Modelling Future Flows of the Volta River System: Impacts of Climate Change and Socio-Economic Changes

Li Jin[1], Paul Whitehead[2], Kwasi Appeaning Addo[3], Barnabas Amisigo[4], Ian Macadam[5] and Tamara Janes[5], Jill Crossman[6], Robert J. Nicholls[7], Matthew McCartney[8] and Harvey J.E. Rodda[9]

[1] Geology Department, State University of New York College at Cortland, Cortland, NY 13045, USA

[2] School of Geography and the Environment, University of Oxford, Oxford, UK

[3] Department of Marine and Fisheries Sciences, University of Ghana, Accra, Ghana

[4] CSIR-Water Research Institute, Box AH 38, Achimota, Accra, Ghana

[5] Met Office, FitzRoy Road, Exeter, EX1 3PB, United Kingdom

[6] Department of Earth and Environmental Sciences, University of Windsor, Windsor, ON, Canada

[7] Faculty of Engineering and the Environment, University of Southampton, Southampton, UK SO17 1BJ, UK

[8] International Water Management Institute, PO Box 2075, Colombo, Sri Lanka

[9]Hydro-GIS Ltd, 10 Coles Lane, Chalgrove, Oxfordshire OX44 7SY, UK

Abstract

As the scientific consensus concerning global climate change has increased in recent decades, research on potential impacts of climate change on water resources has been given high importance. However in Sub-Saharan Africa, few studies have fully evaluated the potential implications of climate change to their water resource systems. The Volta River is one of the major rivers in Africa covering six riparian countries (mainly Ghana and Burkina Faso). It is a principal water source for approximately 24 million people in the region. The catchment is primarily agricultural providing food supplies to rural areas, demonstrating the classic water, food, energy nexus. In this study an Integrated Catchment Model (INCA) was applied to the whole Volta River system to simulate flow in the rivers and at the outlet of the artificial Lake Volta. High-resolution climate scenarios downscaled from three different Global Climate Models (CNRM-CM5, HadGEM2-ES and CanESM2), have been used to drive the INCA model and to assess changes in flow by 2050s and 2090s under the high climate forcing scenario RCP8.5. Results show that peak flows during the monsoon months could increase into the future. The duration of high flow could become longer compared to the recent condition. In addition, we considered three different socio-economic scenarios. As an example, under the combined impact from climate change from downscaling CNRM-CM5 and medium+ (high economic growth) socio-economic changes, the extreme high flows (Q5) of the Black Volta River are projected to increase 11% and 36% at 2050s and 2090s, respectively. Lake Volta outflow would increase +1% and +5% at 2050s and 2090s, respectively, under the same scenario. The effects of changing socio-economic conditions on flow are minor

compared to the climate change impact. These results will provide valuable information assisting future water resource development and adaptive strategies in the Volta Basin.

Key words: river flow, climate impacts, modeling, water resources, Ghana, Africa

INTRODUCTION

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia" (IPCC, 2013b). There is a need now to consider the likely positive and negative impacts of climate change on the natural environment and people across the globe. Deltas are widely recognized as being highly vulnerable to the impacts of climate change particularly sea level rises and river runoff changes (Hoang et al., 2016; Kay et al., 2015; Nepal and Shrestha, 2015; Nicholls et al., 2016; Smajgl et al., 2015; Whitehead et al., 2015b). Many are also impacted by the effects of urbanization and changes in sediment input (Allison et al., 2017; Gu et al., 2011; Syvitski et al., 2005). Low and mid latitude deltas have some of the highest population densities in the world; with more than 500 million, often poor, residents living in deltas globally (Ericson et al., 2006). Therefore it is essential to develop methods to assess the vulnerability of deltaic areas and establish adaptive strategies including migration available to deltas residents. To do so, a set of physical, geographical and chemical models are needed to simulate the catchments and the river systems that go into the delta estuary. The simulations from the catchment models are a valuable source of information to assess impacts of climate change on the downstream delta estuary and coastal systems.

As the scientific consensus concerning climate change, and awareness of the impacts on river systems has increased in recent years, there is a growing need to incorporate climate change into water resources management and water storage planning for large catchments (Sadoff and Muller, 2009). However, across much of sub-Saharan Africa, climate change is given low priority. In many countries there has been few systematic evaluations of changing river flow regimes and the potential influence to the coastal zone under climate change, which is given little consideration in the planning of future water resources development. This is addressed as part of the DECCMA project (Hill et al., 2018) with a focus on the Volta River Basin and Volta delta in Ghana, Africa.

The Volta River system is a transboundary catchment and the principal water source for approximately 24 million people in six riparian states, namely Ghana, Burkina Faso, Benin, Cote d'Ivoire, Mali and Togo (McCartney et al., 2012). The catchment drains into Lake Volta in Ghana, the largest man-made lake in the world, and a major supplier of hydropower to Ghana. The catchment is primarily agricultural providing food supplies to rural and urban areas, demonstrating the classic water, food, energy nexus. The basin's population is projected to nearly double in number from 19 million in 2000 to 31 million in 2025 and 32 million in 2050 (McCartney et al., 2012). Water resources in the Volta Basin have been under increasing pressure in recent years as significant population growth and economic development in Ghana and Burkina Faso has resulted in larger abstractions to meet increasing demand (Van de Giesen et al., 2001).

Several studies in the past indicated a reduction in rainfall and runoff in the Volta Basin since the 1970s (Gyau-Boakye and Tumbulto, 2000; Lacombe et al., 2012; Owusu et al., 2008), as well as an increase in drought frequency (Kasei et al., 2010). This may be attributable to changing climate. There is an agreement between different climate models that the climate of Volta Basin will warm over the course of the 21st century, though the magnitude of the warming differs between different models and different scenarios for future greenhouse forcing of the global climate system (IPCC, 2013a). It is uncertainty between models in the sign of future rainfall changes in the basin that is more likely to complicate the management of the basin's water resources. For example, McCartney et al., 2012 used a dynamic regional climate model (CCLM), a hydrological model (SWAT) and a water resource model (WEAP) to assess a "middle impact" (between extremes) climate change scenario on existing water uses within the basin (McCartney et al., 2012). This work suggested that annual average rainfall, runoff and mean groundwater recharge will decrease by 2050. In contrast, Awotwi et al. (2015) (Awotwi et al., 2015) used an ensemble of the Regional Climate Model (REMO) and suggested that the White Volta sub-basin will experience 8% precipitation increase with a 26% increase in surface runoff. The disagreement between these studies largely reflects the inconsistency in projecting rainfall from different climate models/scenarios.

In this paper we use the INtegrated CAtchment (INCA) dynamic process based model for flow to assess impacts of changes in climate and socio-economics driven by population, agriculture and water demands for public supply and hydropower. To sample uncertainty in future climate and socio-economic conditions, we considered climate scenarios downscaled from three different Global Climate Models (GCMs) and three different socio-economic scenarios.

Our aim is to conduct a comprehensive assessment on flow changes to the end of the century and assist future water resources development in the Volta Basin. The outcomes of this work will also be important for studies on the coastal zone downstream from the Lake Volta. The future changes in river flow dynamics could alter the sediment load and nutrient load into the Volta delta.

Study area and Methods

The Volta Basin

The Volta Basin (403,000 km^2) is shared by six riparian countries in West Africa (Figure 1a). It lies mainly in Ghana (42%) and Burkina Faso (43%) with the remainder in Benin, Cote d'Ivoire, Mali and Togo. There are three major tributaries: the Black Volta River (147,000 km^2), the White Volta River (106,000 km^2) and the Oti River (72,000 km^2), which merge together to form the Lower Volta (73,000 km^2) (Figure 1b). The Black Volta River originates as the Mouhoun in Burkina Faso and drains western Burkina Faso, northwest Ghana and small parts of Mali and Cote d'Ivoire. The White Volta River originates as the Nakambe in Burkina Faso and flows northern and central Burkina Faso and Ghana. The Oti River originates as the Pendjari in Benin and flows through Togo. The Lower Volta flows directly into the Lake Volta, which is created by the Akosombo Dam and is the major man-made feature of the Volta River system. The outflow from the Lake Volta discharges into the Gulf of Guinea in the Atlantic Ocean through the Volta delta (Figure 1a).

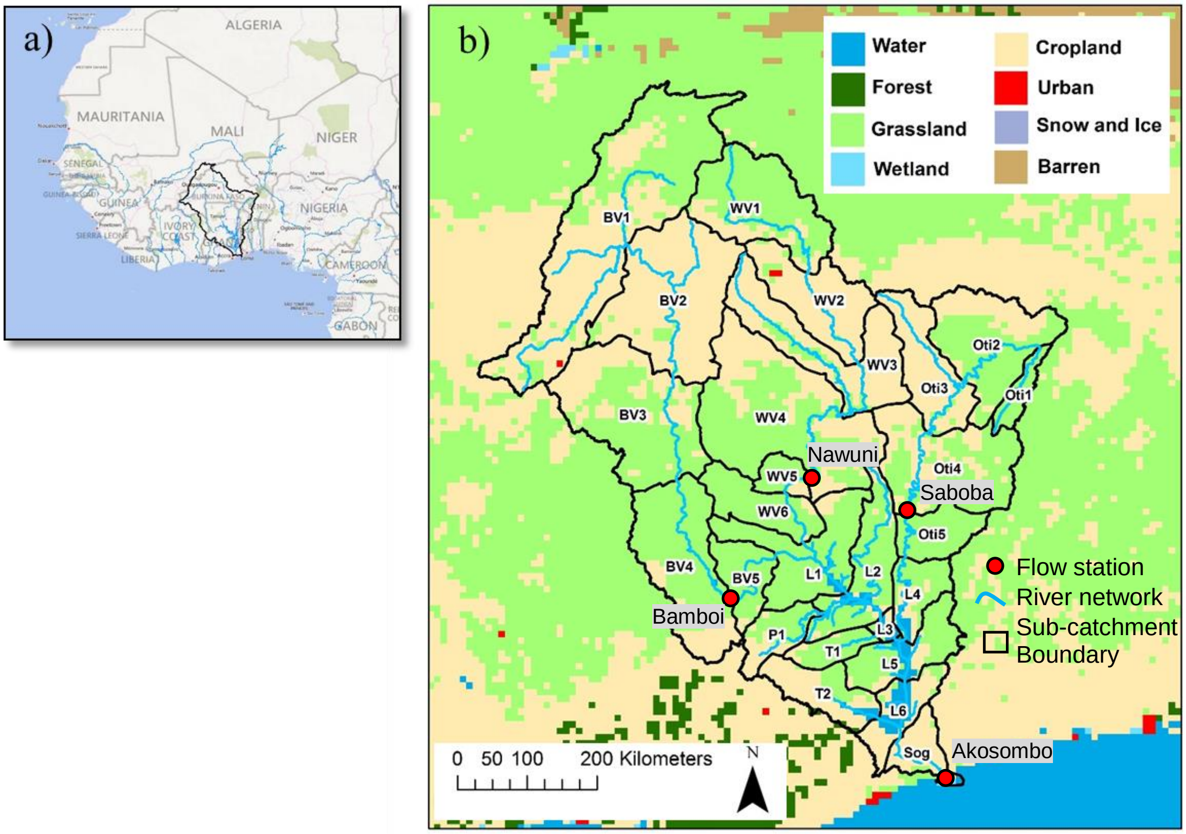


Figure 1. a) a map of the Volta River Basin in West Africa draining into the Gulf of Guinea in the Atlantic Ocean; b) the Volta River Basin consisting primarily of the Black Volta River (INCA reaches: BV1 to BV5), White Volta River (INCA reaches: WV1 to WV6) and Oti River (INCA reaches: Oti1 to Oti5) and Lower Volta River (INCA reaches: L1 to L6); major land use types are grassland and cropland within the basin; three flow stations (Bamboi, Nawuni and Saboba) are located near the mouth of each main river and a final flow station is located at the Akosombo dam outflow.

The Volta River is one of the largest rivers in Africa. The Lower Volta has the total average annual flow of approximately 40,000 million cubic meters (Mm^3) (McCartney et al., 2012). The flow varies considerably from year to year (Andah et al., 2004). The construction of the Akosombo dam in 1964 (Anthony et al., 2016) resulted in the formation of the Lake Volta, covering an area of approximately 8,500 square kilometers (km^2) with a storage capacity of

148,000 Mm^3, which gives an average residence time of 3.7 years for the reservoir (Barry et al., 2005).

The climate of West Africa is dominated by a north-south trend in rainfall between a dry continental air mass over the Sahara and a moist tropical maritime air mass over the Gulf of Guinea (Dickson and Benneh, 1988). The two air masses meet at the Inter-Tropical Convergence Zone (ITCZ). Due to the movement of the ITCZ with seasons, precipitation in the Volta Basin varies significantly from season to season. Nearly 70% of annual rainfall in the basin occurs during the three months of July, August and September, with little or no rainfall between November and March over most parts of the basin (Mul et al., 2015). The amount of precipitation also varies significantly from year to year (Nicholson, 2005; Van de Giesen et al., 2001).

Temperature generally increases from the south to the north of the Volta Basin. The mean annual temperature ranges from 27 °C in the south to 36 °C in the north with a large diurnal temperature range (6-8 °C in the south to 10-13 °C in the north) (Oguntunde, 2004). The seasonal variation in temperatures is characterized by two extremely hot periods (March-April and after the rainy season) and two relatively cool periods (December-February and during the rainy season) (Barry et al., 2005). Potential evapotranspiration is relatively high (1,800 mm-2,500 mm), especially in the northern part of the catchment (Amisigo, 2006; Amisigo et al., 2015).

The main land use types in the Volta River Basin are grassland and cropland (Figure 1b and Table 1). The most agriculturally productive area is in the south and southwest of the basin in Ghana. Crops grown in this region include cassava, yams, maize and sorghum.

There are a number of flow stations within the basin (Figure 1b). Daily flow data from Bamboi (Black Volta River) and Nawuni (White Volta River) as well as monthly flow data from Saboba (Oti River) and Akasombo dam outflow were used for calibration due to their sufficient data and sampling periods.

INCA models and PERSiST

The Volta River Basin is complex and requires a distributed model such as INCA to account for the spatial variability across the catchment. INCA is a process-based model that simulates flow and water quality (e.g. Nitrogen, Sediment, Phosphorus, Carbon, Chloride, Contaminants, Metals) in soil, groundwater and in-stream (Futter et al., 2007; Jackson-Blake et al., 2016; Jin et al., 2011; Lazar et al., 2010; Lu et al., 2017; Wade et al., 2009; Wade et al., 2002; Whitehead et al., 2009; Whitehead et al., 2011; Whitehead et al., 1998a; Whitehead et al., 1998b). It was first developed as a simple single stem river network model and was then developed into a more comprehensive hydrological and water quality model which can capture both the main river and tributaries in multiple-branch setups. The INCA model structure has four levels as follows (1) generic cell (1 km^2) in which terrestrial processes are simulated, (2) the land use scale where different land uses are considered, (3) the sub-catchment level that sums the land use inputs and also transports fluxes along the sub-catchment reaches, and (4) the multi-branch river basin scale in which distributed river networks are simulated (Whitehead et al., 2011). INCA models have been applied to both small and large river systems with catchment sizes ranging from a few tens of square kilometers to a million square kilometers e.g. (Bussi et al., 2017; Jin et al., 2015; Rankinen et al., 2013; Whitehead et al., 2015a; Whitehead et al., 2011). It has also been applied to sites where a substantial portion of the catchment comprises lakes e.g. Lake Simcoe in Canada (Crossman et al., 2013; Jin et al., 2013).

The data required for running the INCA model include river network topology, reach characteristics (e.g. reach length), sub-catchment areas, land use, hydrological parameters including hydrologically effective rainfall (HER) and soil moisture deficits (SMD). HER calculates the proportion of precipitation that eventually becomes surface runoff after accounting for evapotranspiration and interception, whereas SMD is defined as the depth of water required to return soil water content to maximum field capacity. HER and SMD were generated by the PERSiST model (Futter et al., 2014; Futter et al., 2015). PERSiST is a watershed-scale hydrological model, which has been applied to large river basins like the Ganga river system (Futter et al., 2015; Jin et al., 2015). It is a conceptual, daily time-step, semi-distributed model designed primarily for use with the INCA models. PERSiST simulates water fluxes from precipitation through the terrestrial part of a catchment and uses an evaporation mass balance to determine the evapotranspiration from which the HER and SMD are calculated.

The INCA flow is largely controlled by velocities and residence times within each reach which are characterized by specifying the a and b parameters of the velocity-flow relationship,

$$v = aQ^b \qquad \text{EQ.1}$$

where v (m/sec) is velocity and Q is discharge in the model. Although this is a simple representation, it is effective in capturing the dynamic response between velocity and flow (Whitehead et al., 1998a).

Application of INCA to Volta River

The Volta River system has been divided into 26 reaches to reflect its complex network including main rivers, tributaries and the Lake Volta (Figure 1b and Figure 2). The downstream modeling boundary was at the top of the Volta delta. The boundaries of reaches were selected based on the locations of the flow and water quality monitoring stations, and tributary confluences. A Digital Elevation Map was used to delineate the subcatchment for each reach. Table 1 shows the reach and subcatchment characteristics (reach length, catchment size, land use percentages). Water abstraction for public consumption and irrigation use as well as wastewater effluent discharge were calculated and taken into account in the model based on population and area of the agricultural land use.

Model performance was assessed at flow monitoring stations by comparing INCA modeled with observed flow data using r^2 and Nash-Sutcliffe (N-S) values.

Table 1 INCA reach and subcatchment characteristics in the Volta River Basin.

Reach	Area (km^2)	Length (km)	Land Use (%)					
			water	forest and scrub	grassland	Wetland	cropland	urban
BV1	54219	381.4	0	0	41.7	0	58.1	0.2
BV2	33421	350.3	0	0	3.9	0	96.1	0
BV3	31568	196.3	0	0	61.4	0	38.6	0
BV4	25092	263.1	0.3	0	78.4	0	21.3	0
BV5	7837	158.5	0	0	95.6	0	4.4	0
WV1	22320	356.3	0	0	78.6	0	21.4	0
WV2	16073	202.7	0	0	5.3	0	93.6	1.1
WV3	21236	134.0	0	0	14.1	0	85.9	0
WV4	40749	250.6	0	0	59.3	0	40.7	0
WV5	3895	53.8	0	0	83	0	17	0
WV6	10258	97.1	0	0	94.9	0	5.1	0
Oti1	3583	174.7	0	0	100	0	0	0
Oti2	20860	212.6	0	0	63.7	0	36.3	0
Oti3	13806	386.3	0	0	6.9	0	93.1	0
Oti4	24284	234.9	0	0	62.4	0	37.6	0
Oti5	7892	121.0	0	0	98.9	0	1.1	0
P1	6532	174.9	0	0	58.9	0	41.1	0
T1	4535	67.8	0	0	90	0	10	0
T2	9616	104.3	6.3	1.8	25.2	0	66.7	0
L1	17744	136.9	3.4	0	91.2	0	5.4	0
L2	14470	70.1	6.7	0	80.6	0	12.7	0
L3	1291	71.4	64.3	0	21.4	0	14.3	0
L4	7061	205.6	9.4	0	64.7	0	25.9	0
L5	10942	75.5	11.6	0	72.1	0.8	15.5	0
L6	7818	88.5	27.2	0	9.8	0	63	0
Sog	5913	129.8	4.3	0	5.8	1.4	88.5	0

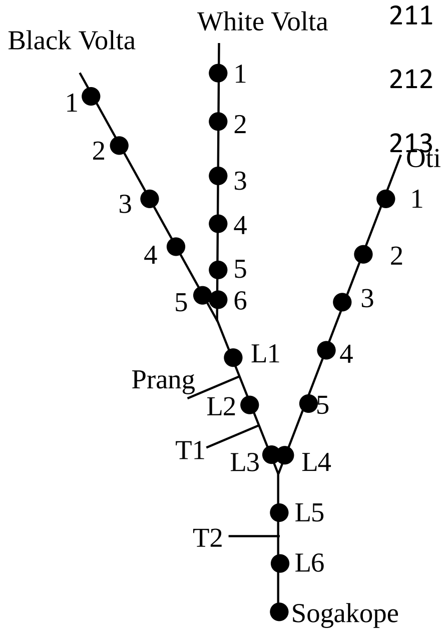


Figure 2 INCA model reach structure for the whole Volta River System.

Climate data and bias correction

In DECCMA, the global RCP8.5 scenario has been selected as the main focus of all the climate change research, as RCP8.5 is considered to be the strongest climate signal with the greatest atmospheric greenhouse gas concentrations in the late 21st century (Kebede et al., 2018). For the Volta River Basin, future regional climate data at 50km resolution were obtained for the 1951-2100 period from the CORDEX Africa dataset (http://www.csag.uct.ac.za/cordex-africa/cordex-africa-publications/). Three simulations were chosen from within the CORDEX ensemble in order to reduce computational expensive, and these particular three were selected to capture a large range of plausible future climate scenarios for the Volta Basin (Janes et al., 2018). Specifically, data downscaled from RCP8.5 simulations of the CNRM-CM5, HadGEM2-ES and CanESM2 GCMs using the SMHI RCA4 Regional Climate Model were obtained. The gridded daily precipitation and temperature data from the climate models were averaged over the Volta River Basin and the resulting time series were then used to calculate basin evapotranspiration rates, hydrologically effective rainfall (HER) and soil moisture deficit (SMD) using the PERSIST model (Futter et al., 2015). The daily HER, SMD and temperature data then used to drive the Integrated Catchment Model INCA (Jin et al., 2015; Whitehead et al., 2015a; Whitehead et al., 2015b).

For the Volta River basin, observed rainfall data from six stations were only available between 1990 to 2005 and showed large spatial variations due to its climatic condition and large size. In order to maximize available temporal longevity of flow data for calibration, the daily rainfall and temperature data from a regional climate model were used as input to the INCA model instead of these limited observations. This same approach was used in the Ganges study (Jin et al., 2015; Whitehead et al., 2015a). All climate models were analyzed for their suitability as a calibration dataset. Of all available models, the downscaled CNRM-CM5 was closest to the observed data with the lowest residual sum of squares when comparing annual precipitate and monthly mean precipitation (Figure 3). As a result, it was selected to use as the input to PERSiST and INCA models for calibration.

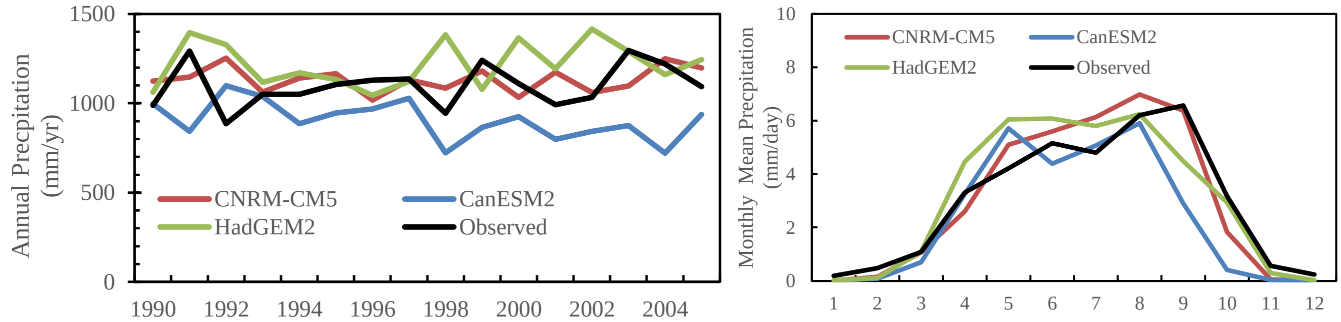


Figure 3 Annual and monthly mean rainfall data comparison between the downscaled CNRM-CM5, HadGEM2-ES and CanESM2 GCMs with observed data.

All climate data were bias corrected to the regional data from the downscaled CNRM-CM5 model, used as the input to the INCA model (Figure 4 a and b). A standard linear scaling method (Fang et al., 2015) was used for the bias correction of the daily temperature and precipitation data, using a 30-year baseline period of 1971-2000.

$$Tc,daily = To,daily + (To,monthly - Tm,monthly) \quad \text{EQ. 2}$$

$$Pc,daily = Po,daily \times (Po,monthly/Pm,monthly) \quad \text{EQ. 3}$$

where *Tc,daily* and *Pc,daily* are the corrected daily values of temperature and precipitation; *To,daily* and *Po,daily* are the downscaled CNRM-CM5 daily values of temperature and precipitation; *To,monthly* and *Po,monthly* are the means of the downscaled CNRM-CM5 monthly values over the baseline; and *Tm,monthly* and *Pm,monthly* are the means of the monthly baseline values from downscaled climate models HadGEM2-ES and CanESM2 over the same period.

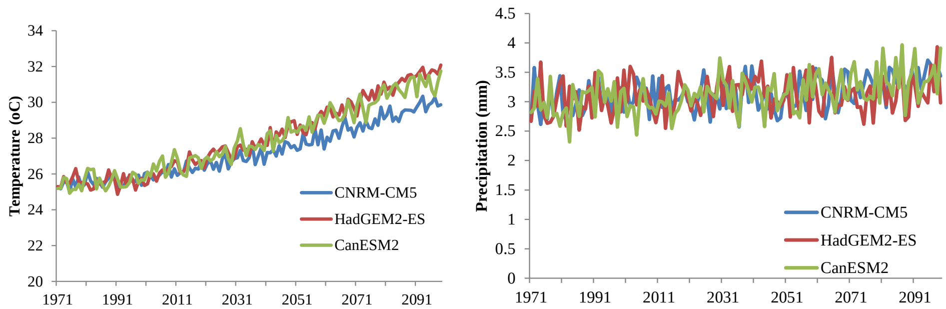


Figure 4 a) and b) biased corrected annual data of temperature and precipitation from 1971 to 2100 for the Volta Basin.

Socio-Economic Scenarios

The IPCC Shared Socio-economic Pathway (SSP) scenarios consider different socio-economic pathways as a means of integrating social aspects of future change using the following five broad classifications for future conditions: SSP1 for Sustainability (low mitigation and adaptation challenges), SSP2 for Business as Usual (intermediate mitigation and adaptation challenges), SSP3 for Fragmented World (high mitigation and adaptation challenges), SSP4 for Inequality Rules (high adaptation and low mitigation challenges), and SSP5 for Conventional Development in terms of energy sources (high mitigation and low adaptation challenges) (IPCC, 2014). From these five narratives, three have been selected for analysis here that are consistent with the RCP8.5 climate scenario (Kebede et al., 2018): medium (~SSP2), medium- (~SSP3) and medium+ (~SSP5). The medium- scenario represents low economic growth, high population growth and low level of urbanization, while medium+ scenario represents high economic growth, low population growth and high level of urbanization. Up to 2050, all three SSPs fall within the band of results compatible with RCP8.5 climate forcing scenario. Therefore, these three narratives are considered up to 2050. Beyond 2050, only SSP5 is consistent with RCP8.5, being associated with the highest economic growth and the highest emissions. A comprehensive description of the socio-economic assumptions are given elsewhere (Kebede et al., 2018) and the catchment-specific scenarios are given below.

Population change, effluent discharge, water demand for irrigation and public supply, land use change and water transfer plans can all affect potential futures in a region from a flow and a water quantity perspective. Table 2 provides summary details for the three socio-economic scenarios being considered in this study (Nicholls et al., 2017) and Table 3 list numbers used in INCA model.

The medium growth scenario has a relatively high population increase, as the national population is expected to grow more than 20% up to 2020 with 10% every decade up to 2050 (Kebede et al., 2018) (Table 2). In the case of the Volta delta, the phenomena of high out migration and urbanization makes the coastal area likely to lose population, not having a clear big city attraction of immigration within the delta. The population peak is not reached until the year 2100, but from 2050 onwards the population growth is projected to be much slower. The medium+ population is expected to grow more than 20% each decade up to 2040, whereas the medium- population is expected to increase by 20% up to 2020, and then increase by 6% per decade up to 2050 (Kebede et al., 2018).

These pressures will generate significant demands for enhanced water supply for people, industry and agriculture. Quantitative data provided for Western Africa for land use change and agriculture has been obtained using an integrated assessment model using projections for population, GDP, GDP per capita, urbanization and with the RCP projections (Kebede et al., 2018). Coupled to these changes in population growth, there are predicted to be increased gross domestic product (GDP) with the Ghana GDP rising from 40 billion US dollars currently to 162 billion US dollars in the year 2050 (Kebede et al., 2018). In Ghana, presently out of 20 million hectares of land, about 30% is cropland, another 30% forest and 40% permanent pastures and grazing land. In the medium scenario, the permanent pasture and grazing land will decline and agricultural production is expected to grow significantly (Table 2). Water intense crops such as rice are expected to increase and the water returns to the Volta from industrial and domestic effluents will increase as population levels rise (Table 2 and 3). Lake Volta created by the Akosombo Dam dominates the water distribution system, controlling 90% of the downstream water. Thus any water transfers are likely to be limited compared to this dam. However, there are other dams planned for upstream reaches and these will enhance water supply for irrigation.

Table 2 A summary of three socio-economic scenarios for the Volta Basin.

	2050s			**2090s**
	Medium	***Medium+***	***Medium-***	***Medium+***
Population change	+91%	+129%	+62%	+354%
STP effluent discharge change	+60%	+70%	+45%	150%
Water demand for irrigation and public supply	abstraction +84%	abstraction +130%	abstraction +81%	abstraction +150%
Land use change (increases in agricultural land)	+75%	+130%	+94%	+175%

Table 3 Future water and agricultural change in the Volta Basin and associated changes in INCA model.

	1990s	***2050s***			***2090s***
	Baseline	Medium	Medium+	Medium-	Medium+
Population (million)	24	46	55	39	85
Intensive Agricultural land (% change)	-	78%	130%	94%	175%
Irrigated Area (Ha)	30500	54290	70150	59170	53375

INCA Reach Irrigation Water Demand (m^3/s)	0.53	0.94	1.22	1.03	0.93
INCA Reach Public Consumption/Effluent Discharge (m^3/s)	0.37	0.72	0.86	0.61	1.32
Reach Total Water Demand (m^3/s)	0.9	1.66	2.07	1.63	2.25

Evaporation from Lake Volta

In INCA as we allow for the rainfall falling directly on the lake so we need to also account for the lake water losses due to evaporation. Evaporation from lakes is extremely difficult to estimate with any accuracy. The normal pan evaporation measurements do not account for the changing effects of wind, variable solar energy, water circulation in lakes and are also likely to be measured some distance from the lake so do not necessarily give a good local estimate. The calculated methods of potential evaporation also have some limitations but are thought to provide the best estimates. There have been several studies estimating evaporation from Lake Volta (Amisigo et al., 2015; McCartney et al., 2012; Oguntunde, 2004; Van de Giesen et al., 2001) and a range of values have been used in the different studies.

Oguntunde (2004) considers in great detail evaporation from a range of surfaces and for the Lake Volta estimates an annual actual evaporation of 1270 mm/year. Barry et al. (2005) estimate the pan evaporation at 1500 mm/year in the southern part of the Volta Basin. Potential evapotranspiration in the basin varies both spatially and temporally with an annual mean varying from 2500 mm in the north of the basin to 1800 mm in the coastal zone according to Amisgo (2015). McCartney et al. (2012) calculate evaporation potential at 2729 mm/year and actual at 717mm/year for the Lake Volta Basin as a whole. Thus it is difficult to estimate a definitive number. We have taken the Oguntunde estimate of 1270 mm/year. When multiplied by the Lake Volta area of 8500 km^2 then this equates to a water loss of 342 m^3/sec, which is an enormous loss of water from the lake surface. Clearly there is considerable uncertainty with the estimate and it is important to remember that this evaporation is largely balanced by the rainfall falling on the lake open water surface. These rates will vary with temperature and in the present study, we have used the more rapid climate change of RCP8.5 and this generated average temperature changes of 2.3 ºC degree and 4.9 ºC degrees for the 2040s and 2090s respectively. As might be expected these temperature increases alter the evaporation from the lake, increasing water losses to 369 m^3/sec and 441 m^3/sec, respectively.

Results and Discussion

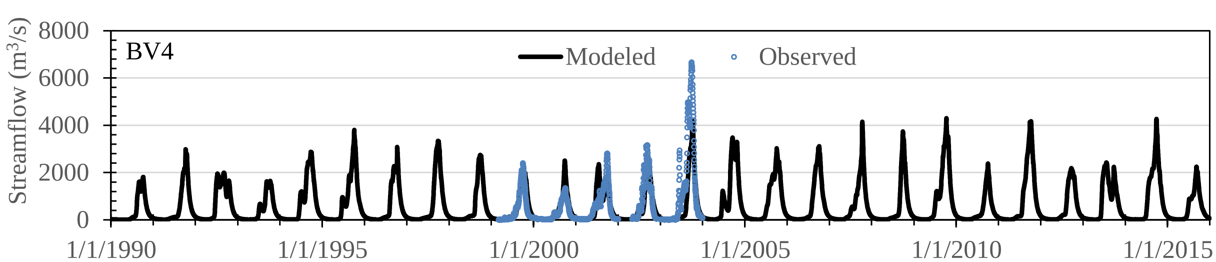
Model calibration

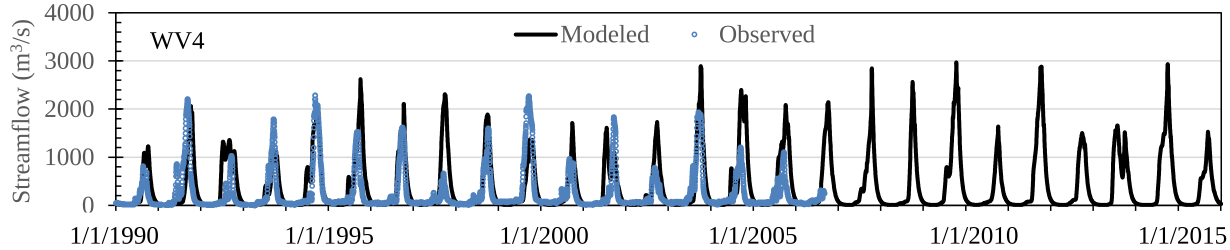
The Black Volta River, White Volta River and Oti River all show strong seasonal pattern with high flow occurring from July to November (peak often in September) and low flow from January to June. The magnitude of the flow varies significantly from 10s m^3/s to 1000s m^3/s. The Black Volta River, the largest tributary among the three, contributes approximately 3,000 to 6,500 m^3/s at peak flow to the main Volta River and Lake Volta, which is much greater than that from the White Volta River and Oti River (~2,000 m^3/s). In contrast, Lake Volta observed monthly mean flow with a small range between 900 to 1300 m^3/s (except year 1998) due to its relatively long residence time of 3.7 years. The average mean annual flow from Lake Volta is 1100 m^3/s.

INCA model was calibrated from 1990-2015 using observed daily and monthly mean flow at three flow stations within the Volta River Basin. A summary of model performance statistics is provided in Table 4 and examples of daily model output are given in Figure 5 at the lower reaches of Black Volta River and White Volta River. Monthly flow output is also illustrated at the lower reach of Oti River (Figure 5). INCA model was able to capture the flow dynamics e.g. timing and magnitude of the rising and falling limbs (Figure 5). Peak flow are sometimes underestimated or overestimated however (Figure 5). The overall fit has an r^2 from 0.45 to 0.68 and N-S values from 0.51 to 0.65 (Table 4).

Table 4 Statistical results of INCA model calibration.

Name of Flow station	**River System and INCA reach**	**Data availability**	**R^2**	**N-S value**
Bamboi	Black Volta (BV4)	1999-2003 daily data	0.68	0.65
Nawuni	White Volta (WV4)	1990-2003 daily data	0.45	0.62
Saboba	Oti (Oti4)	1990-2006 monthly data	0.60	0.51





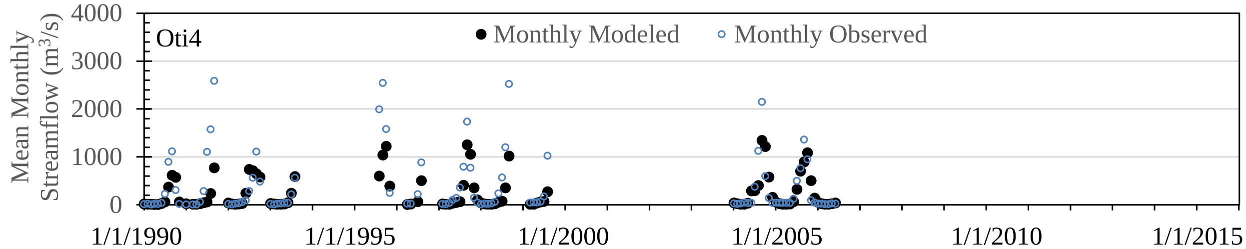


Figure 5 INCA daily flow calibration results at Black Volta River (reach BV4) and White Volta River (WV4) as well as monthly flow calibration results for Oti River (reach Oti4).

At the outlet of the Lake Volta (Akosombo dam outflow), modeled flow remained pretty constant at approximately 1,100 m^3/s which is in close agreement with the observed average flow of 1100 m^3/sec. From 1990 to 2000, modeled flow matches observed flow quite well except in the year of 1998 when the observed flow decreased dramatically which might be due to abnormal abstraction that year.

Future flow changes from Climate Impact

Annual temperature from three climate scenarios shows a steadily increasing trend (Figure 6). The downscaled HadGEM2-ES and CanESM2 models projected much greater increases in temperature after 2030 with 5-6 ºC higher at the end of 2100 than the baseline condition (Figure 6). The projected temperature rises from the downscaled CNRM-CM5 model are generally less than that from the downscaled HadGEM2-ES and CanESM2 models with the temperature increase of 4-5 ºC at the end of 2100 compared to the baseline condition. Annual precipitation varies from year to year. Despite the variation, future precipitation displays a slight upward trend up to 300 mm/day (30% increase) relative to the baseline at the end of the century under the downscaled CanESM2 scenario.

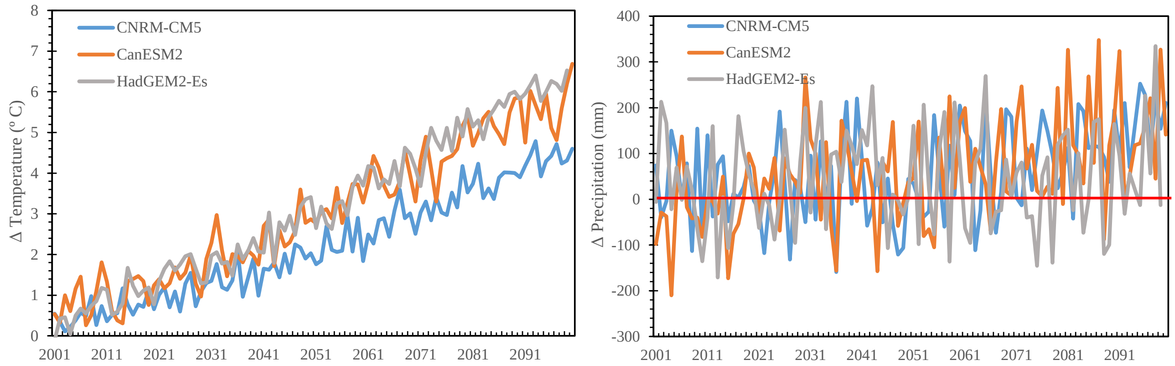


Figure 6 Annual mean temperature and annual precipitation changes relative to the baseline condition from 2001 to 2100.

Monthly mean temperature and precipitation changes relative to the baseline were also assessed (Figure 7). Three climate scenarios consistently show increases in temperature at both 2050s and 2090s. The downscaled CanESM2 and HadGEM2-ES models projected higher temperatures than the downscaled CNRM-CM5 model at 2090s. The Volta Basin has greater temperature rises in the months from January to April and from October to December than the months of May to September. In terms of precipitation, the downscaled CanESM2 model projects the wettest condition (except June) amongst the three climate models. In September and October, the downscaled CanESM2 model shows an increase in monthly mean precipitation up to 3 mm/day. During dry months (January, February, November and December), the precipitation is at a minimum however with some small increases in all three climate models. The downscaled HadGEM2-ES model projected less rainfall compared to the baseline toward the end of the century.

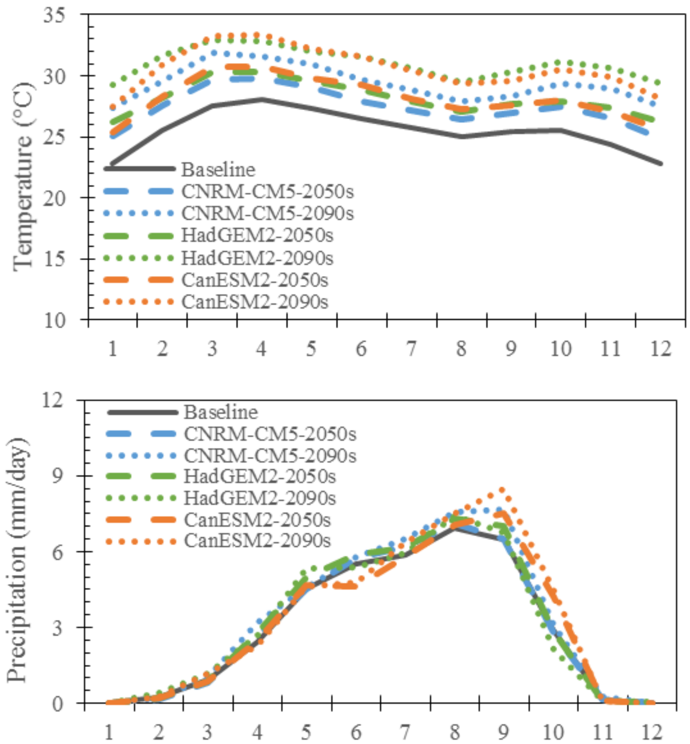


Figure 7 Monthly mean temperature (ºC) and precipitation (mm/day) at 2050s and 2090s compared to the baseline condition for the downscaled CNRM-CM5, CanESM2 and HadGEM2-ES climate scenarios.

Future flow changes from climate impact were assessed for two periods: 2050s (2030-2059) and 2090s (2070-2099). For example, at the mid-century, at the outflow of the Black Volta River, both the downscaled CanESM2 and HadGEM2-ES models showed increases in flow throughout the year except for a substantial decrease in August for the downscaled CanESM2 model (Figure 8a). The downscaled CNRM-CM5 model projected decreases in flow from January to May and from October to December and increases in flow during high flow months from June to September. At peak flow in September, all three climate models indicated a consistent increase in flow up to 25% at 2050s. At the end of the century, both the downscaled CNRM-CM5 and CanESM2 models projected increasing flow throughout the year except for May and August for the CanESM2 model. The start of the wet season flow seem to be delayed from July to August in these two scenarios and flow remains high into October. The downscaled HadGEM2-ES model shows strong decreases in flow at the beginning of the year (January to March) and at the end of the year (October to December) while indicating significant increases in flow from April to July. Similarly at mid-century, the three climate models generated an increase in peak flow in September of up to about 50% at 2090s. Future flow of White Volta River and Oti River were also assessed and they showed comparable changes as Black Volta River (Figure 8b and 8c).

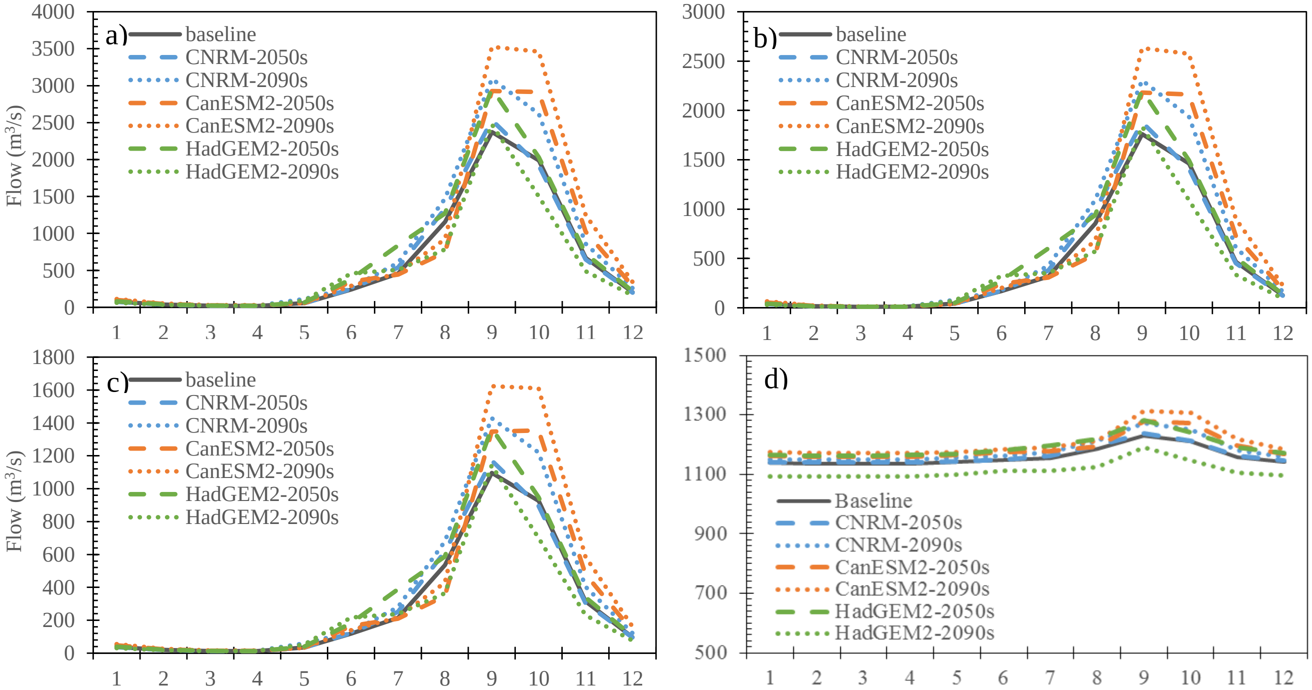
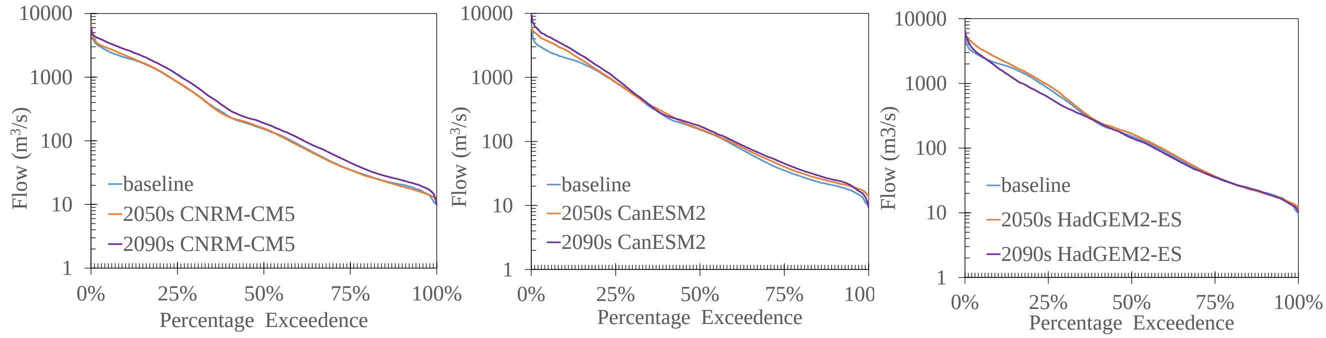


Figure 8 Future monthly flow changes at 2050s and 2090s due to climate change from three climate models at outlets of a) Black Volta River (BV5), b) White Volta River (WV6), c) Oti River (Oti5) and d) Lake Volta outflow (last reach).

From the flow duration curves, the three climate models projected an increase in flood flow (<Q5) for both 2050s and 2090s (Figure 9). Mixed results are obtained at low flow condition (>Q75). The downscaled CNRM-CM5 and HadGEM2-ES models indicate decreasing flow in the mid-century while the downscaled CanESM2 showed slight increases in flow. In Between (Q5 to Q75), the downscaled HadGEM2-ES model projects significant decreases at 2090s while the other two show increases in flow.

Lake Volta outflow responds to the climate change differently from the tributaries. Changes are less significant due to the damping effect of the lake with its longer residence time of 3.7 years. By 2050s, all three models projected slight increases in monthly flow (Figure 8d). By the end of the century, outflow from the Lake Volta would continue to rise with the highest flow of 1,300 m^3/s from the downscaled CanESM2 projection. However the downscaled HadGEM2-ES model had a contrasting result and it indicates that the flow will decline by 2090s. The discrepancy between these projected future flows at Lake Volta are likely driven by the different climate patterns. Between climate scenarios, the downscaled HadGEM2-ES projected least amount of summer monsoon rainfall and greatest temperature rises toward the end of the century (Figure 6 and 7), which could lead to an overall HER reduction in INCA input and strong evaporation from the lake. These combined effects possibly resulted in the declining flow from the Lake Volta at 2090s.



		CNRM-CM5 Flow		CanESM2 Flow		HadGEM2-ES Flow	
Percentile	baseline	2050s	2090s	2050s	2090s	2050s	2090s
99	11.3	**13.2**	**15.0**	**15.9**	**13.6**	**13.3**	**12.3**
95	17.0	15.9	**20.0**	**19.7**	**20.1**	16.4	16.2
90	20.5	19.2	**24.0**	**22.9**	**25.0**	19.8	20.1
75	35.1	34.9	**45.4**	**40.2**	**45.2**	**36.7**	**35.7**
50	152.4	**157.0**	**190.1**	**157.0**	**173.1**	**167.4**	143.4
25	837.8	**841.8**	**1098.0**	**845.6**	**964.0**	**937.8**	609.4
10	2021.0	**2187.0**	**2726.0**	**2712.0**	**3133.0**	**2423.0**	1725.0
5	2561.0	**2851.0**	**3489.0**	**3664.0**	**4339.0**	**3340.0**	**2657.0**
1	3590.0	**3932.0**	**4422.0**	**5030.0**	**6344.0**	**4863.0**	**4429.0**

Figure 9 Comparison of flow duration curves at the outflow of Black Volta River for three climate scenarios at three time periods (bold indicates an increase when comparing to the baseline value).

The results of this study differ from McCartney et al., 2012 in which overall drying is seen with a decrease in annual average rainfall of approximately 20% by the end of the century. This is due to the different climate scenarios used in each study, with McCartney et al. (2012) using a dynamic regional climate model, COSMOCLM(CCLM). The three climate models for DECCMA are for a worst case scenario, namely RCP8.5, which project higher precipitation and a wetter and warmer environment into the future (Figure 6 and 7) which leads to increased flows (Figure 8 and 9).

Socio-economic changes

The three socio-economic scenarios (medium, medium+, and medium-) were also run with the combination of climate change (downscaled CNRM-CM5) at 2050s and 2090s. In general, the effects of changing socio-economic conditions on flow are minor compared to the climate change impact. For example, mean monthly flow at the outlet of Black Volta River shows almost identical flow conditions under climate change and combined climate and socio-economic changes (Figure 10). The variation between the three socio-economic scenarios is also small (less than 5%) (Figure 10). However, it could be that massive dam construction could alter this perspective and create lower water volumes moving down the system. This needs to be explored in a further study when dam plans for the region are being considered.

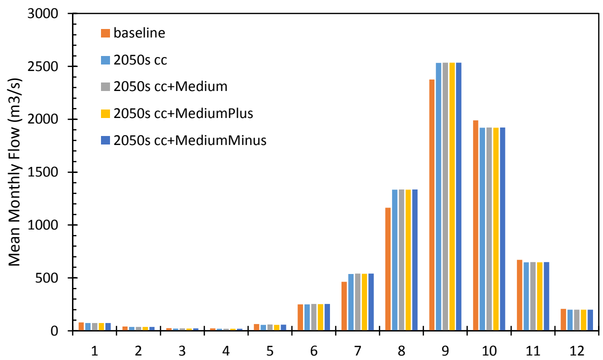


Figure 10 Mean monthly flow changes at 2050s due to climate change (downscaled CNRM-CM5) alone and combined climate and socio-economic changes at the outflow of Black Volta River (BV05).

Floods and droughts under combined impacts of climate and socio-economic change

The projected climate change has the greatest impact during the wet season with the higher flows having the potential to increase flood risk within the Volta Basin. Under combined impact from both climate change (CNRM-CM5) and medium+ socio-economic changes and for the main tributary Black Volta River, the extreme high flow (Q5) increases from 2,565 m^3/s to 2,851 m^3/s (+11%) at 2050s and from 2565 m^3/s to 3491 m^3/s at 2090s (+36%) (Figure 11a). The duration period for high flow (flow above Q5) also increases from 18 days to 26 days and to 42 days at 2050s and 2090s, respectively (Figure 11b). These changes suggest a higher probability of floods with a longer duration of the wet season. For the outflow of Lake Volta, similar changes are seen as Black Volta River but with much smaller magnitude due to its long residence time, which has a damping effect on the hydrological dynamics. Under combined impact from climate change (CNRM-CM5) and medium+ socio-economic changes, Q5 at Lake Volta outlet increases from 1250 m^3/s to 1267 m^3/s (+1%) and to 1317 m^3/s (+5%) at 2050s and 2090s, respectively (Figure 11a). The duration of high flow (>Q5) increases from 18 days to 30 days at 2050s and to 65 days at 2090s (Figure 11b). Although the increases in Q5 are minor, the duration of high flow is much longer at the mid-century and at the end of century.

For the low flow periods, Black Volta River and Lake Volta respond in a different way. At the outflow of Black Volta River, Q90 decreases from 23 m^3/s to 19 m^3/s (-17%) at 2050s but increases to 25 m^3/s at 2090s (+8%) (Figure 11a). The duration for low flow (flow below Q90) increases from 37 days to 51 days at 2050s which indicates there will be an increased duration of droughts. However the duration would decrease to 29 days by the end of century due to the pattern of future climate (Figure 11b). For Lake Volta, Q90 actually increases slightly from 1,132 m^3/s to 1,141 m^3/s at 2050s and from 1,132 m^3/s to 1,155 m^3/s at 2090s (Figure 11a). The duration of low flow (<Q90) decreases significantly from 40 days to 0 days at both 2050s and 2090s due to an overall increase of flow for the Lake (Figure 11b).

Under climate change, medium and medium- socio-economic changes were also assessed for the Black Volta River and Lake Volta. Similar results were seen as medium+ scenario.

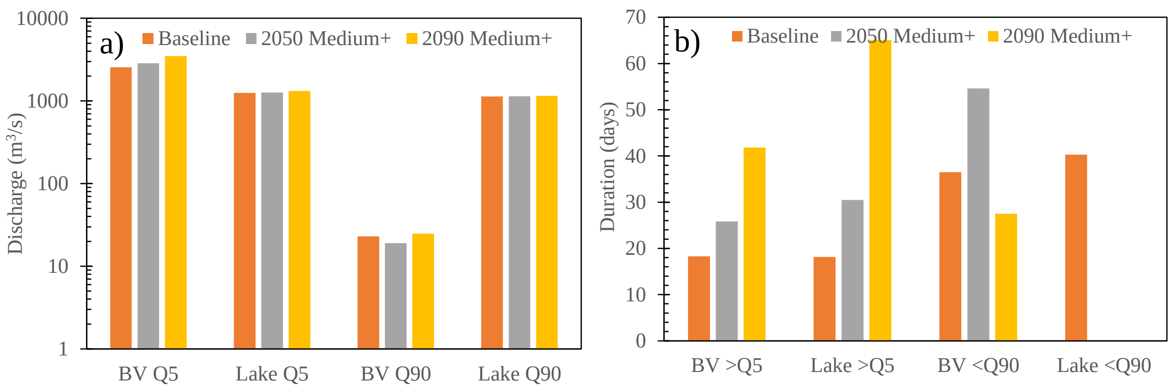


Figure 11 a) Q5 and Q90 for Black Volta River (BV) and Lake Volta (Lake) at 2050s and 2090s with medium+ socio-economic changes; b) number of days above Q5 and below Q90 for Black Volta River (BV) and Lake Volta (Lake) at 2050s and 2090s with medium+ socio-economic changes.

Model uncertainty

It is recognized that using a model chain unavoidably involves uncertainty at every stage of the process. Three climate models for the Volta Basin were downscaled using driving conditions from three CMIP5 Global Climate Models (GCMs) including CNRM-CM5, HadGEM2-ES and CanESM2. Each downscaling experiment, which uses a regional climate model, inherits uncertainty from the GCMs via their own physics and parameterizations. Also, there are a number of uncertainties within PERSiST and INCA models, such as input data and model parameters. Following the same approach used in the Ganga studies (Futter et al., 2015; Jin et al., 2015; Whitehead et al., 2015a), climate model data were used as input to PERSiST and INCA models due to lack of long term observed daily rainfall data. To minimize introducing the biases from this rainfall input, comparison of annual and monthly mean precipitation between observed and climate data was undertaken to demonstrate reasonable agreement between the two (Figure 3). In addition, parametric uncertainty within PERSiST and INCA models may also influence model results. To assess parametric uncertainties, sensitivity analyses were undertaken to evaluate how the model fit varied with changes in parameter values. The most sensitive parameters were velocity-flow parameters a and b, baseflow index and groundwater residence time. In order to accurately represent catchment behaviors to external forcing on the model, these parameters were therefore carefully calibrated to observed flow at three monitoring stations within the catchment. Monsoon flow in the Volta Rivers varies greatly from tens to a few thousands m^3/s. Calibration was based on the overall fit of flow including peak flows and low flows using widely applied goodness-of-fit criterions, i.e. r^2 and Nash-Sutcliffe (N-S) values. Research has however shown that uncertainties related to hydrological models are higher for the dry season than for the wet season (Pushpalatha et al., 2012; Velazquez et al., 2013). Therefore great care must be taken in interpreting the results of low flows. Lastly, the future socio-economic conditions are subject to multiple uncertainties and difficult to quantify for modeling studies (Kebede et al., 2018). Whilst there are a range of uncertainties associated with climate and hydrological modelling, process based modelling does provide the best available approach of understanding catchment responses to possible future conditions (Jin et al., 2012).

Conclusions

The application of the PERSiST and INCA models to the Volta River System provides an important planning and management avenue for exploring future scenarios under changing climate and socio-economic conditions. In general, the climate changes from the three RCP8.5 climate model simulations considered have substantial impacts on future flows, while the socio-economic changes have less relative impact. The RCP8.5 scenario is consistent with the greatest atmospheric greenhouse gas concentrations in the late 21st century of the scenarios available. However, for the first half of the 21st century, the magnitude of projected precipitation changes for the Volta is not much reduced if a less extreme scenario is considered (Kebede et al., 2018), meaning that this result is likely also true of such less extreme scenarios.

Results from all three climate model simulations suggest a significant increase in wet season flows. For example, the monsoon peak flows are projected to increase up to approximately 50% and 10% by 2090s at Black Volta River and Volta Lake outflow respectively. Combined climatic and socio-economic changes impact the streamflow to a similar degree as climate change does because the impacts from changing socio-economic conditions on flow are minor (less than 5%). These increased flows will increase the likelihood of flooding in the future with an extended wet season. Changes in low flow illustrate mixed results. For tributaries like the Black Volta River, drought duration might become more frequent until the 2050s, after which overall wetter climatic conditions lead to less drought at the end of the century. For Lake Volta, future drought duration is projected to be less frequent due to the climate pattern and long residence time of the lake system. There will also be implications and impacts downstream of the lake as increased flows will alter the flushing of sediments and nutrients into the coastal zone. The changes in freshwater fluxes into the coastal system could also alter the water quality and hence ecology of the rivers and coastal zone downstream.

ACKNOWLEDGEMENTS

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References:

Allison, M.A., Nittrouer, C.A., Ogston, A.S., Mullarney, J.C., and Nguyen, T.T., 2017, Sedimentation and Survival of the Mekong Delta A Case Study of Decreased Sediment Supply and Accelerating Rates of Relative Sea Level Rise: Oceanography, v. 30, p. 98-109.

Amisigo, B.A., 2006, Modelling river flows in the Volta Basin of West Africa: A data-driven framework: Delft, the Netherlands: Faculty of Civil Engineering and Geosciences, TUDelft University of Technology.

Amisigo, B.A., McCluskey, A., and Swanson, R., 2015, Modeling impact of climate change on water resources and agricultural demand in the Volta Basin and other basin systems in Ghana: Sustainability, v. 7, p. 6957-6975.

Andah, W., van de Giesen, N., Huber-Lee, A., and Biney, C.A., 2004, Can we maintain food production without losing hydropower? The Volta Basin (West Africa). In: Climate change in contrasting river basins: Adaption for water, food and environment, (eds.), Aerts, J.C.J.H.; Droogers, P. Wallingford, UK: CABI Publishing. , p. 181-194.

Anthony, E.J., Almar, R., and Aagaard, T., 2016, Recent shoreline changes in the Volta River delta, West Africa: the roles of natural processes and human impacts: African Journal of Aquatic Science, v. 41, p. 81-87.

Awotwi, A., Yeboah, F., and Kumi, M., 2015, Assessing the impact of land cover changes on water balance components of White Volta Basin in West Africa: Water and Environment Journal, v. 29, p. 259-267.

Barry, B., Obuobie, E., Andreini, M., Andah, W., and Pluquet, M., 2005, The Volta River Basin synthesis. Comparative study of river basin development and management. Comprehensive Assessment of Water Management in Agriculture: Colombo, Sri Lanka: International Water Management Institute (IWMI).

Bussi, G., Janes, V., Whitehead, P.G., Dadson, S.J., and Holman, I.P., 2017, Dynamic response of land use and river nutrient concentration to long-term climatic changes: Science of the Total Environment, v. 590, p. 818-831.

Crossman, J., Futter, M.N., Oni, S.K., Whitehead, P.G., Jin, L., Butterfield, D., Baulch, H.M., and Dillon, P.J., 2013, Impacts of climate change on hydrology and water quality: Future proofing management strategies in the Lake Simcoe watershed, Canada: Journal of Great Lakes Research, v. 39, p. 19-32.

Dickson, K.B., and Benneh, G., 1988, A new geography of Ghana: Longman Group UK Limited. Longman House, Burnt Mill, Harlow, Essex, England.

Ericson, J.P., Vorosmarty, C.J., Dingman, S.L., Ward, L.G., and Meybeck, M., 2006, Effective sea-level rise and deltas: Causes of change and human dimension implications: Global and Planetary Change, v. 50, p. 63-82.

Fang, G.H., Yang, J., Chen, Y.N., and Zammit, C., 2015, Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China: Hydrol. Earth Syst. Sci., v. 19, p. 2547-2559.

Futter, M.N., Butterfield, D., Cosby, B.J., Dillon, P.J., Wade, A.J., and Whitehead, P.G., 2007, Modeling the mechanisms that control in-stream dissolved organic carbon dynamics in upland and forested catchments: Water Resources Research, v. 43, p. W02424, doi:10.1029/2006WR004960.

Futter, M.N., Erlandsson, M.A., Butterfield, D., Whitehead, P.G., Oni, S.K., and Wade, A.J., 2014, PERSiST: a flexible rainfall-runoff modelling toolkit for use with the INCA family of models: Hydrology and Earth System Sciences, v. 18, p. 855-873.

Futter, M.N., Whitehead, P.G., Sarkar, S., Rodda, H., and Crossman, J., 2015, Rainfall runoff modelling of the Upper Ganga and Brahmaputra basins using PERSiST: Environmental Science-Processes & Impacts, v. 17, p. 1070-1081.

Gu, C.L., Hu, L.Q., Zhang, X.M., Wang, X.D., and Guo, J., 2011, Climate change and urbanization in the Yangtze River Delta: Habitat International, v. 35, p. 544-552.

Gyau-Boakye, P., and Tumbulto, J.W., 2000, The Volta Lake and Declining Rainfall and Streamflows in the Volta River Basin: Environment, Development and Sustainability, v. 2, p. 1-11.

Hill, C., Nicholls, R.J., Whitehead, P.W., Dunn, F., Haque, A., Appeaning Addo, K., and Raju, P.V., 2018, Delineating Climate Change Impacts on Biophysical Conditions in Populous Deltas Science of the Total Environment.

Hoang, L.P., Lauri, H., Kummu, M., Koponen, J., van Vliet, M.T.H., Supit, I., Leemans, R., Kabat, P., and Ludwig, F., 2016, Mekong River flow and hydrological extremes under climate change: Hydrology and Earth System Sciences, v. 20, p. 3027-3041.

IPCC, 2013a, Annex I: Atlas of Global and Regional Climate Projections: [van Oldenborgh, G.J., M. Collins, J. Arblaster, J.H. Christensen, J. Marotzke, S.B. Power, M. Rummukainen and T. Zhou (eds.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2013b, Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change: [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014, Summary for Policymakers. In: Climate Change 2014 Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, Cambridge Univ Press.

Jackson-Blake, L.A., Wade, A.J., Futter, M.N., Butterfield, D., Couture, R.M., Cox, B.A., Crossman, J., Ekholm, P., Halliday, S.J., Jin, L., Lawrence, D.S.L., Lepisto, A., Lin, Y., Rankinen, K., and Whitehead, P.G., 2016, The INtegrated CAtchment model of phosphorus dynamics (INCA-P): Description and demonstration of new model structure and equations: Environmental Modelling & Software, v. 83, p. 356-386.

Janes, T., McGrath, F., Macadam, I., and Jones, R., 2018, High-resolution climate projections for South Asia to inform climate impacts and adaptation studies in the Ganges-Brahmaputra-Meghna and Mahanadi deltas: Science of the Total Environment.

Jin, L., Whitehead, P., Siegel, D.I., and Findlay, S., 2011, Salting our landscape: An integrated catchment model using readily accessible data to assess emerging road salt contamination to streams: Environmental Pollution, v. 159, p. 1257-1265.

Jin, L., Whitehead, P.G., Baulch, H.M., Dillon, P.J., Butterfield, D., Oni, S.K., Futter, M.N., Crossman, J., and O'Connor, E.M., 2013, Modelling phosphorus in Lake Simcoe and its subcatchments: scenario analysis to assess alternative management strategies: Inland Waters, v. 3, p. 207-220.

Jin, L., Whitehead, P.G., Futter, M.N., and Lu, Z.L., 2012, Modelling the impacts of climate change on flow and nitrate in the River Thames: assessing potential adaptation strategies: Hydrology Research, v. 43, p. 902-916.

Jin, L., Whitehead, P.G., Sarkar, S., Sinha, R., Futter, M.N., Butterfield, D., Caesar, J., and Crossman, J., 2015, Assessing the impacts of climate change and socio-economic changes on flow and phosphorus flux in the Ganga river system: Environmental Science-Processes & Impacts, v. 17, p. 1098-1110.

Kasei, R., Diekkruger, B., and Leemhuis, C., 2010, Drought frequency in the Volta Basin of West Africa: Sustainability Science, v. 5, p. 89-97.

Kay, S., Caesar, J., Wolf, J., Bricheno, L., Nicholls, R.J., Islam, A., Haque, A., Pardaens, A., and Lowe, J.A., 2015, Modelling the increased frequency of extreme sea levels in the Ganges-Brahmaputra-Meghna delta due to sea level rise and other effects of climate change: Environmental Science-Processes & Impacts, v. 17, p. 1311-1322.

Kebede, A.S., Nicholls, R.J., Allan, A., Arto, I., Cazcarro, I., Fernandes, J.A., Hill, C.T., Hutton, C.W., Kay, S., Lazar, A.N., Macadam, I., Palmer, M., Suckall, N., Tompkins, E.L., Vincent, K., and Whitehead, P.G., 2018, Applying the Global RCP–SSP–SPA Scenario Framework at Sub-National Scale: A Multi-Scale and Participatory Scenario Approach: Science of the Total Environment, v. DECCMA Special Issue.

Lacombe, G., McCartney, M., and Forkuor, G., 2012, Drying climate in Ghana over the period 1960-2005: evidence from the resampling-based Mann-Kendall test at local and regional levels: Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, v. 57, p. 1594-1609.

Lazar, A.N., Butterfield, D., Futter, M.N., Rankinen, K., Thouvenot-Korppoo, M., Jarritt, N., Lawrence, D.S.L., Wade, A.J., and Whitehead, P.G., 2010, An assessment of the fine sediment dynamics in an upland river system: INCA-Sed modifications and implications for fisheries: Science of the Total Environment, v. 408, p. 2555-2566.

Lu, Q., Whitehead, P.G., Bussi, G., Futter, M.N., and Nizzetto, L., 2017, Modelling metaldehyde in catchments: a River Thames case-study: Environmental Science-Processes & Impacts, v. 19, p. 586-595.

McCartney, M., Forkuor, G., Sood, A., Amisigo, B., Hattermann, F., and Muthuwatta, L., 2012, The water resource implications of changing climate in the Volta River Basin: Colombo, Sri Lanka: International Water Management Institute (IWMI). 40p. (IWMI Research Report 146). .

Mul, M., Obuobie, E., Appoh, R., Kankam-Yeboah, K., Bekoe-Obeng, E., Amisigo, B., Logah, F.Y., Ghansah, B., and McCartney, M., 2015, Water resources assessment of the Volta River Basin: Colombo, Sri Lanka: International Water Management Institute (IWMI). 78p. (IWMI Working Paper 166). doi: 10.5337/2015.220.

Nepal, S., and Shrestha, A.B., 2015, Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature: International Journal of Water Resources Development, v. 31, p. 201-218.

Nicholls, R.J., A.S., K., Allan, A., Arto, I., Cazcarro, I., Fernandes, J.A., Hill, C.T., Hutton, C.W., Kay, S., Lawn, J., Lázár, A.N., Macadam, I., Whitehead, P.G., and al, e., 2017, The DECCMA scenario framework: A multi-scale and participatory approach to explore the future migration and adaptation in deltas: DECCMA Working Paper, Deltas, Vulnerability and Climate Change: Migration and Adaptation, IDRC Project Number 107642. Available online at: www.deccma.com, date accessed

Nicholls, R.J., Hutton, C.W., Lazar, A.N., Allan, A., Adger, W.N., Adams, H., Wolf, J., Rahman, M., and Salehin, M., 2016, Integrated assessment of social and environmental sustainability dynamics in the Ganges-Brahmaputra-Meghna delta, Bangladesh: Estuarine Coastal and Shelf Science, v. 183, p. 370-381.

Nicholson, S., 2005, On the question of the "recovery" of the rains in the West African Sahel: Journal of Arid Environments, v. 63, p. 615-641.

Oguntunde, P.G., 2004, Evapotranspiration and complementarity relations in the water balance of the Volta basin: Field measurements and GIS-based regional estimates: Ecology and Development Series No. 22. Göttingen, Germany: Cuvillier Verlag. 169p.

Owusu, K., Waylen, P., and Qiu, Y., 2008, Changing rainfall inputs in the Volta basin: implications for water sharing in Ghana: GeoJournal, v. 71, p. 201-210.

Pushpalatha, R., Perrin, C., Le Moine, N., and Andreassian, V., 2012, A review of efficiency criteria suitable for evaluating low-flow simulations: Journal of Hydrology, v. 420, p. 171-182.

Rankinen, K., Granlund, K., Futter, M.N., Butterfield, D., Wade, A.J., Skeffington, R., Arvola, L., Veijalainen, N., Huttunen, I., and Lepisto, A., 2013, Controls on inorganic nitrogen leaching from Finnish catchments assessed using a sensitivity and uncertainty analysis of the INCA-N model: Boreal Environment Research, v. 18, p. 373-386.

Sadoff, C., and Muller, M., 2009, Water management, water security and climate change adaptation: Early impacts and essential responses. : TEC Background Papers No.14.

Smajgl, A., Toan, T.Q., Nhan, D.K., Ward, J., Trung, N.H., Tri, L.Q., Tri, V.P.D., and Vu, P.T., 2015, Responding to rising sea levels in the Mekong Delta: Nature Climate Change, v. 5, p. 167-U167.

Syvitski, J.P.M., Vorosmarty, C.J., Kettner, A.J., and Green, P., 2005, Impact of humans on the flux of terrestrial sediment to the global coastal ocean: Science, v. 308, p. 376-380.

Van de Giesen, N., Andreini, M., Van Edig, A., and Vlek, P., 2001, Competition for water resources of the Volta basin, *in* Schumann, A.H., Acreman, M.C., Davis, R., Marino, M.A., Rosbjerg, D., and Jun, X., eds., Regional Management of Water Resources: Iahs Publication, p. 199-205.

Velazquez, J.A., Schmid, J., Ricard, S., Muerth, M.J., St-Denis, B.G., Minville, M., Chaumont, D., Caya, D., Ludwig, R., and Turcotte, R., 2013, An ensemble approach to assess hydrological models' contribution to uncertainties in the analysis of climate change impact on water resources: Hydrology and Earth System Sciences, v. 17, p. 565-578.

Wade, A.J., Butterfield, D., Lawrence, D.S., Bärlund, I., Ekholm, P., Lepistö, A., Yli-Halla, M., Rankinen, K., Granlund, K., Durand, P., and Kaste, Ø., 2009, The Integrated Catchment Model of Phosphorus (INCA-P), a new structure to simulate particulate and soluble phosphorus transport in European catchments, Deliverable 185 to the EU Euro-limpacs project, UCL, London, pp 67.

Wade, A.J., Durand, P., Beaujouan, V., Wessel, W.W., Raat, K.J., Whitehead, P.G., Butterfield, D., Rankinen, K., and Lepisto, A., 2002, A nitrogen model for European catchments: INCA, new model structure and equations: Hydrology and Earth System Sciences, v. 6, p. 559-582.

Whitehead, P.G., Barbour, E., Futter, M.N., Sarkar, S., Rodda, H., Caesar, J., Butterfield, D., Jin, L., Sinha, R., Nicholls, R., and Salehin, M., 2015a, Impacts of climate change and socio-economic scenarios on flow and water quality of the Ganges, Brahmaputra and Meghna (GBM) river systems: low flow and flood statistics: Environmental Science-Processes & Impacts, v. 17, p. 1057-1069.

Whitehead, P.G., Butterfield, D., and Wade, A.J., 2009, Simulating metals and mine discharges in river basins using a new integrated catchment model for metals: pollution impacts and restoration strategies in the Aries-Mures river system in Transylvania, Romania: Hydrology Research, v. 40, p. 323-346.

Whitehead, P.G., Jin, L., Baulch, H.M., Butterfield, D.A., Oni, S.K., Dillon, P.J., Futter, M., Wade, A.J., North, R., O'Connor, E.M., and Jarvie, H.P., 2011, Modelling phosphorus dynamics in multi-branch river systems: A study of the Black River, Lake Simcoe, Ontario, Canada: Science of the Total Environment, v. 412, p. 315-323.

Whitehead, P.G., Sarkar, S., Jin, L., Futter, M.N., Caesar, J., Barbour, E., Butterfield, D., Sinha, R., Nicholls, R., Hutton, C., and Leckie, H.D., 2015b, Dynamic modeling of the Ganga river system: impacts of future climate and socio-economic change on flows and nitrogen fluxes in India and Bangladesh: Environmental Science-Processes & Impacts, v. 17, p. 1082-1097.

Whitehead, P.G., Wilson, E.J., and Butterfield, D., 1998a, A semi-distributed Integrated Nitrogen model for multiple source assessment in Catchments (INCA): Part I - model structure and process equations: Science of the Total Environment, v. 210, p. 547-558.

Whitehead, P.G., Wilson, E.J., Butterfield, D., and Seed, K., 1998b, A semi-distributed integrated flow and nitrogen model for multiple source assessment in catchments (INCA): Part II - application to large river basins in south Wales and eastern England: Science of the Total Environment, v. 210, p. 559-583.