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Article *in* Nature Environment and Pollution Technology · January 2017

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Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
e-ISSN: 2395-3454

Vol. 16 | No. 4 | pp. 1095-1105 | 2017

Original Research Paper | Open Access

Modelling the Spatial Variation of Hydrology in Volta River Basin of West Africa Under Climate Change

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 02-01-2017
Accepted: 22-02-2017

Key Words:
Climate Change
Hydrologic cycle
Volta river basin
Soil and Water Assessment Tool (SWAT)

ABSTRACT

Spatial variability in Volta basin's climate coupled with climate change increases unpredictability and unreliability of rain-fed agriculture, putting livelihoods of the inhabitants under severe risk. Though there have been numerous studies on the hydrological response of the basin to climate change, only a few have dealt into its spatial variation. To fill up the existing gap, the spatial variation of hydrology of Volta basin under projected impacts of climate change is investigated using high resolution (0.3°~3 km) National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data as observational data, Global Climate Model HadCM3, IPCC A1B emissions scenario and Soil, and Water Assessment Tool (SWAT). Calibration results from flow stations Dapola (R^2 =0.74, NSE=0.72), Nawuni (R^2 =0.86, NSE=0.88), and Bamboi (R^2 =0.82, NSE=0.80) show reasonable simulation of the basin's hydrology, in general. Overall the simulation indicates higher spatial variability, with variability much higher at the end of the century (2071-2100). There is a greater average increase in rainfall and surface runoff in northern catchments compared to the south with average potential evapotranspiration and evapotranspiration much higher in southern catchments compared to the north. Contrary to projected increase in rainfall in the basin, some sub-basins in north and south show a decrease. Decrease ranges from 2% to 10%, whilst increase in surface runoff is in the range of 16% to 76% in some sub-basins is far greater than the basin-wide range of increase i.e., 9% to 14%. This might impact negatively on the rain-fed agriculture and also intensify flood events, respectively, in these sub-basins. There is, therefore, a call for a decentralized approach in the basin's water resources management that incorporates the spatial variability of the hydrologic cycle into local climate change adaptation mechanisms.

INTRODUCTION

Although there are many discussions still ongoing, it is widely recognized that the future impacts of climate change will be difficult to avoid. The African continent will particularly be vulnerable due to the considerably limited adaptive capacity. Precipitation intensities, as well as annual rainfall amounts in West Africa show a strong spatial and temporal variability increasing vulnerability of the population to climate change. Historically, the occurrence of a repeated cycle of drought and floods has continued to affect the West African sub-region, especially the Sahel (15°N-17°N band across Africa) resulting in catastrophic famine (Mohammed et al. 2002). Precipitation experienced in the 1950s in West Africa facilitated an increase in national reliance on rain-fed agriculture and the embracing of hydroelectricity as the main source of energy for domestic and industrial consumption. Uncertainty associated with climate change will further complicate future management of water resources in West Africa putting most economies under severe economic stress.

Volta River basin experiences high degree of spatial and temporal variability in rainfall. A north (above latitude 9°N) to south (below latitude 9°N) variability in rainfall is exhibited in the basin. According to Opoku-Ankomah (Opoku-Ankomah 2000), since the 1970s, there has been a number of changes in precipitation patterns in some sub-catchments in the basin. Some areas have only one rainfall season instead of the bi-modal system experienced in the past. According to Van de Giesen (Van de Giesen et al. 2010), farmers have experienced forward shifts in the onset of the rainy season later in the year, from April towards May; farmers now sow 10-20 days later than before. A forward shift in the onset of the rainy season has also been predicted by Jung & Kunstmann (2007), Lacombe et al. (2012) and Laux et al. (2008). This high degree of spatial and temporal variability in rainfall in the basin makes it unreliable for agricultural production, resulting in diminishing food security and endangering livelihoods. Significant numbers of studies (Schuol & Abbaspour 2006, Obuobie 2008, Schuol et al. 2008, Mohammed 2009, Mango et al. 2010, Aditya et al. 2013, Awotwi et al. 2015, Akpoti et al. 2016) have used climate models to evaluate impact of climate change on water resources in Africa and the Volta River basin of West Africa. Although these studies have investigated the hydrologic response to climate change in the basin, only little research has been done on the spatial response of the hydrologic cycle to projected impacts of climate change in the Volta River basin. Given the spatial variability of the climate regime and vulnerability of societies in the Volta River basin, with respect to changes in the hydrological cycle, research is needed to assess impacts and design local adaptation mechanisms. To fill up the existing gap, the spatial variation of hydrology of Volta basin under projected impacts of climate change is investigated using high resolution (0.3°~3km) National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data as observational data, Global Climate Model HadCM3, IPCC A1B emissions scenario and the Soil and Water Assessment Tool (SWAT). The results arising from this research will serve as a crucial input into local climate change adaptation mechanisms.

MATERIALS AND METHODS

Study Area

Volta River basin of West Africa (Fig. 1) is a transboundary river basin shared by six Riparian countries in West Africa. Ghana and Burkina Faso occupy 42% and 43% respectively, and the remainder lies in Benin, Cote d'Ivoire, Mali and Togo. It has an area of 403,000 km^2. It has four main drainage basins: Black Volta (147,000 km^2), White Volta (106,000 km^2), Oti (72,000 km^2) and Lower Volta (73,000 km^2). The total mean annual runoff is estimated at 40.4 km^3 (Andah et al. 2004). An important feature of the basin is Lake Volta, which generates hydropower. Water from Volta River is crucial to the economies of the Riparian countries. It serves as a lifeline for agriculture and helps in producing electricity to meet energy demand. The Volta River basin has semi-arid to sub-humid climate. The semi-arid climate is located above latitude 9°N, whilst the sub-humid climate lies below latitude 9°N. Mean annual rainfall exhibits high degrees of spatial variability i.e. north (above latitude 9°N) to south (below latitude 9°N) variability. Mean annual rainfall ranges from less than 300 mm in the north to more than 1500 mm in the south. The time and distribution of rainfall are largely influenced by the West African Monsoon (WAM) and is divided into a dry (November-March) and rainy season (April-October) (Kasei 2009). Mean annual potential evapotranspiration is below 1500 mm in the south, but exceeds 2500 mm in the north of the basin; annual average potential evapotranspiration varies between 2,500 mm and 1,800 mm from the north of the basin to the south; mean annual temperature in the northern part ranges between 27°C and 36°C and 24°C-30°C in the southern part of the basin.

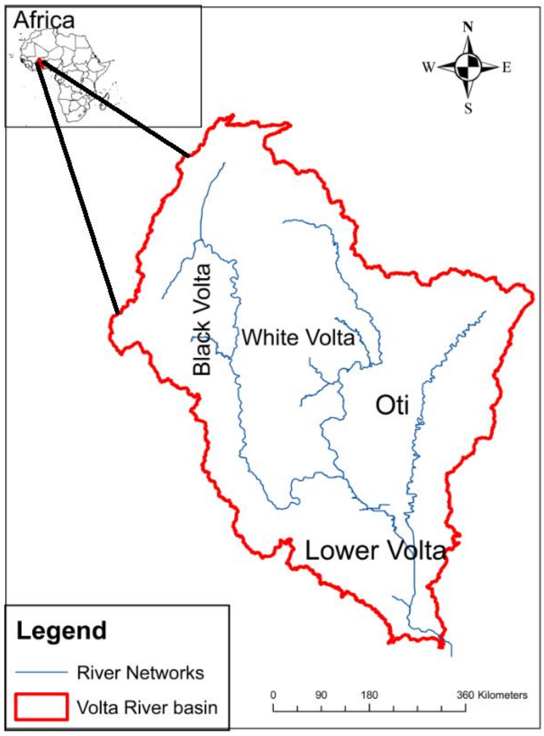


Fig. 1: Map of Volta river basin.

SWAT Model Description

SWAT is a process-based, continuous-time, semi-distributed hydrological model. It was developed in the early 1990s by the United States Department of Agriculture (USDA), Agricultural Research Service (ARS) to predict the impact of land use practices on water, sediment and agricultural chemical yields in large and complex watersheds with diverse weather, varying soils, land use and management and topographic conditions over a long period (Neitsch et al. 2009). It uses GIS interface and operates on a daily time step.

Model Input Data

Digital elevation model (DEM): DEM is of 90 m resolution obtained from Shuttle Radar Topographical Mission (SRTM). The DEM was used for watershed delineation including slope definition, stream definition, outlets and inlets definition and calculation of sub-basin parameters.

Land use/cover data: Land-use/cover map is a modified Food and Agricultural Organization (FAO) map. It has a resolution of 250 m and in raster format. The legend is based on FAO Land Cover Classification System (LCCSS) and had to be modified to match land-cover classes in SWAT.

Soil data: Soil map was obtained from the FAO digital soil map of the world and derived soil properties. It has a spatial resolution of 10 km and almost 5000 soil types can be differentiated (Schuol et al. 2008). Data on soil properties were obtained from FAO-derived soil properties and Soil Research Institute of Ghana.

Climate data: High resolution (0.3°~3 km) daily Climate Forecast System Reanalysis (CFSR) (daily rainfall, temperature (both maximum and minimum), wind speed, solar radiation and humidity) spanning from 1979-2009 from the National Centers for Environmental Prediction (NCEP) were used for the modelling process. 52 climate stations were used for modelling the Volta River basin.

River discharge data: The discharge data used in calibrating and validating the SWAT model for the basin were obtained from Global Runoff Data Centre (GRDC), Koblenz, Germany. The discharge data had gaps for most of the stations retrieved. Some of the gaps were filled with mathematical algorithms developed by Amisigo (2006).

SWAT Model Set Up

SWAT model was set-up for Volta River basin through Arc SWAT 2009 following step by step procedure outlined in the SWAT user guide. Each basin was divided into sub-basins based on DEM and stream networks of the basin. The number of sub-basins obtained was determined by threshold input value for defining a drainage area in SWAT model. Sub-basin delineation was followed by the automatic parameterization of streams and subdivision of sub-basins into Hydrologic Response Units (HRUs) based on soil and land-use data and predefined threshold for soil and land use within sub-basins. A threshold drainage area of 8,166.260 km^2 was used and this created 52 sub-basins and 956 HRUs. Analysis of digital elevation model (DEM) of the basin shows the topography of the basin is predominantly flat, with about 96% of the land having a slope less than 5%, hence single slope class option was used. In this work, multiple HRUs option was chosen; land use class percentage over sub-basin areas was set to 20%, soil class percentage over the land use area was 10% and slope class percentage over soil area was 20%. The model was configured and run using the baseline data for the period of 1979-2008.

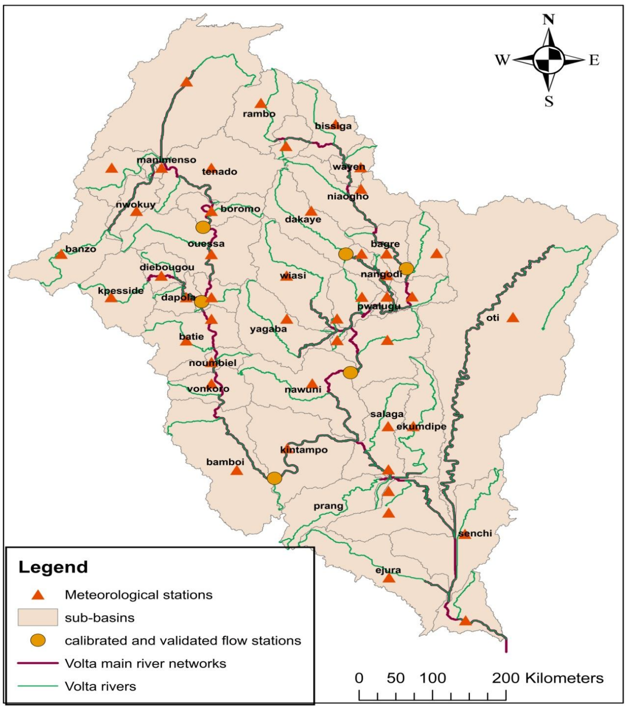


Fig. 2: Sub-basins, meteorological and discharge stations in Volta river basin.

Calibration and Validation

SWAT Calibration and Uncertainty Program (SWATCUP) were used to calibrate the model. It is an automated calibration model which provides a link between input/output of a calibration program and the model. For this project, sequential uncertainty fitting (SUFI2) was used to quantify uncertainty in the model. It is measured by two quantitative measures: the P-factor and the R-factor. The P-factor indicates the percentage of observed data that falls within 95% of prediction uncertainty (95PPU). The R-factor is the average thickness of 95PPU band divided by the standard deviation of observed data. Perfect simulation is when 100% of observed data is bracketed in 95PPU, while at the same time R-factor is close to zero. Other performance indicators i.e., Nash-Sutcliffe efficiency (Nash & Sutcliffe 1970) and coefficient of determination, R^2 were also used for model evaluation. Data constraints meant that only six sub-basins (Fig. 2) could be calibrated.

Since only the monthly observed flow data at the gauging stations were available, calibration was performed on

Table 1: SWAT parameters used for calibration and their ranges used.

Parameter	Suggested ranges in SWAT	Mode of change during calibration[1]	Final values/ ranges used	Comparative range[2]
Baseflow Alpha factor (Alpha_Bf)	0-1	-	0-1	0.08-0.24#,0.1-0.6*
Maximum canopy storage (mm water) (CANMX)	0-10	v	3.42	0-4.58#
Effective hydraulic conductivity in main alluvial channel(mm/h)(Ch_K2)	0-150	r	10-170	1.11-2.26#, 6-190*
SCS runoff curve number (Cn2)	±25	r	38-70	56-90#, 35-70*
Plant uptake compensation factor (EPCO)	0-1	r	0.05-1.0	0.08-0.98*
Soil evaporation compensation factor (ESCO)	0-1	r	0.05-1.0	0.02-0.98*
Groundwater revap coefficient (GW_REVAP)	±0.036	r	0.08-0.20	0.1-0.25*
Threshold depth of shallow GW for return flow to occur (mm) (GWQMN)	±1000	r	10-600	1-520*
Deep aquifer percolation coefficient (RCHRG_DP)	0-1	-	0-1	0.07-0.75#, 0.15-0.9*
Threshold depth for revap or percolation to occur in shallow GW (mm) (REVAPMN)	±100	r	7-584	10-604*
Available water capacity of soil (SOL_AWC) (mm water/ mm soil)	±25	r	0.08-1.00	0.06-0.41#, 0.1-1.0*
Groundwater delay time (GW_DELAY) (days)	±10	r	27-310	9-144#, 33-500*
Surface runoff lag coefficient	0-10	-	0-10	4.65#

[1] v refers to the absolute change in the parameter made by replacing a parameter by a given value; r refers to the relative change in the parameter made by multiplying the parameter by 1 plus a factor in the given range (Abbaspour 2007).
[2] Sources: #Masih (Masih et al. 2011); *Aditya (Aditya et al. 2013)

monthly time steps. Historical monthly flows from six hydrological stations, namely, Nawuni (White Volta River basin outlet), Bamboi (Black Volta River basin outlet), Dapola, Boromo, Dakaye and Bagre (i.e., those with sufficient data, spanning a common period) were used over the period January 1985 to December 1996. The time period selected for calibration was January 1985 to December 1991, with the first two years as a warm-up period (i.e., 5 years of data for actual calibration (January, 1987-December, 1991)) and January 1992 to December 1996 (i.e. 5 years of data) for validation. Only three stations, Nawuni (White Volta River basin outlet), Bamboi (Black Volta River basin outlet) and Dapola had data for validation. Multi-step calibration methodology used by Aditya (Aditya et al. 2013), and Schuol & Abbaspour (Schuol & Abbaspour 2006) for previous studies in the region was adopted for this study. The most upstream sub-basins were calibrated first and most downstream last. Thirteen parameters (Table 1) that affect runoff, groundwater recharge and evapotranspiration were calibrated.

Determination of Spatial Variation of Hydrology

To quantify spatial variation of hydrology under projected impacts of climate change in the Volta River basin, sub-basins were categorized into northern (above latitude 9°N) and southern catchments (below latitude 9°N) to reflect north-south climate gradient that exists in the basin. The simulated hydrologic components were then analysed at sub-basin level for both catchments. Results for both catchments were then compared with each other and also basin-wide averages to detect any spatial variability. The northern and southern catchments used in the study are presented in Table 2.

Climate Change Projections

This study uses LARS-WG stochastic downscaling model-version 5.5 for predicting future changes in climate. LARS-WG uses lengths of wet and dry day series, daily precipitation, daily maximum and minimum temperature and daily solar radiation as inputs. It does not directly use large-scale atmospheric variables, and local station climate variables are adjusted proportionally to represent the climate change (Sajjad Khan et al. 2006). It has successfully been applied to climate change studies around the world (Hashmi et al. 2009, Semenov & Stratonovitch 2010). LARS-WG model itself consists of 15 different GCM model results according to different emission scenarios. However, this study utilizes HadCM3 GCM and A1B SRES scenarios for performing climate change analysis. The A1B scenario assumes a balance of energy consumption in the world that produces medium emissions of greenhouse gases and aerosols. The

Table 2: Northern and southern sub-basins used in the study.

Sub basin	Location (Latitude, Longitude)
Northern catchment	
Pwalugu	10.58N, 0.85W
Dapola	10.57N, 2.92W
Niaogho	11.77N, 0.75W
Rambo	13.60N, 2.07W
Nawuni	9.70N, 1.08W
Bissiga	12.75N, 1.15W
Nwokuy	12.52N, 3.55W
Tenado	12.17N, 2.82W
Boromo	11.78N, 2.92W
Bagre	11.25N, 0.33W
Batie	9.98N, 2.90W
Diebougou	10.93N, 3.17W
Noumbiel	9.68N, 2.77W
Banzo	11.32N, 4.82W
Kpesside	9.62N, 0.95W
Manimenso	12.75N, 3.40W
Ouessa	11.02N, 2.82W
Wiasi	10.33N, 1.35W
Yagaba	10.23N, 1.28W
Dakaye	11.78N, 1.60W
Nangodi	10.87N, 0.62W
Wayen	12.38N, 1.08W
Oti	9.28N, 0.23E
Vonkoro	9.19N, 2.71W
Southern catchment	
Kintampo	8.03N, 1.43W
Salaga	8.55N, 0.52W
Ejura	7.23N, 1.22W
Prang	7.98N,0.88W
Ekumdipe	8.47N,0.22W
Bamboi	8.15N, 2.03W
Senchi	6.20N, 0.10E

GCM output was disaggregated by LARS-WG into daily meteorological data at single sites based on statistical properties of observed data. Three steps are performed in the LARS-WG model to develop future climate change data. The model calibrates and validates past 30 years (1979-2008) of historical climate data of Volta River basin using site analysis (step 1), and Q-Test (step 2) options. It then generated future meteorological data from 2009 to 2100 for precipitation, temperature, and solar radiation for each site based on statistics of historical data and future climate scenarios using generator option (step 3). The generated future weather data are used in site analysis step to obtain basic statistics for comparison. Details on weather generation by LARS-WG has been described by Racsko (Racsko et al. 1991). LARS-WG is site specific and GCM model specific tool. Thus, this procedure is repeated for each of 52 climate stations used in the study. Thus, fifty-two time series for 52 precipitation and temperature gauges (grid centers) were stochastically generated. The performance of LARS-WG in simulating the baseline (1979-2008) climate (rainfall,

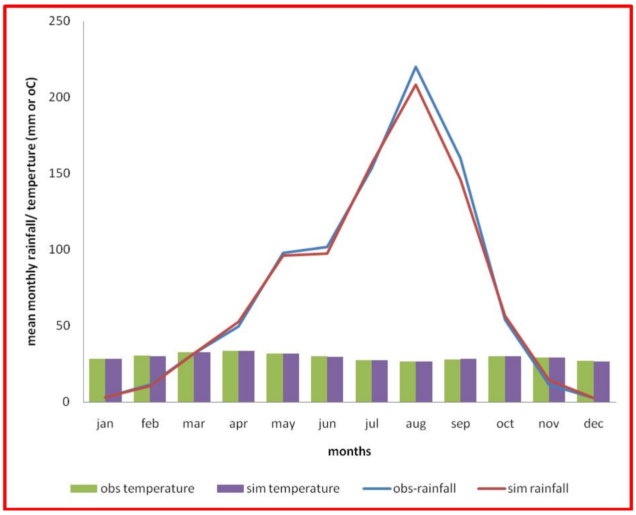


Fig. 3: Comparison of observed/baseline and simulated mean monthly rainfall and temperature for Volta basin.

minimum and maximum temperatures) was assessed using the p value for statistical significance testing provided in the model. The average p values for simulating daily rainfall, minimum and maximum temperatures were 0.989, 1.000 and 0.998, respectively, which indicates that baseline values (Fig. 3) are very well reproduced and that internal model bias and errors are minimal.

RESULTS AND DISCUSSION

SWAT model calibration and validation results: The performance indicators (Table 3) show that the model calibrated well for gauging stations Nawuni, Bamboi and Dapola.

Nawuni and Bamboi represent outlets of the two biggest sub-basins; White Volta and Black Volta basin respectively. These stations are more downstream and represent the larger river basin. On the other hand, some upstream gauging stations (Bagre, Boromo and Dakaye) did not perform very well. Similar calibration issues were faced by Schuol and Abbaspour (Schuol & Abbaspour 2006) and Aditya (Aditya et al. 2013), when they applied SWAT model to the basin. Some of the reasons for this are limitations in quality observed flow data, lack of management practices in agricultural land use information, and non-inclusion of dams, reservoirs and ponds in the model. Finally, although the model was set up using 2007 land use map, the model was calibrated for 1987-1991, and there is probability that land cover has changed significantly between these periods. The validation of the model was done for the years 1992 to 1996 for those gauging stations which had data. Only three gauging stations had observed data from 1992 to 1996; these were Nawuni, Bamboi and Dapola. In general, the validation was best for those stations where the calibration was good. The

Table 3: Summary of performance indicators for the calibration process.

Gauging station	Calibration				Validation	
	P factor	R-factor	NSE	R^2	NSE	R^2
Nawuni	0.93	0.30	0.88	0.86	0.85	0.86
Bagre	0.48	0.73	0.13	0.15	-	-
Dapola	0.64	0.43	0.72	0.74	0.61	0.64
Boromo	0.24	1.25	0.34	0.28	-	-
Bamboi	0.74	0.82	0.80	0.82	0.83	0.84
Dakaye	0.80	0.67	0.50	0.47	-	-

Note: The blanks in the table indicate that validation was not done for those stations because of lack of data for the specific periods.

Table 4: Statistical properties (mean maximum and minimum of hydrological fluxes for the Volta River basin for baseline (1979-2008) and future time periods 2011-2040, 2041-2070 and 2071-2100.

Statistics/Time period	PRECIP (mm)	Surface Runoff (mm)	PET (mm)	ET (mm)	SW (mm)	Groundwater Recharge (mm)	Water yield (mm)
Mean (1979-2008)	690.16	114.72	2315.25	452.54	55.28	55.13	266.92
Mean (2011-2040)	711.80	125.45	2355.29	461.46	56.16	64.00	278.63
Mean (2041-2070)	719.38	127.99	2421.89	468.07	56.39	71.82	280.20
Mean (2071-2100)	726.53	130.16	2495.18	470.86	57.04	80.04	284.38
Max (1979-2008)	791.92	162.70	2367.12	468.90	58.51	63.35	365.16
Max (2011-2040)	910.50	215.84	2408.53	497.67	59.19	81.95	436.62
Max (2041-2070)	916.51	215.25	2480.61	504.99	58.83	91.65	435.09
Max (2071-2100)	920.09	216.97	2545.90	507.27	58.92	101.21	436.41
Min (1979-2008)	597.54	76.29	2214.87	424.06	52.65	47.80	197.60
Min (2011-2040)	655.31	93.50	2238.75	438.43	52.65	58.98	228.88
Min (2041-2070)	662.93	96.55	2299.14	451.13	53.85	66.29	233.39
Min (2071-2100)	667.70	98.68	2464.70	448.22	53.33	73.45	235.21

Table 5: Ranges of change in hydrological fluxes for northern and southern catchments as predicted by A1B scenario for 2011-2040, 2041-2070 and 2071-2100 compared to the baseline 1979-2008.

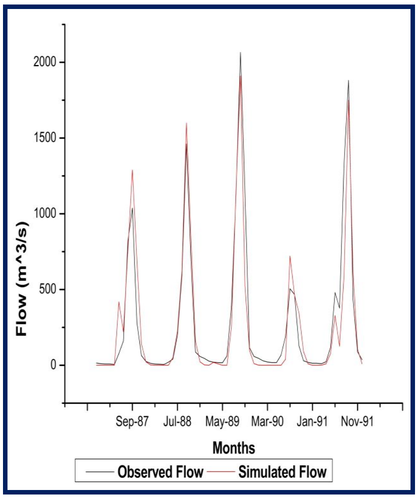
Catchment//Time period	PRECIP (mm)	Surface Runoff (mm)	PET (mm)	ET (mm)	SW (mm)	Water yield (mm)
Northern (2011-2040)	-9.3% to 21.8%	-21.2% to 72.6%	-0.2% to 3.9%	-6.0% to 13.1%	-32.5% to 63.1%	-14.3% to 73.4%
Northern (2041-2070)	-8.3% to 23.1%	-20.1% to 74.4%	2.6% to 6.8%	5.4% to 13.9%	-31.8% to 62.4%	-13.5% to 77.4%
Northern (2071-2100)	-8.0% to 24.3%	-16.7% to 76.2%	5.5% to 10.0%	-3.8% to 14.6%	-32.5% to 61.1%	-13.1% to 80.4%
Southern (2011-2040)	-8.7% to 4.5%	-12.8% to 20.6%	-0.3% to 6.5%	-2.5% to 11.1%	-5.6% to 15.4%	-19.7% to 10.5%
Southern (2041-2070)	-7.7% to 6.2%	-10.2% to 24.2%	2.6% to 9.3%	-0.7% to 14.8%	-5.9% to 14.3%	-19.3% to 12.2%
Southern (2071-2100)	-7.2% to 8.32%	-9.5% to 25.1%	5.3% to 13.5%	1.4% to 18.0%	6.5% to 14.4%	-18.7% to 12.7%

NSE during validation ranged from 0.64 for gauging station Dapola to 0.86 for gauging station Nawuni. Although some of the smaller (upstream) sub-basins did not calibrate well, results from gauging stations Dapola, Nawuni and Bamboi representing the outlets of the two biggest sub-basins, White Volta and Black Volta basin respectively (Fig. 4), show reasonable simulation of Volta River basin hydrology, in general.

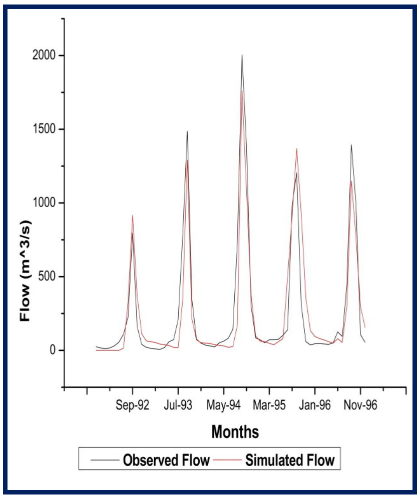
Climate change projections for Volta River basin: HadCM3 model with A1B scenario anticipates basin-wide increase in annual average rainfall and temperature. Compared to baseline 1979-2008 (Fig. 5), increase in rainfall is about 3%, 4% and 5% whilst temperature is about 0.6°C, 1.9°C and 3.5°C for 2011-2040, 2041-2070 and 2071-2100 respectively.

The results are in agreement with previous studies by Jung (Jung 2005), Jung and Kunstmann (Jung & Kunstmann 2005) and Van de Giesen (Van de Giesen et al. 2010), but disagrees with previous studies by Aditya (Aditya et al. 2013) and Kasei (Kasei 2009) who projected decrease in mean annual rainfall.

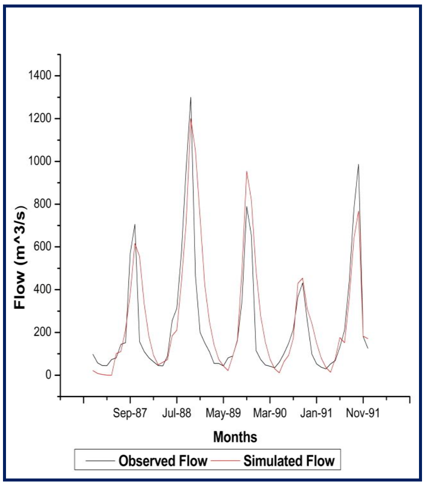
Hydrological response to climate change in Volta River



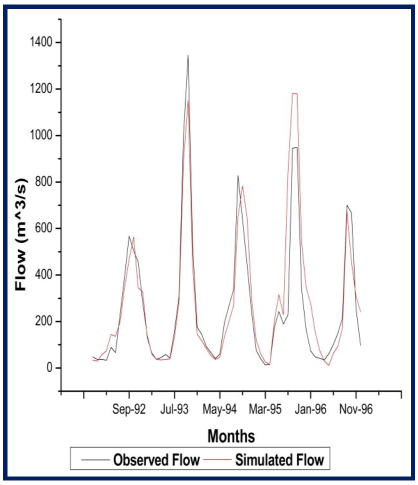
(**a**) Calibration plot for Nawuni



(**b**)Validation plot for Nawuni



(**c**) Calibration plot for Bamboi

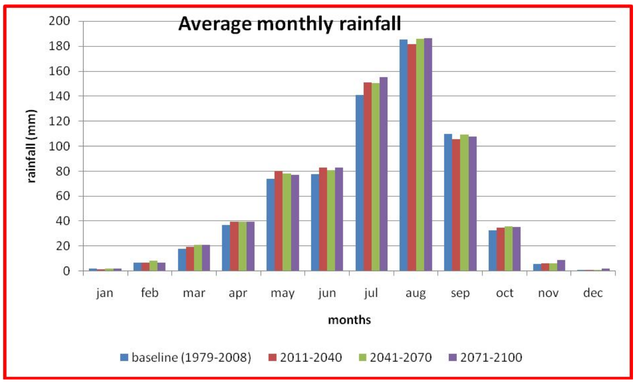


(**d**) Validation plot for Bamboi

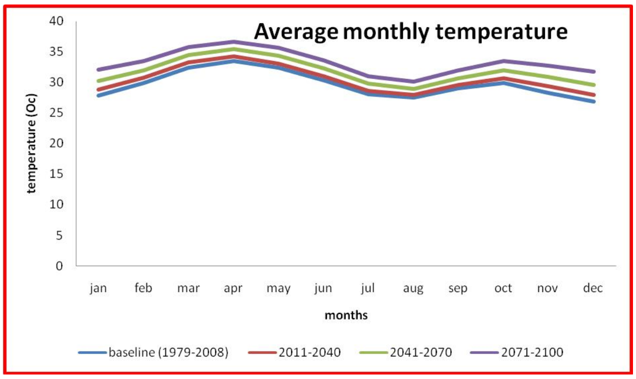
Fig. 4: Calibration and validation plots for Nawuni (White Volta basin outlet) and Bamboi (Black Volta basin outlet).

basin: The increase in mean annual rainfall and temperature leads to variations in other hydrological processes. The statistical properties of the hydrological fluxes are summarized in Table 4.

Mean annual surface runoff and groundwater recharge (GW) show increase in response to increase in mean annual rainfall. Compared to baseline, basin-wide surface runoff increases by about 9%, 12% and 14%, whilst groundwater recharge increases by 16%, 24% and 32% in response to small increase of 3%, 4% and 5% of the mean annual precipitation in 2011-2040, 2041-2070 and 2071-2100, respectively. Also, as a result of projected increase in mean daily temperature, potential evapotranspiration (PET) increase in the basin. PET increases by about 2%, 4% and 8% in 2011-2040, 2041-2070 and 2071-2100, respectively. Also due to increased rainfall, actual evapotranspiration (AET) which is a measure of available water for plant utilization also increases. AET increases by about 3%, 4% and 5% for 2011-2040, 2041-2070 and 2071-2100, respectively. This has significant bearing on water yield. The water yield (surface runoff + lateral flow + groundwater flow-transmission losses-pond abstraction) is a measure of net amount of water that leaves the sub-basin and contributes to discharge in the reach. The basin-wide water yield also increases by about 4%, 5% and 6% in 2011-2040, 2041-2070 and 2071-2100, respectively. The slight increase in rainfall also leads to slight increase in soil water availability (SW). SW increases by about 1.6%, 2.0% and 3.2% in 2011-2040, 2041-2070 and 2071-2100, respectively. The results show that the variability of the hydrologic fluxes is much higher at the end of the century (2071-2100) compared to other future time periods. Surface runoff and groundwater recharge show dis-



(a)



(b)

Fig. 5: Monthly averages of a) rainfall and b) temperature for 2011-2040, 2041-2070 and 2071-2100 compared to the baseline 1979-2008 for Volta River basin.

proportionate change in response to changes in mean annual precipitation and temperature. These results support Jung (2005), Jung & Kunstmann (2005), Aditya et al. (2013), Obuobie (2008) and Awotwi et al. (2015) assertions that there is a much larger non-linear response of runoff and groundwater recharge to smaller changes in rainfall.

Spatial variation of hydrology of Volta River basin under climate change: Fig. 6 shows the spatial variability of hydrologic fluxes for the sub-basins analysed, whilst Tables 5 and 6 summarize the variability of the various hydrologic fluxes at sub-basin level.

Contrary to the projected basin-wide increase in all hydrologic fluxes, some sub-basins in northern and southern catchment show decrease. Sub-basins Niaogho, Vonkoro, Yagaba and Ekumdipe (Fig. 6a) show decrease in rainfall for all future time periods with the decrease ranging from 2% to 10%. Dapola, Nawuni and Salaga show decrease in mean annual rainfall for only 2011-2040. The range of decrease is 1% to 2%. Salaga shows decrease of about 1% for 2041-2070. Northern sub-basin with highest decrease in mean annual rainfall is Yagaba with decrease of 9.3%, 8.3% and 8% for 2011-2040, 2041-2070 and 2071-2100 respectively. Southern sub-basin with highest decrease is Ekumdipe with decrease of 8.7%, 7.7% and 7.2% for 2011-2040, 2041-2070 and 2071-2100 respectively. Decrease in rainfall in these sub-basins will have negative impact on rain-fed agriculture. The increase in surface runoff (Fig. 6b) for all future time slices for sub-basins Rambo, Pwalugu, Nwokuy, Tenado, Kouri, Boromo, Lawra, Banzo, Ouessa, Dakaye, Bagre, Nangodi, Wiasi, Senchi and Kintampo is higher compared to the basin-wide increase. The increase range from 16% to 76% compared to the basin-wide increase in the range of 9% to 14%. The increase in surface runoff in 2041-2070 and 2071-2100 for sub-basins Manimenso and Ejura is higher compared to the basin-wide increase for the same periods. Increase in surface runoff for Manimenso and Ejura is about 13% in 2041-2070 compared to 12% for the whole basin whilst for 2071-2100, the increase for Manimenso and Ejura are 18% and 17% respectively compared to a basin-wide increase of 14%. Northern sub-basin with highest increase in mean annual surface runoff is Nwokuy with increase of 73%, 74% and 76% for 2011-2040, 2041-2070 and 2071-2100 respectively, whilst southern sub-basin with highest increase is Senchi with increase of 21%, 24% and 25% for 2011-2040, 2041-2070 and 2071-2100 respectively. These increases above the basin-wide increase are likely to increase flood events. Both northern and southern catchment show similar increase in most hydrologic fluxes (Tables 5 and 6) as that of the entire basin, but spatial variability exists. There is greater average increase in rainfall in northern catchment (4.4%, 5.4% and 6.3%) compared to southern catchment (0.6%, 2.1% and 3.6%) for 2011-2040, 2041-2070 and 2071-2100 respectively. The increase is much higher at the end of the century (2071-2100) compared to 2011-2040 and 2071-2100. Projected average increase in mean annual rainfall for northern catchment (4.4%, 5.4% and 6.3%) is greater than projected average increase for the entire basin (3%, 4% and 5%), whilst southern catchment shows lower average increase (0.6%, 2.1% and 3.6%) compared with projected average increase of (3%, 4% and 5%) for the entire basin for 2011-2040, 2041-2070 and 2071-2100 respectively. As with PET, the increase in southern catchment is higher than northern catchments for all future time periods. Similar to rainfall, the increase in PET is much higher at the end of the century (2071-2100). For 2011-2040, 2041-2070 and 2071-2100, the increase in PET for southern catchment is 2.2%, 5.2% and 9% respectively, compared to 1.5%, 3.6% and 7.1% for northern catchment. Average PET increase of 2.2%, 5.2% and 9%

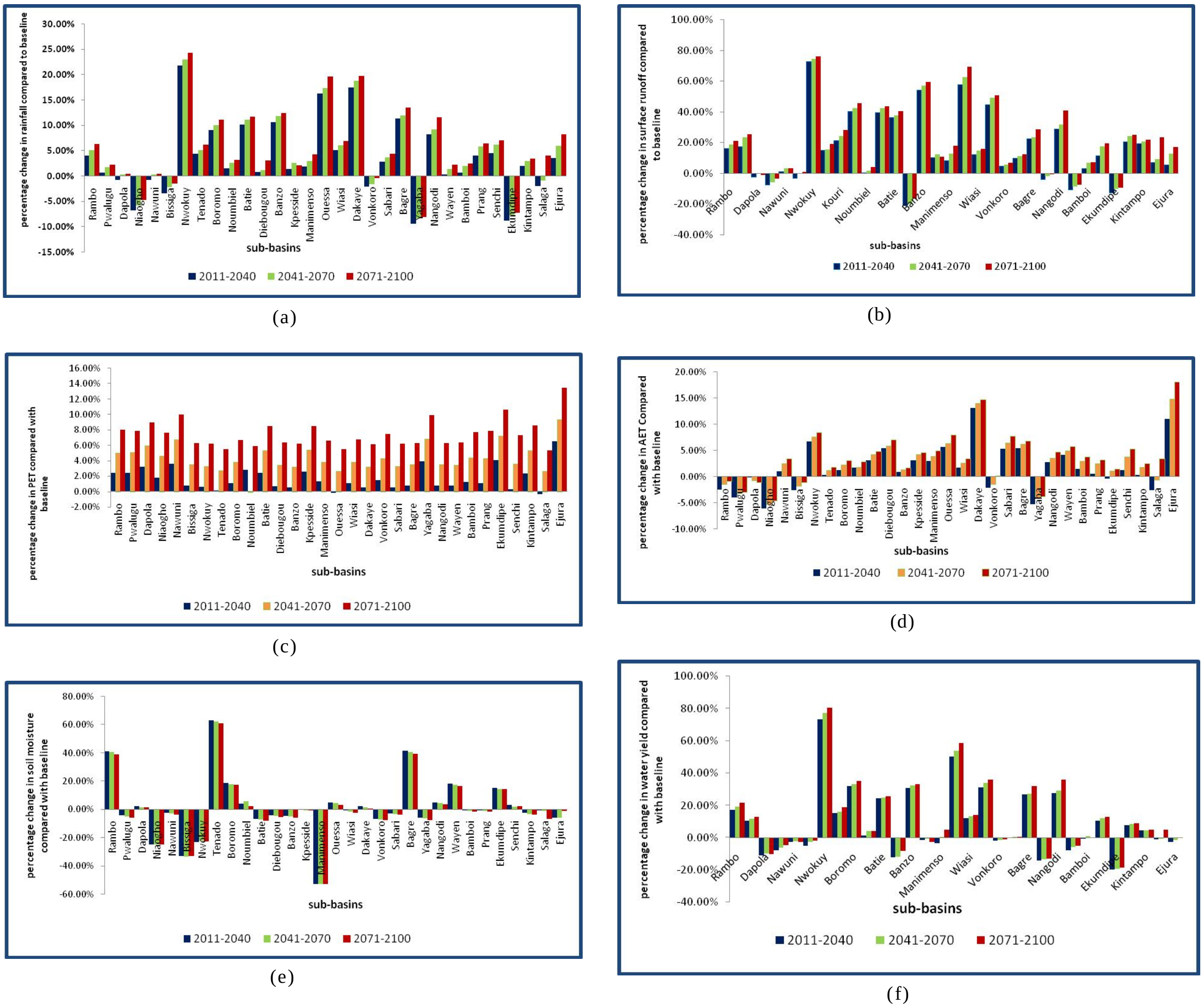


Fig. 6: Percentage change in (a) rainfall, (b) surface runoff, (c) PET, (d) AET, (e) SW and (f) water yield for the sub-basins relative to the baseline (1979-2008).

for southern catchment for 2011-2040, 2041-2070 and 2071-2100 respectively, is higher than the basin-wide increase of 2%, 4% and 8%, whilst the average increase of 1.5%, 3.6% and 7.1% for northern catchments is lower than the basin-wide average increase of 2%, 4% and 8% for 2011-2040, 2041-2070 and 2071-2100 respectively. Similar to PET, average AET increase of 1.7%, 3.7% and 5.3% for southern catchments is higher than the average increase of 1.5%, 2.5% and 3.3% for northern catchments for 2011-2040, 2041-2070 and 2071-2100 respectively. As with PET and rainfall, the increase in AET is also much higher at the end of the century (2071-2100) compared to 2011-2040 and 2071-2100. The average increase in AET for northern catchments (1.5%, 2.5% and 3.3%) is lower than the basin-wide increase of 3%, 4% and 5% for 2011-2040, 2041-2070 and 2071-2100 respectively. The increase in ET of 1.7% and 3.7% for southern catchments in 2011-2040 and 2041-2070 respectively, is lower than the basin-wide increase of 3% and 4%. For surface runoff, northern catchment shows higher average increase (16.8%, 19.2% and 21.7%) for 2011-2040, 2041-2070 and 2071-2100 respectively, when compared to average increase of 7.8%, 11.6% and 12.6% for southern catchment. Once again, the increase in surface runoff is also much higher at the end of the century (2071-2100). Projected average increase in surface runoff of 16.8%, 19.2% and 21.7% for northern catchment for 2011-2040, 2041-2070 and 2071-2100 respectively, is higher than the basin-wide average increase of 9%, 12%, and 14%, whilst average

Table 6: Average change in hydrological fluxes for northern and southern catchment as predicted by A1B scenario for 2011-2040, 2041-2070 and 2071-2100 compared to the baseline 1979-2008.

Catchment//Time period	PRECIP (mm)	Surface Runoff (mm)	PET (mm)	ET (mm)	SW (mm)	Water yield (mm)
Northern (2011-2040)	4.4%	16.8%	1.5%	1.5%	1.4%	12.0%
Northern (2041-2070)	5.4%	19.2%	3.6%	2.5%	1.0%	13.5%
Northern (2071-2100)	6.3%	21.7%	7.1%	3.3%	0.2%	15.2%
Southern (2011-2040)	0.6%	7.8%	2.2%	1.7%	1.4%	-0.2%
Southern (2041-2070)	2.1%	11.6%	5.2%	3.7%	0.6%	0.7%
Southern (2071-2100)	3.6%	12.6%	8.7%	5.3%	0.4%	1.9%

increase of 7.8%, 11.6% and 12.6% for southern catchment is lower than the basin-wide average. Projected average increase in soil moisture (SW) of 1.0% in 2041-2070 in northern catchment is higher than the projected increase of about 0.6% for southern catchment, but lower (0.2%) than the southern catchment (0.4%) for 2071-2100. Projected SW for both northern (1.4%, 1.0% and 0.2%) and southern catchment (1.4%, 0.6% and 0.4%) is lower than the basin-wide average of about 1.6%, 2.0% and 3.2% in 2011-2040, 2041-2070 and 2071-2100, respectively. The results indicate higher spatial variability with the variability much higher at the end of the century (2071-2100) compared to 2011-2040 and 2041-2070.

CLIMATE CHANGE ADAPTATION MECHANISMS

Contrary to the projected basin-wide average increase in all the hydrologic fluxes, some sub-basins in both northern and southern catchment show decrease, which will have a negative impact on rain-fed agriculture. An adaptation option would be to exploit groundwater. The higher value of RCHRG_DP (deep aquifer percolation fraction, i.e. the fraction of percolation from the root zone that recharges the deep aquifer), upto 0.9 in some parts of the basin, indicates the potential for harvesting groundwater for agriculture. Similarly, some sub-basins have average projected runoff above the basin-wide average e.g., 23% for northern catchment at the end of the 21st century compared to a basin-wide average of 14%. This might lead to the intensification of flood events in those catchments. An adaptation strategy that comes to mind is water storage through small reservoirs. Small reservoirs impound water behind small dams constructed across headwaters of ephemeral streams and rivers. The water stored during the rainy season is used for dry-season farming. Thus, they do not only store water for irrigating crops in the dry season, they reduce flood peaks by the process of attenuation. In the light of changing climate, a top to down approach for water resources management and climate change adaptation, where the same policies are formulated for the entire basin would be ineffective due to the spatially highly heterogeneous nature of climate in the Volta River basin. This, therefore, calls for a decentralized approach in the basin's water resources management incorporating the spatial variability of the hydrologic cycle into local climate change adaptation mechanisms.

CONCLUSIONS

The spatial variation of the hydrology of Volta basin under projected impacts of a climate change (CC) scenario based on Intergovernmental Panel on Climate Change (IPCC) A1B emission scenarios for 2011-2040, 2041-2070 and 2071-2100 using 1979-2008 as a reference period has been assessed using the Soil and Water Assessment Tool (SWAT). Compared to the baseline 1979-2008, the increase in rainfall is about 3% for 2011-2040, 4% for 2041-2070 and about 5% for 2071-2100, whilst the increase in temperature is about 0.6°C, 1.9°C and 3.5°C for 2011-2040, 2041-2070 and 2071-2100 respectively. The SWAT simulated outputs were then analysed at sub-basin level for northern (above latitude 9°N) and southern (below latitude 9°N) catchment based on the north-south spatial variability of rainfall in the basin. Overall the simulation indicates higher spatial variability in all the hydrologic fluxes with the variability much higher at the end of the century (2071-2100) compared to 2011-2040 and 2041-2070. There is greater average increase in rainfall and surface runoff in the northern catchments compared to the south. Average Potential Evapotranspiration (PET) and Evapotranspiration (AET) are much higher in southern catchments compared to northern catchments. Contrary to the projected average increase in rainfall for the entire basin, some of the sub-basins in both the northern and southern show decrease. The decrease range is from 2% and 10%. The decrease in rainfall might impact negatively on the rain-fed agriculture in those basins. The increase in surface runoff in the range of 16% to 76% in some sub-basins are far greater than the basin-wide range of increase of 9% to 14%. This might increase the probability of flood events in those basins. In all, the spatial variability in most of the hydrologic fluxes is much higher at the end of the century (2071-2100) compared to 2011-2040 and 2041-2070.

Exploitation of groundwater and the use of small reservoirs will go a long way in ameliorating the negative impacts of climate change on the livelihoods and wellbeing of people living in the basin. It is also suggested that instead of a top to down approach, there should be a decentralized approach in the basin's water resources management that incorporates the spatial variability of the hydrologic cycle into local climate change adaptation mechanisms.

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