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Assessing the impact of land use/land cover and climate changes on water stress in the derived savanna

AMIDU AYENI[1], EVISON KAPANGAZIWIRI[2], ALABI SONEYE[1], SAJITH VEZHAPPARAMBU[3] & JIMMY ADEGOKE[4]

1 Department of Geography, University of Lagos, Lagos, Nigeria
aayeni@unilag.edu.ng, ayeniao2000@yahoo.com
2 HydroSciences Research Group, Natural Resources & the Environment, CSIR Pretoria, South Africa
3 Global Change & Ecosystem Dynamics Group, CSIR Pretoria, South Africa
4 Department of Geo-Sciences, University of Missouri, Kansas City, USA

Abstract Understanding the impact of land use/land cover (LULC) and climate patterns on basin runoff is necessary in assessing basin water stress. This assessment requires long-term observed rainfall time series and LULC spatial data. In order to assess the potential water stress, the study used long-term (1981–2007) rainfall data to drive the Pitman monthly rainfall–runoff model to assess changes in runoff for three selected basins in Nigeria: Asa, Ogun and Owena. In spite of the limitations in the availability of spatio-temporal hydro-meteorological data, the model results revealed commensurate increase in the runoff coefficient with decreases in forest cover between 1981 and 2000. Low runoff coefficients of 5.3%, 12.0% and 6.4% were recorded for Asa, Ogun and Owena basins, respectively, based on C-CAM projection of low rainfall for 2010–2050. These results indicated that in the future, water stress in Asa and Owena basins would be much higher, when compared with Ogun basin.

Key words land-use/land-cover; climate change; rainfall; runoff; hydrological modelling; water stress; derived savanna; Nigeria

INTRODUCTION

Historically, changes and/or variability in climate and land use/land cover (LULC) remain the major drivers of the global water cycle/balance and have extensively altered the Earth's surface through conversion from one land-use class to another, such as from cultivation to urbanization, with resulting impacts (e.g. low flows, flooding/erosion, water quality degradation) on river flows (Mahmood *et al.*, 2010; Vimal *et al.*, 2010). According to Oki & Kanae (2006), river flow as a naturally and constantly circulating and recharging resource should be the main focus in water resources assessments. The alteration of river flows as a consequence of climate and land use/land cover change (LULCC) and climate change (CC) is expected to increase pressure on available water resources, thereby accelerating conditions of water scarcity and water stress in many societies. In addition, water control structures – surface storage (dams and reservoirs) – originally designed to relieve water stress may exacerbate the problem. In some cases upstream users influence when, how much and, at times, the quality of water downstream users may receive (Padowski & Jawitz, 2009), with limited knowledge of the hydrological processes of the catchment and future implication of their actions.

In hydro-climatic scenario modelling, long-term rainfall and temperature play important roles; for instance, the amount of runoff considerably depends on spatio-temporal variability of rainfall (Kepner *et al.,* 2008; Kumar and Duffy, 2009). In addition to climatic factors, the basin's anthropogenic and physiographic (including edaphic and LULC characteristics) factors are also very important in generating and explaining monthly river flow patterns (Mulholland *et al*, 2008; Kumar and Duffy, 2009; Peel, 2009, Potter *et al.*, 2010; Davidson *et al.*, 2012). In data scarce regions of the world, hydrological simulations still face various challenges which include inadequate understanding of hydrological processes and mechanisms, coupled with limited historical observations at appropriate model spatio-temporal scales, and high capacity super computers (Kumar & Duffy, 2009). The Fourth Assessment Report of the IPCC predicts an intensification of the global hydrological cycle due to climate change that will affect both groundwater and surface water supplies. The report concluded that the negative impacts of climate change on freshwater systems may significantly outweigh its benefits, with runoff declining in most streams and rivers (IPCC 2007). River basins may be in the severe water stress category for different reasons. In low-flow periods relatively high water consumption may cause absolute threats of water shortages and, conversely, increase the pressure on both water quality and quantity in water stress river basin (Falkenmark, 1989; Amber & Matlock, 2011). In 2002, IPCC assessment revealed projected climate change could further decrease streamflow and groundwater recharge in many water stressed countries (Henrichs *et al*., 2002).

Nonetheless, understanding the relative impact of regional LULCC patterns and future climate change on basin runoff is necessary in regional water stress assessment (Vimal *et al.*, 2001). Therefore, depending on catchment hydrogeological and physico-geographical characteristics, and the amount of storage water (surface or groundwater), basins may respond differently to the same climate change drivers (Gosain *et al.*, 2006).

STUDY AREA

The derived savanna of southwestern Nigeria is located in the southern corridor of the River Niger. It cuts across five (Ogun, Oshun, Ose, Kampe and Niger 6) of seven major basins in southwestern Nigeria. The sub-basins within these five major basins are many and include the Asa, Apoje, Opeki, Ofiki, Ose, Osun and Owena. Three basins were selected for this study: one major basin, the Ogun, and two sub-basins the Asa and Owena (Fig. 1).

The mean temperature of the area ranges between 32°C in the northern part around Asa sub-basin and 26°C in the southern part of Ogun basin and Owena sub-basin. The annual rainfall ranges between 1000 and 1800 mm from the vegetation zones of the north (Asa and northern part of Ogun basin) to the south (southern parts of Ogun and Owena). However, the whole area has two distinguishable seasons, a wet season between April and October and a dry season from November to March.

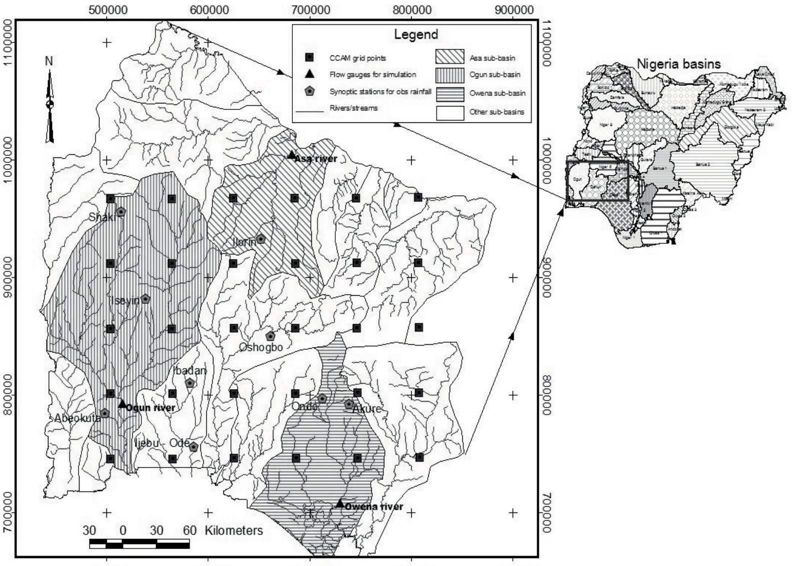

Fig. 1 The study area.

MATERIALS AND METHODS

Long-term observed rainfall and temperature data, obtained from eight different weather stations across the catchment were used to study the climate of the region and to simulate river flows. The observed rainfall and discharge data for the Asa, Ogun, and Owena basins were collected from the Lower Niger Basin Authority at Ilorin, Ogun-Osun Basin Authority at Abeokuta, and Benin-Owena at Benin, respectively. The monthly rainfall records of 50 years (1960–2010) for Asa and Owena basins, and 30 years (1980–2010) for Ogun basin, were available for the study. As a result of challenges in accessing historical observed river flow data in the area, only limited monthly data for 7 water years (1966–1973) for Asa and 9 water years (1990–1999) for Owena were available. No discharge data were available for Ogun. The Pitman rainfall–runoff monthly model (Pitman, 1973; Hughes *et al.*, 2006) was chosen for the generation of monthly time series of flow. Data on basin hydro-meteorological and physiographic characteristics were used to assist in the training and estimation of model parameters (Kapangaziwiri & Hughes, 2008).

For the assessment of CC impacts, projected climate data (rainfall and temperature) up to the year 2050 dynamically downscaled to a 60 km × 60 km grid using the Conformal-Cubic Atmospheric Model (C-CAM) (McGregor 2005; Engelbrecht *et al.,* 2009) were used. The C-CAM model was adopted because it employs a wide range of physical parameterizations of the CSIRO mass-flux cumulus convection scheme, which includes downdrafts and the evaporation of rainfall (Engelbrecht et *al*., 2009). Since C-CAM has the ability to simulate both yearly and intra-annual rainfall totals, the validation of C-CAM over the study area was qualitatively verified against observed data from eight synoptic stations in the region of interest before the simulation of rainfall–runoff projection. Both historical observed and simulated future climate data were input to the rainfall–runoff model to generate probable time series of river flows that were used to evaluate the impacts of LULCC and CC on the water stress.

Brief description of the Pitman rainfall–runoff model used

The main purpose of the modelling component of this study was to set up the hydrological baseline of the study area. Given the paucity of historical observed data for model calibration in the study area, the application of the model used an *a priori* physically-based parameter estimation routine described in Kapangaziwiri & Hughes (2008) and Kapangaziwiri (2011) to directly establish parameter values for the model in the study basins. The information on critical soil attributes, such as soil depth and texture, were inferred from the soil maps of Nigeria and literature (e.g. Sonneveld, 1996; Iloeje, 2001; Aregheore, 2009).

The model parameters derived from the estimation process and all other available relevant information on water use were input to the model to generate the hydrological scenarios for the area. Where there were limited observed runoff data (i.e. for some parts of the Asa and Ogun basins), these were also used only to guide the model simulations given that the short periods of available data are inadequate for proper training of the monthly model. In spite of these limitations in the available data, the simulations were deemed acceptable based on comparisons of flow duration curves such as at Owena River (Fig. 2). The reasonable success of the simulations in this (poorly) gauged basin provided the confidence to apply the *a priori* parameter estimation approach in the ungauged parts of the basins for this study.

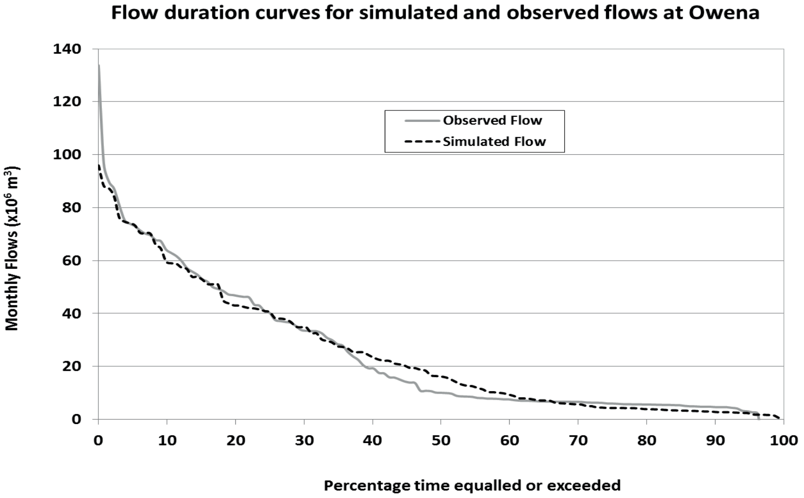

Fig. 2 Comparison of flow duration curves of simulation and observed flows at the outlet of Owena sub-basin.

Analysis of impacts of climate change

In order to simulate expected river flows for future climate change (CC) scenarios, the model was driven by projected C-CAM rainfall time series datasets. Bias was removed from these datasets before they were used. The C-CAM projected rainfall was adjusted by a weighting factor dependent on the relationship between the mean annual precipitations (MAPs) of the observed and projected rainfall datasets.

Land use/land cover change analysis methods

The LULCC analysis was based on spatio-temporal ortho-rectified Landsat imagery datasets between 1972 and 2007. The datasets were sourced from the Global Land Survey (GLS) portal (http://glovis.usgs.gov/) and include the following scenes: the Multispectral Scanner (MSS) in the 1970s, the Thematic Mapper (TM) in 1990, the Enhanced Thematic Mapper Plus (ETM+) in 2000 and 2006. The paths and rows images for each time T year were downloaded and processed within ENVI using a maximum likelihood (MLH) classification technique. For the purpose of this study, four major land uses were identified and classified: built-up, forest (the study target), cultivation/others and water-bodies.

RESULTS AND DISCUSSION

Land use/land cover changes

The LULC analysis results shown in Table 1 reveal that forested areas have reduced significantly while cultivation and built-up areas increased within the derived savanna area from 1972 to 2006. In 1972, forest covered almost 76.4% out of the total land cover of 56 072.3 km^2. This was followed by cultivation/others (23.4%) while built-up and water-bodies together represent only 0.2% of the total area. By 2000/2002, massive increase had occurred in cultivation/others (246.6%) with slight increases in built-up (7.2%) and water-bodies (1.4%) as forest land cover continued to decrease in spatial extent (255.1%). The trend continued until 2007 as forest lost more area to built-up, cultivation/other and water-bodies through urbanization, farming and dam construction. LULCC has the potential to influence rates of runoff and thereby increase the risk of flooding and evaporation (Amber & Matlock, 2011). In such cases, more urbanized areas are likely to experience higher runoff and high rates of evaporation, whereas cultivated areas will be susceptible to more infiltration and less surface flow, meaning lower runoff coefficients.

Table 1 LULC values from classified images (between 1972 and 2007).

	1972		1986/87		2000/02		2006/07	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Built-up	83	0.2	307	0.6	803	1.4	1 134	2.0
Forest	42 819	76	21 856	39	17 305	31	16 148	29
Cultivations & others	13 144	23	33 838	60	37 802	67	38 617	69
Water-bodies	27	0.05	72	0.1	162	0.3	174	0.3
Total	56 072	100	56 072	100	56 072	100	56 072	100

Climate change

The LULCC and CC trends were analysed to evaluate their influence on water resources and assess water stress conditions in the derived savanna of southwest Nigeria. The present day trends in climate and the model-predicted future climatic changes, in connection with the anthropogenic LULCC, provide vital information on the evolution of freshwater dynamics in the study area.

Trends in rainfall and temperature

Long-term time series for rainfall and temperature anomalies were generated using both observed and C-CAM simulated datasets. The rainfall datasets were prepared as input for the Pitman

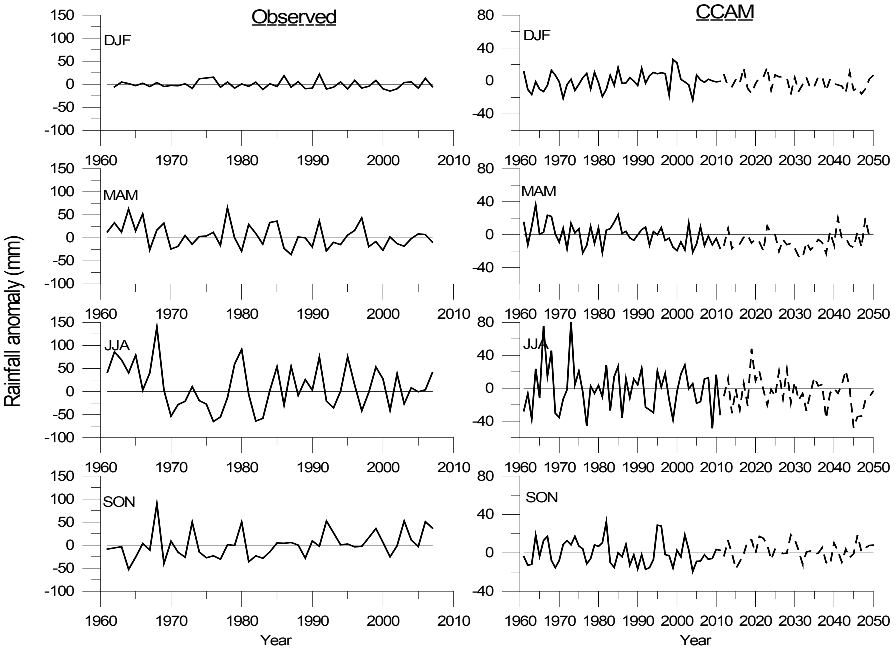

Fig. 3 Rainfall (observed and C-CAM projected anomalies) over the area.

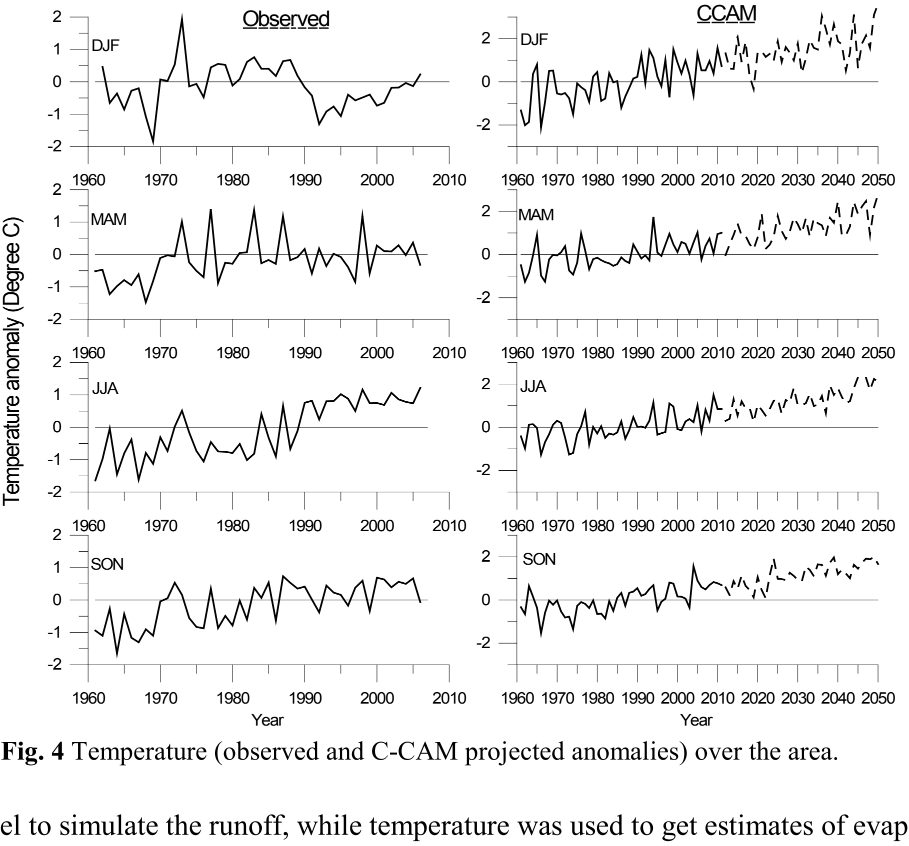

Fig. 4 Temperature (observed and C-CAM projected anomalies) over the area.

model to simulate the runoff, while temperature was used to get estimates of evapotranspiration for the model. Inter-annual variations of the seasonally averaged rainfall from 1961 to 2010 (C-CAM data spans up to the year 2050) showed a negative trend in the rainfall anomaly (Fig. 3).

The temperature anomaly time series clearly presented an increasing trend for all the seasons except for the December-January-February (DJF) averaged observed temperature (Fig. 4). The temperature is near to 1°C more than the 40-year mean in 2010, and a more than 2°C increase is predicted in 2050 (see also IPCC 2007; Boko *et al.*, 2007).

These results imply that the area will be at more risk of water stress in 2050. IPCC (2007) predictions also imply an increase in the number of people that will experience water stress in Africa.

Runoff

The three basins demonstrated spatial-temporal variability in their simulated mean annual runoff (MAR). As at 2008, MAR was $146.5 \times 10^6 m^3$ (±58.3), $433.2 \times 10^6 m^3$ (±128.1), and $150.3 \times 10^6 m^3$ (±33.5) for the Asa, Ogun and Owena basins, respectively (Table 2). The runoff coefficient showed average increases commensurate with decreases in forest cover between 1981 and 2000 (Table 1). On average, the model revealed that between 1981 and 2007, Asa, Ogun and Owena basins had runoff coefficients of 15.3%, 20.3%, and 11.8%, respectively. The decadal time series analysis depicted increases in the runoff coefficient (Table 2). One of the most important concerns regarding these increases was that the period experiences relatively high rainfall, continuous forest degradation and rapid urbanization. These changes were commensurate with significant changes in runoff coefficient over the three selected basins.

Table 2 Hydro-climatic and physical details for the three basins.

	1981–1990			1991–2000			2001–2008		
	Asa	Ogun	Owena	Asa	Ogun	Owena	Asa	Ogun	Owena
Mean flow ($\times 10^6$ m^3)	121.0	399.9	166.5	138.1	488.7	193.1	146.5	433.2	150.3
Area of sub-basin (km^2)	9600	22000	11000	9600	22000	11000	9600	22000	11000
Mean monthly runoff (mm)	12.6	18.2	15.1	14.4	22.2	17.6	15.3	19.7	13.7
Mean monthly rainfall (mm)	90.9	99.5	132.4	90.7	98.1	142.2	89.7	98.1	124.2
Runoff coefficient (%)	13.9	18.3	11.43	15.9	22.6	12.34	17.0	20.1	11.00

Although the simulation does not exhibit consistent changes in runoff for the three basins as well as for the whole period (i.e. 1981–2008), nevertheless, there were conspicuous changes in runoff which reflect changes in LULC (Table 2) and climate (Figs 3 and 4). Increases in runoff coefficient predominantly occur within two basins (Asa and Ogun) that have over 50% of highly degraded forest areas. The model parameters of observed runoff simulation were assumed unchanged for future scenarios given that information on how the basin physical characteristics would change in response to climate changes was not available. Based on this, the 40-year (2010–2050) model predictions based on C-CAM projected rainfall data resulted in lower runoff coefficients of 5.3%, 12.0% and 6.4% for Asa, Ogun and Owena basins, respectively.

The runoff coefficients of the Asa and Owena basins are much lower, when compared to Ogun basin. These indicate that, in the near future, water stress in the Asa and Owena basins would be much higher based on the Falkenmark (1989) indicator which expresses water stress as the fraction of the total annual runoff available for human use (consumptive and non-consumptive) and on the estimation that a flow unit of 10^6 m^3 of water can support 2000 people in a society with a high level of development. Therefore, the annual water supplies per person in the two basins will drop far below 1700 m^3 (i.e. < 1700 m^3 and > 1000 m^3)

CONCLUSIONS

Based on the findings from this study, it was observed that the changes in LULC and climate had an impact on the hydrology of the three selected basins. The runoff simulation results for the basin scenarios indicate that LULCC associated with potential CC are significant in the river runoff study. Urbanization and increasing cultivation were commensurate with significant changes of runoff coefficient over the three selected basins. As a result, the continuous urbanization and increase in cultivation could possibly increase evaporation over the three basins and, therefore, a significantly sustained decrease in runoff coefficient in future. The results suggest that it is advisable for all water stakeholders in the area to adopt various options for increasing water supply and capacity as well as reducing LULC and climate change trigger activities, e.g. excessive logging and deforestation within the river catchment areas. For future adaptation, communities in the water stress basins could embrace community water development and management strategies.

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