that partitions water horizontally and vertically, based on the soil, type of land cover, and topography.

The change in storage of the second layer (dz_2/dt) is computed as:

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

where S_{max} is the deep percolation from the upper layer storage; and K_{s2} is the saturated hydraulic conductivity of the lower storage (mm/time) which is given as a single value for the catchment.

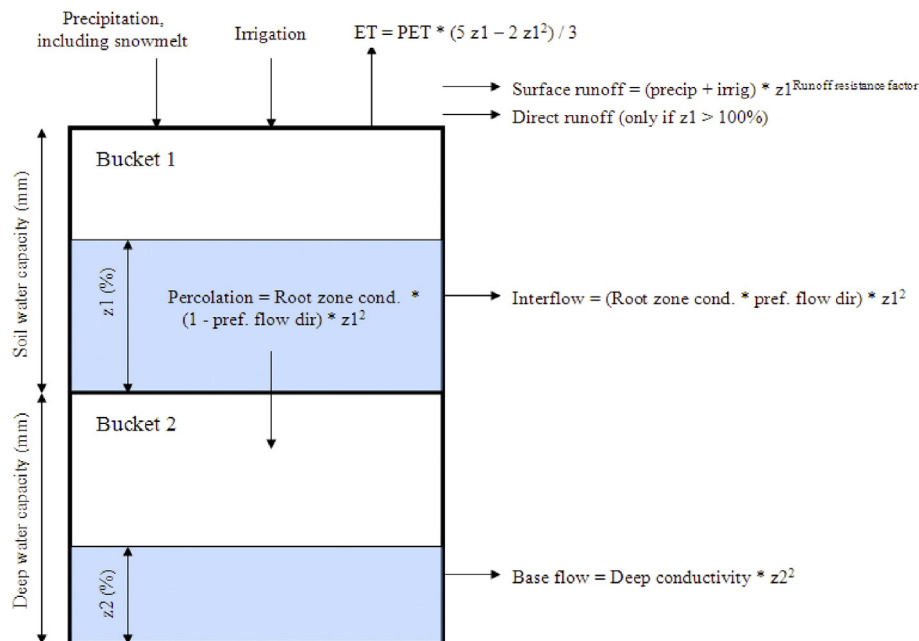


Figure 3. Conceptual diagram and equations incorporated in the Soil moisture method (Seiber and Purkey, 2015).

Table 1. Global Climate Models (GCMs) and Regional Climate Models (RCMs) used in the CORDEX for downscaling.

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

Source: Coordinated Regional Climate Downscaling Experiment (CORDEX).

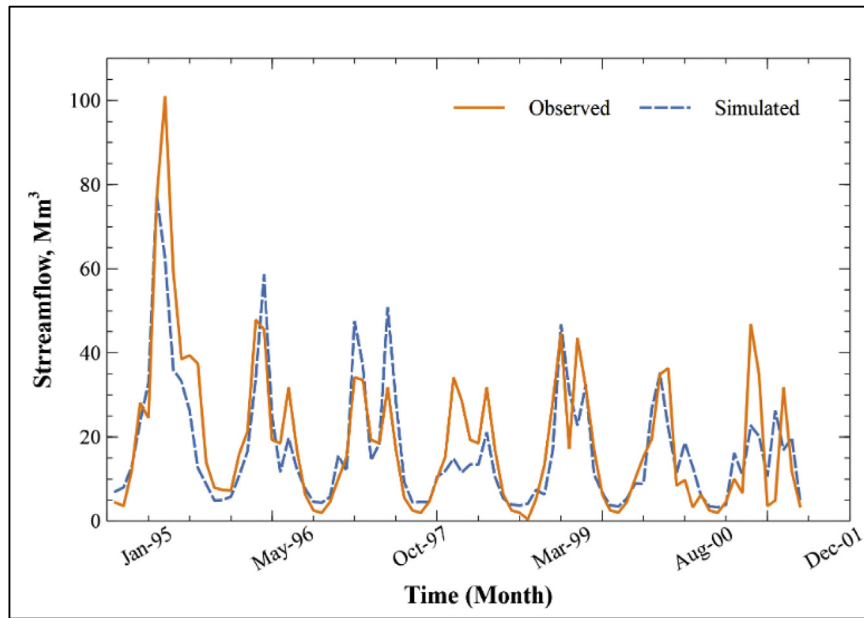


Figure 4. Observed and simulated monthly discharge for the model calibration period.

2.4. Model setup

The WEAP model for the Densu River Basin was set up in the schematic view of the WEAP software. The basin was delineated using the automatic catchment delineation mode incorporated in WEAP. The river network and the hydro station was indicated as well. During the setup,

the current accounts, key assumptions and scenarios were also defined. Current accounts are viewed as calibration step and provide insights of actual demands, and supply within the catchment. The time step of the study was set and the data on streamflow of the Densu river was entered as well as the climate data. After the setup, the model was calibrated and validated before being run.

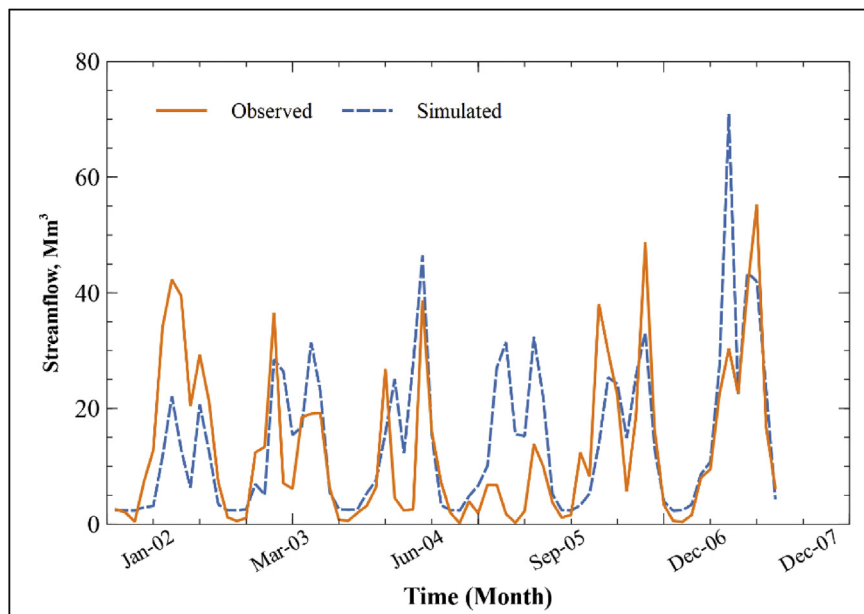


Figure 5. Observed and simulated monthly discharge for the model validation period.

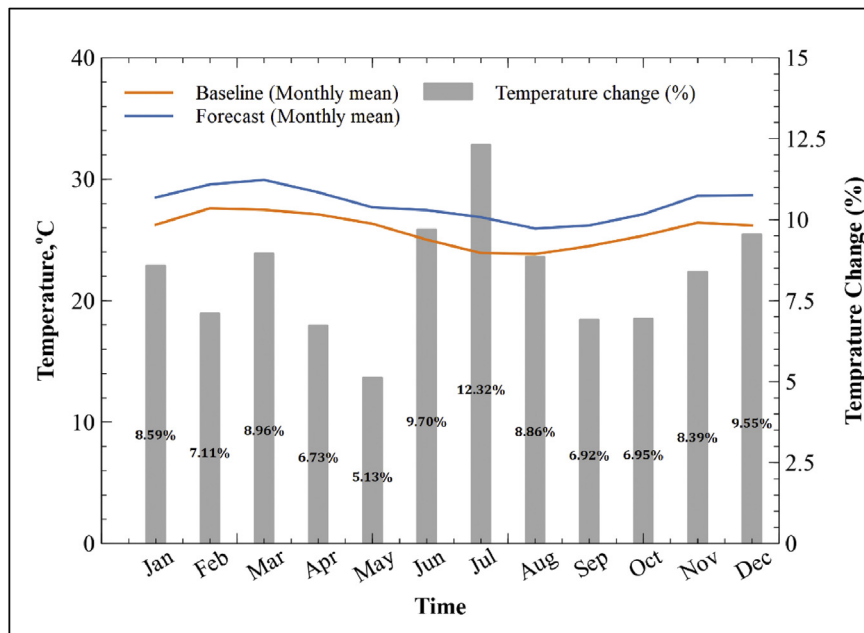


Figure 6. Pattern of occurrence and anticipated increase in the projected temperature (2051–2080) under RCP 4.5 scenario against the baseline.

2.5. Model calibration and validation

The calibration of an integrated river basin model, such as WEAP, is a challenging process. In general, calibration is process of adjusting the parameters of the models to appropriately simulate historical observations. For this research, the monthly observed streamflow data from 1995 to 2007 of the Densu river was used to calibrate and validate the WEAP model. The observed streamflow data of the river between 1995-2001 was used to calibrate the model and the observed streamflow between the period of 2002–2007 was used to validate the model. During the model calibration, the Parameter Estimator Tool (PEST) combined with a manual approach was employed. Some parameters in the model (runoff resistance factor) was adjusted manually while others (soil water capacity and root zone conductivity) were modified using the PEST in order

to get a representative streamflow for the basin. The non-calibrated parameters were based on the default values of the model. The performance of the calibrated model was measured by statistical measures of calibration: Percent BIAS (PBIAS), Nash-Sutcliff efficiency (NSE) and coefficient of determination (R^2) which measures the fit between the simulated and the observed streamflow. The range of R^2 is from 0 to 1, with a higher value indicating less error variance. The closer the value to 1, the better the performance of the model and lesser the error variance (Liew et al., 2003; Santhi et al., 2001). NSE ranges from $-\infty$ to 1, with NSE value = 1 being the optimal value (Nash and Sutcliffe, 1970). Acceptable PBIAS values should be $< \pm 25$. However, the optimal PBIAS value is 0.0 (Gupta et al., 1999). The model performance is deemed accepted when $R^2 > 0.60$, $NSE > 0.50$, and $PBIAS$ is $< \pm 25\%$ (Moriasi

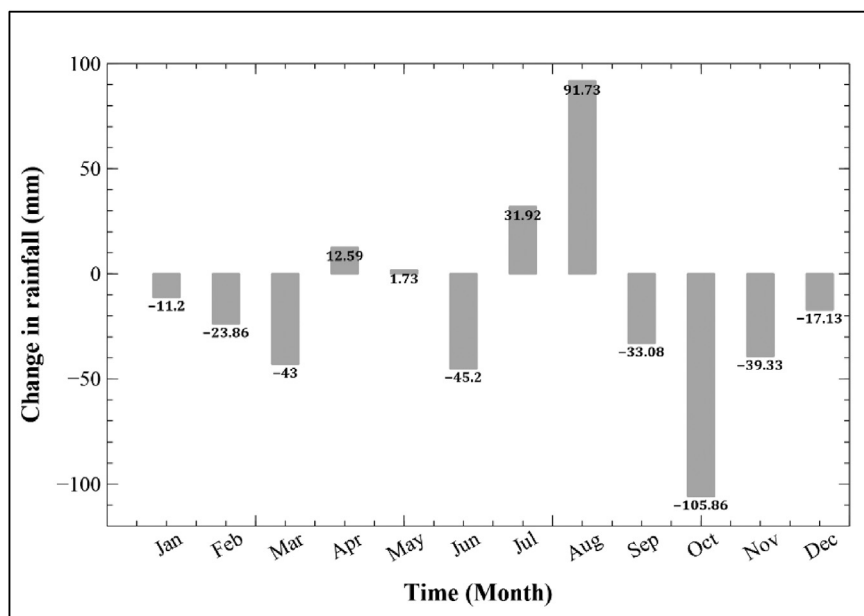


Figure 7. Graph showing the change in projected rainfall between 2051-2080 for RCP4.5 scenario for CORDEX.

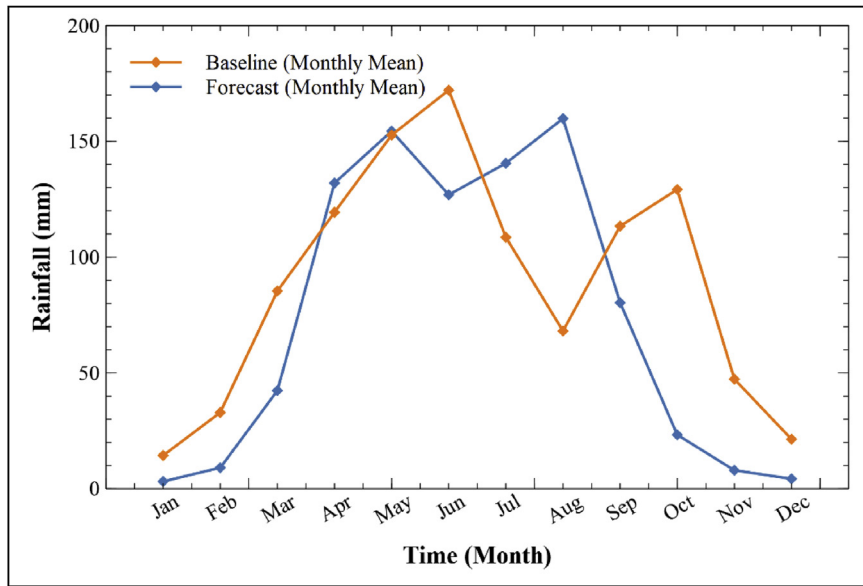


Figure 8. Pattern of occurrence of the projected rainfall (2051–2080) under RCP4.5 scenario against the baseline.

et al., 2007). The efficiency of the model performance depends on how close R^2 and NSE values approach 1 and PBIAS approaches 0.

The statistical measures are explained in the following equations:

$$NSE = 1 - \frac{\sum_i (Q_o - Q_s)^2}{\sum_i (Q_o - \bar{Q}_o)^2} \tag{4}$$

$$R^2 = \left[\frac{\sum_i (Q'_{o,i} - \bar{Q}_o) (Q'_{s,i} - \bar{Q}_s)}{\sqrt{\sum_i (Q'_{o,i} - \bar{Q}_o)^2 \sum_i (Q'_{s,i} - \bar{Q}_s)^2}} \right]^2 \tag{3}$$

$$PBIAS = \left[100 * \frac{\sum_i (Q_{o,i} - Q_{s,i})}{\sum_i (Q_{o,i})} \right] \tag{5}$$

where, Q is the discharge variable, o is the observed variable, s is the simulated variable, t is the time and i is the number of points. The climate

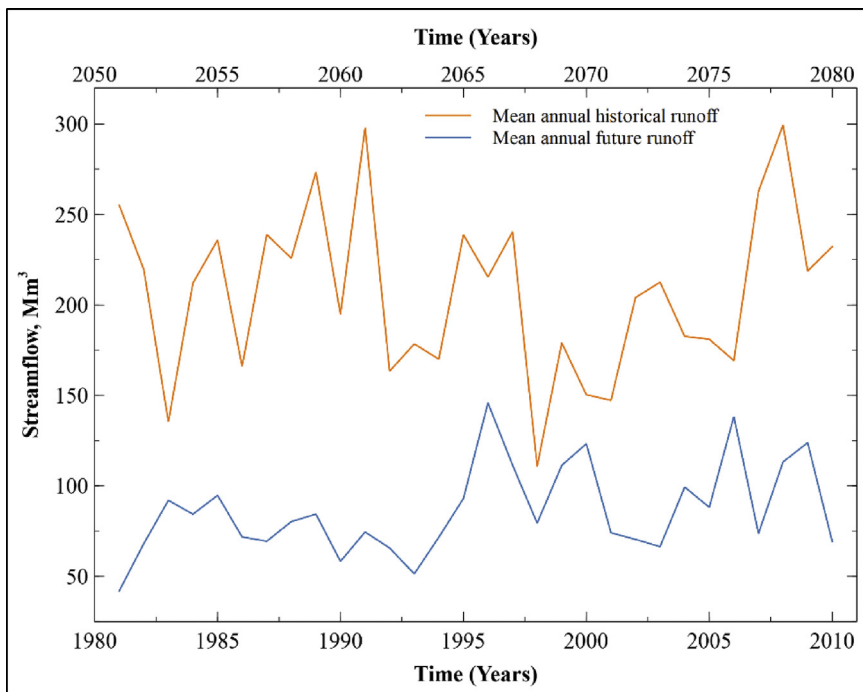


Figure 9. Graph showing the mean annual streamflow trends of the past and the future.

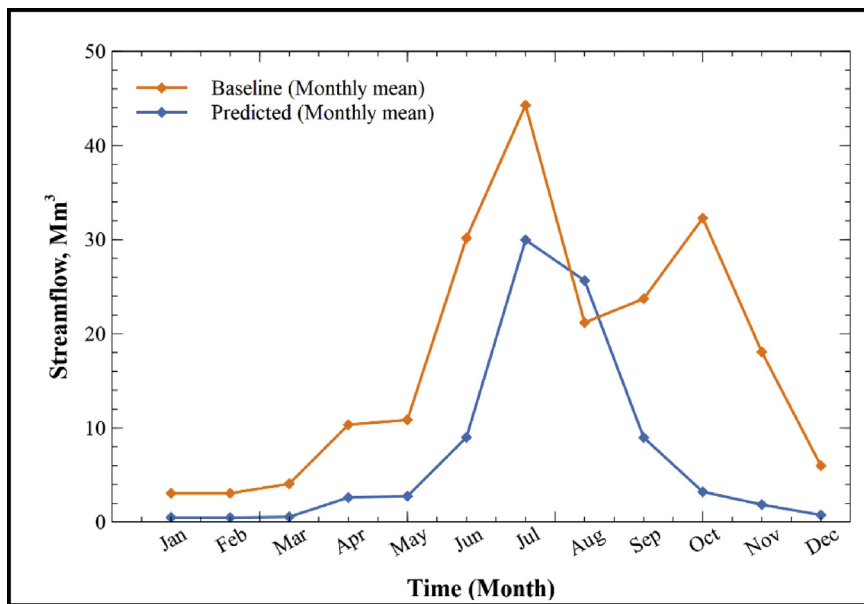


Figure 10. Pattern of occurrence of the projected streamflow (2051–2080) against the baseline (1981–2010).

data used in generating the baseline (1981–2010) was obtained from the “Global Meteorological Forcing Dataset for land surface modeling” (Sheffield et al., 2006) at the Princeton data source (Princeton University, 2007).

2.6. Climate change

The future climate data of the Densu River Basin was obtained from the Coordinated Regional Climate Downscaling Experiment (CORDEX) under the World Climate Research Programme (WCRP) through the Earth System Grid Federation infrastructure (ESGF). The future daily generated climate data for the period 2051-2080-time slice was performed under CORDEX’s Africa domain. One Global Climate Model (GCM) was used to drive one Regional Climate Model (RCM) under one of the most recent IPCC emission scenarios, Representative Concentra-

tion Pathways (RCP 4.5), to generate the future daily climate data for the basin. The RCPs represent the greenhouse gas concentration trajectories. The projected climate data was compared to the baseline data to assess the level of change by percent for the study period. Their changes relative to the baseline were determined by the relation:

$$\text{Relative change (\%)} = \frac{\text{Predicted mean} - \text{Baseline mean}}{\text{Baseline mean}} \times 100\% \tag{6}$$

Details on the GCM and RCM used are showed in Table 1.

2.7. Climate change impact on the hydrological component

To analyze the future impact of climate change on the streamflow, the validated WEAP model was used to simulate the rainfall-runoff process in the basin. The simulated runoff was directed at the

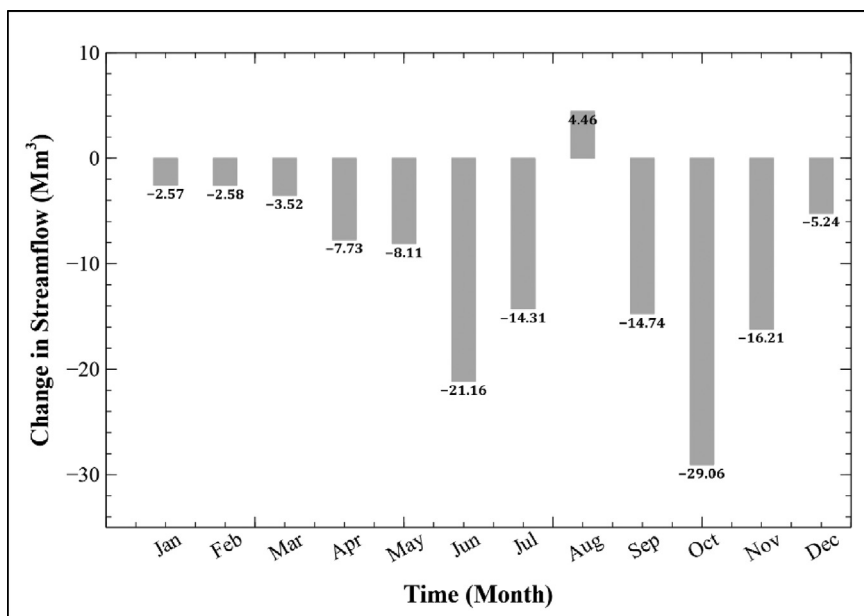


Figure 11. Graph showing the change in projected streamflow between 2051-2080.

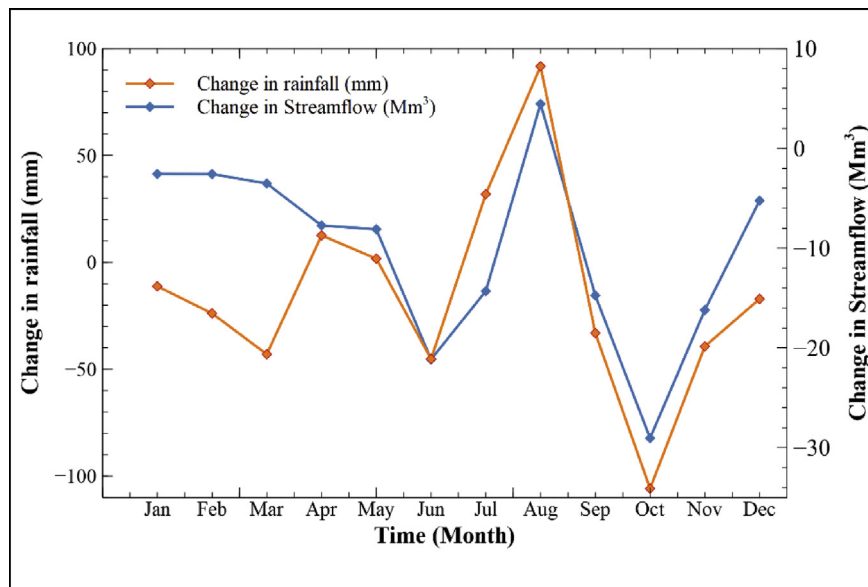


Figure 12. Correlation between the changes in the projected rainfall and the streamflow.

upstream of the river as the headflow of the river. The streamflow was generated from the climatic data after the calibration and validation of the model. It was assumed that the basic characteristics of the watershed will not change for the projected period of analysis to 2080. Once a set of characteristics for the watershed was selected, there was a further assumption that the rainfall-runoff processes will stay reasonably constant under changing precipitation and temperature conditions. The changing temperature and precipitation conditions will impact the runoff simulation through increased evapotranspiration for example and reduction of baseflow. To evaluate the change in hydrology of the basin as an impact of climate change, the streamflow of the baseline was compared to the streamflow of the future scenario. To establish the baseline conditions, the validated WEAP model was used to generate the streamflow during the period of 1981–2010. This procedure was repeated for the future scenario to generate the streamflow for the period of 2051–2080 under RCP 4.5 projections. The baseline streamflow was compared to the projected streamflow to determine the relative change as a result of climate change.

3. Results and discussions

3.1. Performance of the model

The WEAP model was calibrated before analyzing the climate impact on the streamflow. This was necessary to make sure the model is correctly representing the current situation in the study area. The streamflow data between the period of 1995–2001 was used in the calibration of the model whereas streamflow data between 2002–2007 was used in validation of the model. Overall, the model showed an efficient performance for both calibration and validation periods. The NSE values were 0.94 and 0.71 for calibration and validation respectively. The R^2 values were 0.997 and 0.799 for both calibration and validation periods respectively. The PBIAS was estimated to be 9.6% during the calibration and -10.0% during the validation which shows a good model performance (Moriasi et al., 2007). Hydrographs in Figure 4 and Figure 5 shows the performance of the model calibration and validation respectively. Evaluation of the hydrographs and the statistical analysis indicates that the model is reproducing the observed data reasonably well. The goal of calibrating the watershed rainfall runoff model in WEAP was not to exactly reproduce the historical runoff properties of the watershed but rather to develop a good representation of the existing streamflow that could serve as a base condition for the climate change analysis.

3.2. Future climate

3.2.1. Temperature

The Densu River Basin (DRB) is anticipated to be warmer (Figure 6). The mean annual temperature for the study period in the DRB is projected to increase by 8.23% under the RCP 4.5 scenario. The increase in temperature corresponds to the findings of Niang et al., 2014, and Sylla et al., 2016 which projects temperature increase across Africa and West Africa respectively as well as Ghana (McSweeney et al., 2006). The temperature in the DRB is projected to increase for all the months for the study period as shown in Figure 6. The projected mean monthly temperature ranges between 25.9 °C to 29.9 °C with the highest recording in the month of March. August remains the coolest month with reference to the baseline as the projections showed the lowest mean temperature of 25.9 °C representing a percentage increase of 8.86%. Moreover, compared to the baseline, the month of July is projected to have the highest increase of 12.32% for the study period followed by June with an increase of 9.7%. The month of May is anticipated to have the minimum increase (5.13%) (Figure 6). The temperature increase could have an impact on the streamflow of the river as this will increase the rate of evapotranspiration in the basin.

3.2.2. Rainfall

The projected mean monthly rainfall for the DRB ranges between 3.14 mm/month to 159.6 mm/month. The projection shows a reduction in the rainfall over the study period compared to the baseline. Generally, Ghana is expected to experience variation in rainfall in the future (McSweeney et al., 2006). A reduction in rainfall signifies a reduction in the streamflow of the river basin as the principal source of recharge is through rainfall. Compared to the baseline, the future mean annual rainfall will see a reduction of -17% (180.69 mm/year) which fall within the projected range of -30% and 30% for rainfall variability in West Africa (Sylla et al., 2016). The decrease in rainfall will have a devastating impact on the river discharge especially with increasing temperature and evapotranspiration (Kankam-Yeboah et al., 2013). All the months are projected to experience a reduction in the mean rainfall with the exception of April, May, July and August which will experience an increase in the mean monthly rainfall (Figure 7). Based on the projection, the DRB will still exhibit the bi-modal rainfall pattern, however, the monthly peak rainfall has shifted from June (baseline) to August (projected) (Figure 8). The month of August is not only projected to have the minimum mean temperature over the period, it will be the wettest month as it records the highest rainfall over the study

period. August is projected to have the highest increase in rainfall (+91.73mm) in the future as compared with the baseline (Figure 8). The month of November is projected to experience the highest reduction of rainfall for the study period as compared to the baseline (Figure 7).

3.3. Climate change impact on streamflow

The projected mean annual streamflow for the study period (2051–2080) for the study basin shows significant decreases compared to the baseline conditions (Figure 9). In Figure 9, it can be seen that there is drastic decline in the annual streamflow for all the years in the future scenario compared to the historical baseline (see Figure 9). The mean annual streamflow reduction is estimated to be 58.3% by 2080. Figure 10 indicates the mean monthly streamflow for the study period shifting from a bi-modal flow regime (baseline) to a uni-modal flow regime. However, the peak flow is anticipated in July which is same as the baseline. The results from the simulation indicate a projected decrease of the average monthly streamflow from the baseline scenario to the future scenario for all the months excluding August (Figure 11). August is anticipated to increase by approximately 21%.

The month of October will see the highest reduction of (29.06Mm³) 90% at the end of the study period. The months of the dry period (November–March) will all experience a reduction of over 80% relative to the baseline and this might lead to water shortages (Figure 11). The streamflow reduction could be link to the reduction in rainfall over the basin for the study period. This can be explained by a close correlation between the changes in projected rainfall and streamflow. To statistically determine this, a correlation coefficient between the rainfall changes and the streamflow changes was calculated. The correlation coefficient was calculated to be 0.7 which represent a positive correlation between the two variables. Any change in rainfall appends a certain degree of change in the streamflow accordingly as observed by Mahe et al. (2013). A graphical representation of the correlation is shown in Figure 12. Streamflow reduction in September and October will likely exacerbate water shortage in the months ahead (dry season). The reduction of the Densu river streamflow has been predicted in previous research (Kankam-Yeboah et al., 2013; Kasei et al., 2014).

The change in streamflow was determined with the relation below:

$$\text{Change in Streamflow (\%)} = \frac{MAS_p - MAS_b}{MAS_b} \times 100 \quad (7)$$

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

4. Conclusion

In this research, the Water Evaluation and Planning system (WEAP21) was applied to evaluate the climate change impact on the water resources in the Densu River Basin between 2051–2080 period. The overall results showed that a decrease in streamflow due to climate change effect over the study period. The basin is projected to be warmer in the future with expected mean temperature increase of 8.23% over the study period. The projected rainfall at the end of the study period is anticipated to see a drastic decline of -17%. However, the months of April, May, July and August will see an increase in rainfall. River discharge is decreasing over time. The river discharge declined by approximately 58% by the end of the study period. The primary cause of the depletion in the streamflow is as a result of the reduction in the rainfall as predicted by the climate scenarios.

This study concludes that water resources in the basin are consequently affected by climate change. The study therefore recommends future research on climate change adaptation for water management in the Densu River Basin.

Declarations

Author contribution statement

Jonathan Opoku Oti: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Amos T. Kabo-bah: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Eric Oforu: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

- Alemayehu, T., McCartney, M., Kebede, S., 2010. The water resource implications of planned development in the Lake Tana catchment, Ethiopia. *Ecohydrol. Hydrobiol.* 10 (2-4), 211–222.
- Arsisoa, B.K., Tsidua, G.M., Stoffberg, G.H., Tadesse, T., 2017. Climate change and population growth impacts on surface water supply and demand of Addis Ababa, Ethiopia. *Climate Risk Manag.* 18, 21–33.
- Bates, B., Kundzewicz, Z., Wu, S., Palutikof, J.E., 2008. Climate change and water. In: *Technical Paper of the Intergovernmental Panel on Climate Change*. IPCC Secretariat, Geneva.
- Beylene, T., Lettenmaier, D.P., Kabat, P., 2010. Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios. *Climatic Change* 100, 433–461.
- Faramarzi, M., Abbaspour, K.C., A.V., S., Farzaneh, M.R., Zehnder, A.J., Srinivasan, R., Yang, H., 2013. Modeling impacts of climate change on freshwater availability in Africa. *J. Hydrol.* 480, 85–101.
- Gyau-Boakye, P., Tumbulto, J., 2006. Comparison of rainfall and runoff in the humid south-western and the semiarid northern savannah zone in Ghana. *Afr. J. Sci. Technol.: Sci. Eng.* 7 (1), 64–72.
- Gupta, V.H., Sorooshian, S., Yapo, P.O., 1999. Status OF automatic calibration for hydrologic models: comparison with multilevel expert calibration. *J. Hydrol. Eng.* 135–143. April.
- Hrdinka, T., Vlasák, P., Havel, L., Mlejnská, E., 2015. Possible impacts of climate change on water quality in streams of the Czech Republic. *Hydrol. Sci. J.* 60 (2), 192–201.
- Huang, J.-C., Lee, T.-Y., Lee, J.-Y., 2014. Observed magnified runoff response to rainfall intensification under global warming. *Environ. Res. Lett.* 9 (3), 34008.
- IPCC, 2014. In: Pachauri, R.K., Meyer, L.A. (Eds.), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.
- Joyce, B.A., Mehta, V.K., Purkey, D.R., Dale, L.L., Hanemann, M., 2011. Modifying agricultural water management to adapt to climate change in California's central valley. *Climatic Change* 109 (1), 299–316.
- Kabo-bah, A.T., Anornu, G.K., Oforu, E., Andoh, R., Lis, K.J., 2014. Spatial-temporal estimation of evapotranspiration over black Volta of West Africa. *Int. J. Water Resour. Environ. Eng.* 6 (12), 295–302. Retrieved from.
- Kankam-Yeboah, K., Obuobie, E., Amisigo, B., Opoku-Ankomah, Y., 2013. Impact of climate change on streamflow in selected river basins in Ghana. *Hydrol. Sci. J.* 58 (4), 773–778.
- Kasei, R.A., Barnabas, A., Ampadu, B., 2014. The nexus of changing climate and impacts on rainfed water supply and fresh water availability for the inhabitants of Densu Basin and parts of Accra - Ghana, West Africa. *J. Environ. Earth Sci.* 4 (20), 84–96.
- Lettenmaier, D., Major, D., Poff, L., Running, S., 2008. Water resources. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. U.S. Department of Agriculture, Washington, DC.
- Van Liew, M.W., Arnold, J.G., Garbrecht, J.D., 2003. Hydrologic simulation ON agricultural watersheds: choosing between two models. *Trans. ASAE (Am. Soc. Agric. Eng.)* 46 (6), 1539–1551.

- Mahe, G., Lienou, G., Descroix, L., Bamba, F., Paturol, J., Laraque, A., Khomsi, K., 2013. The rivers of Africa : witness of climate change and human impact on the environment. *Hydrol. Process.* 27, 2105–2114.
- McCartney, M., Forkuor, G., Sood, A., Amisigo, B., Hattermann, F., Muthuwatta, L., 2012. The water resource implications of changing climate in the Volta river basin. International Water Management Institute(IWMI), Colombo, Sri Lanka.
- McSweeney, C., New, M., Lizcano, G., 2006. UNDP Climate Change Country Profiles: Ghana. Retrieved July 22, 2019, from UNT Digital Library: <https://digital.library.unt.edu/ark:/67531/metadc226664/>.
- Mehta, V.K., Haden, V.R., Joyce, B.A., Purkey, D.R., Jackson, L.E., 2013. Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California. *Agric. Water Manag.* 117, 70–82.
- Moriassi, D., Arnold, J., Van Liew, M.W., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE (Am. Soc. Agric. Biol. Eng.)* 50 (3), 885–900.
- Nash, J.E., Sutcliffe, J.V., 1970. river flow forecasting through conceptual models Part I—a discussion of principles. *J. Hydrol.* 10, 282–290.
- Niang, I., Ruppel, O., Abdrabo, M., Essel, A., Lennard, C., Padgham, J., Urquhart, P., 2014. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, E.T., White, L.L. (Eds.), *Africa in: Climate Change 2014: Impacts, Adaptation and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, USA.
- Nicholson, S., Grist, J., 2001. A conceptual model for understanding rainfall variability in the west african sahel ON interannual and interdecadal timescales. *Int. J. Climatol.* 21, 1733–1757.
- Peterson, D.F., Keller, A.A., 1990. Effects of climate change on U.S. Irrigation. *J. Irrigat. Drain. Eng.* 116 (2), 194–210.
- Pham, B.Q., Yu, P.-S., Yang, T.-C., Kuo, C.-M., Tseng, H.-W., 2017. Assessment of climate change impacts on hydrological processes and water resources by water evaluation and planning (WEAP) model: case study in THAC MO catchment, Vietnam. In: *Proceedings of the 37th IAHR World Congress.* Kuala Lumpur, Malaysia: International Association for Hydro-Environment Engineering and Research(IAHR).
- Princeton University, 2007. *Global Meteorological Forcing Dataset for Land Surface Modeling.* Retrieved May 2, 2019, from. Terrestrial Hydrology Research Group. <http://hydrology.princeton.edu/getdata.php?dataid=1>.
- Purkey, D.R., Huber-Lee, A., Yates, D.N., Hanemann, M., Herrod-Julius, S., 2007. Integrating a climate change assessment tool into stakeholder-driven water management decision-making processes in California. *Water Resour. Manag.* 21, 315–329.
- Rosenzweig, C., Strzepek, K.M., Major, D.C., Iglesias, A., Yates, D.N., McCluskey, A., Hillel, D., 2004. Water resources for agriculture in a changing climate: international case studies. *Global Environ. Change* 14, 345–360.
- Roudier, P., Ducharne, A., Feyen, L., 2014. Climate change impacts on runoff in West Africa : a review. *Hydrol. Earth Syst. Sci.* 18, 2789–2801.
- Santikayasa, I.P., Babel, M.S., Shrestha, S., 2015. Assessment of the impact of climate change on water availability in the citarum rive basin, Indonesia: the use of statistical downscaling and water planning tools. *Managing water Resources under climate uncertainty.*
- Santhi, C., Arnold, J.G., Williams, J.R., Dugas, W.A., Srinivasan, R., Hauck, L.M., 2001. Validation OF the swat model ON a large river basin with point And NON-point sources. *J. Am. Water Resour. Assoc.* 37 (5), 1169–1188.
- Sheffield, J., Goteti, G., Wood, E.F., 2006. Development of a 50-yr high-resolution global dataset of meteorological forcings for land surface modeling. *J. Climate* 19 (13), 3088–3111.
- Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Leetmaa, A., 2007. Model projections of an imminwnt transition to a more arid climate in southwestern North America. *Science* 316 (5828), 1181–1184.
- Seiber, J., Purkey, D., 2015. *Water Evaluation and Planning System User Guide.* In: Somerville, M.A. (Ed.). Stockholm Environmental Institute.
- Sylla, M.B., Nikiema, P.M., Gibba, P., Kebe, I., Klutse, N.A., 2016. Climate change over West Africa: recent trends and future projections. In: Yaro, J., Hesselberg, J. (Eds.), *Adaptation to Climate Change and Variability in Rural West Africa.* Springer International Publishing, pp. 25–40.
- UNESCO & UN Water, 2020. *United Nations World Water Development Report 2020: Water and Climate Change.* United Nations Educational, Scientific and Cultural Organization, Paris.
- UNFCCC, 2007. *Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries.* United Nations Framework Convention on Climate Change.
- Water Resources Commission, 2007. *DENSU RIVER BASIN - Integrated Water Resources Management Plan.* Accra: Water Resources Commission.
- Water Resources Commission, 2018. *Basins.* Retrieved October 9, 2018, from. Ghana Water Resources Commission. <https://www.wrc-gh.org/basins/densu>.