IWMI Research Report

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The Water Resource Implications of Changing Climate in the Volta River Basin

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Front cover photograph shows people collecting water from a small reservoir in Northern Ghana (*photo credit*: Matthew McCartney, IWMI).

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The views expressed in this document cannot be taken to reflect the official opinions of CGIAR or ESSP.

Contents

Acronyms and Abbreviations

CC	Climate change
CCLM	COSMO-CLM, COnsortium for Small-scale MOdelling - CLimate Model
CR	Index of reliability
CRS	Index of resilience
CV	Index of vulnerability
CV	Coefficient of Variation
GCM	General Circulation Model
GEV	General Extreme Value
HRU	Hydrological Response Unit
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
FAO	Food and Agriculture Organization of the United Nations
$GWhy^{-1}$	Gigawatt hours per year
MW	Megawatt
NSE	Nash-Sutcliffe Efficiency
SEI	Stockholm Environment Institute
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT Calibration and Uncertainty Program
VBA	Volta Basin Authority
VRA	Volta River Authority
WEAP	Water Evaluation And Planning

Summary

The Volta River is one of the major rivers in Africa. A transboundary basin, which is the principal water source for approximately 24 million people in six riparian states, it is likely to experience increasing stress in the near future as a consequence of both greater water demand and climate change. In a study to ascertain the joint impacts of changes in demand and supply within the basin, a dynamic regional climate model (CCLM), a hydrological model (SWAT) and a water resource model (WEAP) were used to provide an assessment of the possible implications of one downscaled 'middle impact' (i.e., lying between extremes) climate change scenario on the performance of existing and planned irrigation and hydropower schemes. The models were used to simulate the climate change in tandem with four scenarios, each reflecting different levels of water resources development as indicated in the plans of the riparian states. It is not possible to quantify the error arising from the models in combination and the results should be considered indicative rather than absolute. Nonetheless, they provide a useful indicator of possible future change and have important implications for water resource planning. The results indicate that, by the middle of the twenty-first century, basin-wide average annual rainfall, mean annual runoff and mean groundwater recharge, will all decline. These changes significantly undermine the technical performance of existing and planned reservoirs, which, in turn, affects development outcomes. In the 'intermediate development' scenario, climate change is anticipated to reduce average annual hydropower generation by approximately 30% and increase average annual unmet irrigation demand four-fold by the middle of the century. By the end of the century and in the 'full development' scenario, the reduction in technical performance of reservoirs is even greater. Therefore, even though investment in reservoirs brings benefits, these benefits are significantly reduced in comparison to those that would accrue in the absence of climate change. The changes are likely to have dire consequences for economic development, food security and poverty in the region. Against this background, water resources development in the basin requires interventions that bolster resilience and water security. This necessitates much more systematic planning of water storage, greater cooperation between the riparian states and consideration of innovative approaches to water storage, such as managed aquifer recharge.

The Water Resource Implications of Changing Climate in the Volta River Basin

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Introduction

As the scientific consensus of the nature of climate change (CC) and awareness of the possible impacts of it on water resources has increased in recent years, there has been a corresponding acknowledgement of the need to incorporate CC into water planning, particularly in the planning of water storage (Sadoff and Muller 2009). However, across much of sub-Saharan Africa, CC is given low priority. In many countries there has been almost no systematic evaluation of the possible implications of CC for water resources and it is given little consideration in the planning of future water resources development.

The Volta River and its tributaries are an important source of water for the inhabitants of the six riparian states. Water plays a vital role in the livelihoods of people in the basin and in the promotion of economic growth. Agriculture, which employs the majority of the basin's inhabitants and generates about 40% of the basin's economic output, is heavily reliant on available water resources (Biney 2010). Water is also used to generate hydropower, which supports major industries in Ghana (i.e., mining, aluminum, etc.) and is also exported to neighboring countries (Owusu et al. 2008). Other uses include livestock raising, fisheries, recreation and tourism.

Water resources in the basin have come under increasing pressure in recent years. Population growth in the two countries that cover the largest proportion of the basin (i.e., Ghana and Burkina Faso) has resulted in larger abstractions of water to meet the increasing demand (van de Giesen et al. 2001). Population is projected to reach 34 million in 2025, up from 18.6 million in 2000 (Biney 2010). There are plans to build more dams to increase electricity production and expand irrigation in the basin.

CC and the uncertainty associated with it, will complicate the management of the basin's water resources. Signs of possible CC (i.e., increased temperatures and shorter rainy seasons) have been reported (Jung and Kunstmann 2007; Conway 2009). A more recent study found no statistically significant trend in annual rainfall totals, but did find trends (significant at the 95% confidence level) in agriculturally important rainfall characteristics, including: i) a reduction in the amount of light rainfall (< 20 millimeters (mm) d^{-1}); ii) a delay in the onset of the rainy season; and iii) a lengthening of periods with no rainfall during the wet season (Lacombe et al. 2012).

Studies have also been conducted into the possible effects of CC on the hydrology of the basin, using a range of approaches and computer models (e.g., Andah et al. 2004; de Condappa et al. 2009; Leemhuis et al. 2009). These approaches and models have highlighted the sensitivity of river flows to rainfall variability. In contrast, the future development of large numbers of additional small reservoirs in the upstream portion of the catchment is expected to have relatively little impact on downstream hydrology. However, currently, there is little information on the possible implications of CC for the planned large-scale water resources development in the basin.

In this report, the findings of research conducted to determine the impact of one specific CC scenario (i.e., the Intergovernmental Panel on Climate Change (IPCC) Special Report Emissions Scenarios (SRES)-AR4 A1B (IPCC 2000)) on the performance of existing and planned dams, irrigation and hydropower schemes, are described. The A1B scenario was chosen because it lies between the extremes produced by other scenarios. As such, it is a relatively conservative, but not overly cautious, scenario. A dynamic regional climate model (COSMO-CLM (CCLM)), a hydrological model (SWAT) and a water resources model (WEAP) were used in combination to provide a detailed evaluation of the potential implications of CC and changes in water demand on water availability, and to ascertain the possible impacts on hydropower generation and irrigation. Simulations were conducted over the period 1983 to 2100. There is great uncertainty on exactly which water resource schemes will be implemented. Consequently, in order to systematically assess the impact of growing water demand on the basin's water resources, four development scenarios were identified and modelled.

The Volta Basin

Natural Characteristics

The Volta Basin (403,000 square kilometers (km^2)) is shared by six riparian countries in West Africa. 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 (147,000 km^2), the White Volta (106,000 km^2) and the Oti (72,000 km^2), which come together to form the Lower Volta (73,000 km^2) (Figure 1). The total average annual flow is approximately 40,400 million cubic meters (Mm^3). Although considerably less than the largest river in West Africa, the Niger (which has an average annual flow at Idah in Nigeria of 146,000 Mm^3 (FAO 1997)), it is nevertheless one of the major rivers of Africa. The flow varies considerably from year to year (Andah et al. 2004).

Climatically, the basin is dominated by the rain-bearing south-westerly tropical maritime air mass and the dry, north-easterly tropical continental air mass (Dickson and Benneh 1988). The two air masses meet at the Inter-Tropical Convergence Zone (ITCZ). At any location, the rainy season begins when the ITCZ has passed overhead moving north and ends with its southwards retreat. Consequently, there is a general tendency for rainfall to decrease from the south to the north, though this general effect is disrupted in a few places as a consequence of local relief. Between May and August (i.e., the West African monsoon), the ITCZ moves to the north and the entire basin lies under the influence of the tropical maritime. These months yield approximately 75% of the total annual rainfall. In the vicinity of the coast, rainfall is approximately 1,500 mmy^{-1} and bimodal falling between May and October, with a short dry season in July/August, separating two peaks (Dickson and Benneh 1988). The two rainfall peaks tend to disappear northward and, in the northern part of the country, the rainfall distribution is uni-modal and averages approximately 500 mmy^{-1}. In addition to seasonality, inter-annual variability is considerable (Nicholson 2005).

Annual mean temperatures range between 27 °C and 30 °C, although daily and night temperatures can reach 44 °C and 15 °C, respectively. Potential evapotranspiration is relatively high (1,800 mm-2,500 mm), especially in the northern part of the catchment (Amisigo 2006). Table 1 summarizes the hydrometeorological information for each of the four major sub-basins.

Current Water Resources Development

To date, the most significant water resources development in the basin is the construction of the Akosombo Dam, which was built between 1961 and 1965 for hydropower generation. This dam created Lake Volta, which is the world's largest human-made lake, covering an area of 8,502 km^2 (i.e., 3.6% of Ghana's land area). The reservoir has an average depth of 18.8 meters (m) and a storage capacity of 148,000 Mm^3 (Barry et al. 2005). The current installed generating capacity is 1,020 megawatts (MW). Other hydropower stations in the basin are Kompienga and Bagre in Burkina Faso, which have total volumes of 2,025 Mm^3 and 1,700 Mm^3 and installed generating capacities of 14 MW and 10 MW, respectively (Table 2).

A number of small, medium and large reservoirs have been constructed in the basin primarily for irrigation. The most notable are the Lerinord Seourou (360 Mm^3) and Subinja (135 Mm^3) dams in Burkina Faso, and the Tono (93 Mm^3), Tanoso (125 Mm^3) and Amate (120 Mm^3) dams in Ghana. The total storage volume of the irrigation reservoirs in the basin, including Bagre which is used for both hydropower and irrigation, is about 2,900 Mm^3 and formal irrigation is estimated to cover approximately 30,500 hectares (ha) (Table 2). Informal irrigation practices are

FIGURE 1. Map of the Volta River Basin showing the four major sub-basins and Lake Volta.

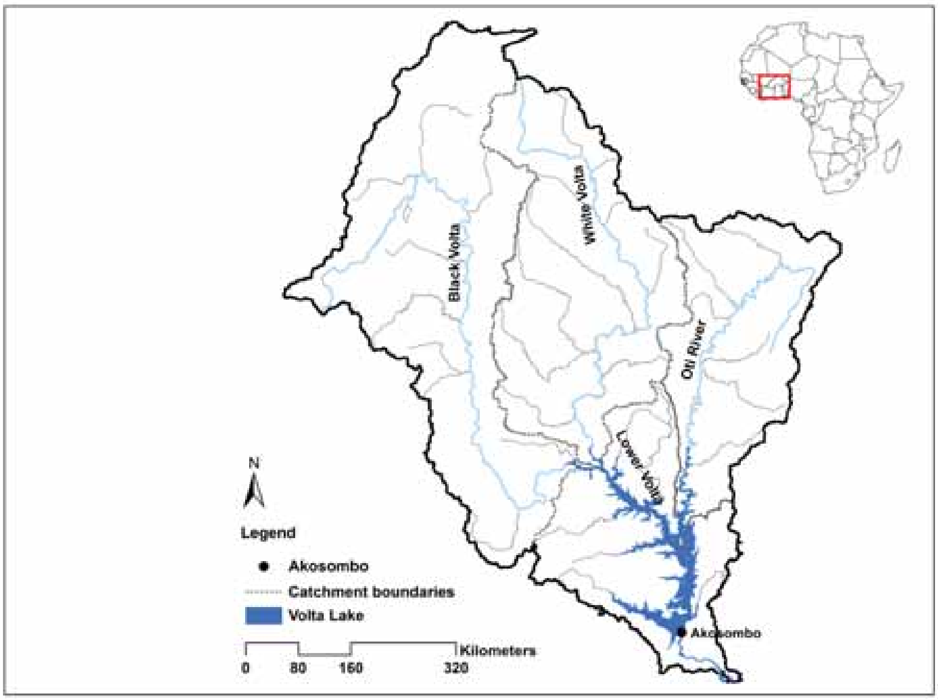


TABLE 1. Summary of the hydrometeorological characteristics of the four major sub-basins.

Volta Basin	Rainfall (mm)	Rainfall Coefficient of Variation (CV)	Pan evaporation (mm)	Potential evapotranspiration (mm)
Black Volta	1,023-1,348	0.17-0.23	2,540	1,450-1,800
White Volta	930-1,054	0.16-0.20	2,540	1,650-1,968
Oti River	1,050-1,500	0.18-0.20	2,540	1,550-1,850
Lower Volta	876-1,565	0.17-0.35	1,778	1,450-1,800

Source: Barry et al. 2005.

widespread, though there is very little information on the overall extent (Drechsel et al. 2006). In addition to the formal dams, there are a large number of small reservoirs (i.e., at least 1,213) with an estimated total storage capacity of approximately 232 Mm^3 located in the northern sub-basins (Liebe et al. 2005; de Condappa et al. 2009).

TABLE 2. Summary of the key characteristics of the existing major water resource schemes (hydropower and irrigation) in the basin.

Catchment	Name of dam/scheme	Country	Storage capacity (Mm^3)	Irrigated area (ha)	Installed hydropower capacity (MW)
Black Volta					
Nwokuy	Nwokuy River Irrigation	Burkina Faso	-	3,291	-
Dapola	Lerinord Seourou	Burkina Faso	360	9,646	-
	Dapola River Irrigation	Burkina Faso	-	1,362	-
Noumbiel	Noumbiel River Irrigation	Burkina Faso	-	230	-
Bamboi	Subinja	Ghana	135	110	-
White Volta					
Wayen	Kanozoe	Burkina Faso	75	5,319	-
	Loumbila	Burkina Faso	42	-	-
	Ziga	Burkina Faso	200	-	-
Yakala	Bagre	Burkina Faso	1,700	4,695	10
Nangodi	Nangodi River Irrigation	Burkina Faso	-	184	-
Nawuni	Tono	Ghana	93	2,430	-
	Vea	Ghana	16	850	-
Oti River					
Kompienga	Kompienga	Burkina Faso	2,025	-	14
Sabari	Sabari River Irrigation	Ghana	-	1,915	-
Lower Volta					
Prang	Tanoso	Ghana	125	129	-
Senchi	Amate	Ghana	120	308	-
Lower Volta	Akosombo	Ghana	148,000	-	1,020

Source: Various, including GIDA and Stockholm Environment Institute (SEI).

Future Water Resources Development

Major developments planned for the basin focus primarily on hydropower generation and irrigation development. In Ghana, for instance, the VRA has identified potential sites for hydropower generation in the Black and White Volta sub-basins, as well as the Oti River. Altogether, these planned schemes, including the Bui scheme which is currently under construction, will have a generating capacity of over 950 MW and a total storage capacity of close to 49,000 Mm^3 (Table 3).

Expansion in the irrigated area of existing schemes and construction of new schemes is expected to increase the irrigated area in the basin by approximately 47,000 ha. This includes 30,000 ha of irrigation by the Bui scheme. GIDA plans to develop an additional 22,590 ha of small or micro-scale irrigation and drainage schemes within five years in five regions of Ghana, including the three northern regions.

TABLE 3. Planned water resources development in the Volta Basin.

Catchment	Name of dam/scheme	Country	Total reservoir volume (Mm^3)	Irrigated area (ha)	Installed hydropower capacity (MW)	Projected date of completion
Black Volta						
Nwokuy	Samendeni	Burkina Faso	610	5,000	2.4	2027
	Bonvale	Burkina Faso	130	-	0.3	2024
Dapola	Bagri	Ghana	-	100	-	-
	Bontioli	Burkina Faso	320	-	5.1	2024
	Bon	Burkina Faso	2,000	-	7.8	2024
Noumbiel	Duuli	Ghana	-	150	-	-
	Gbari	Ghana	-	100	-	-
	Noumbiel	Burkina Faso	11,300	7,800	48	2024
	Gongourou	Burkina Faso	1,000	-	5	-
Bamboi	Bui	Ghana	12,570	30,000	400	2012
	Koulbi	Ghana	2,950[1]	-	68	-
	Ntereso	Ghana	1,370[1]	-	64	-
	Lanka	Ghana	-	-	95	-
	Jambito	Ghana	760[1]	-	55	-
White Volta						
Nawuni	Daboya	Ghana	3,430	-	43	-
	Pwalugu	Ghana	3,260	-	50	2020
	Kulpawn	Ghana	7,200	-	40	-
	Dipala	Ghana	-	100	-	-
	Sogo	Ghana	-	100	-	-
	Daboya	Ghana	-	50	-	-
Pwalugu	Tiego Yarugu	Ghana	-	200	-	-
	Sambolekuliga	Ghana	-	200	-	-
Yakala	Bagre Aval	Burkina Faso	107	-	14	2024
Nangodi	Bandongo	Burkina Faso	480	-	3	2024
Oti River						
Sabari	Juale	Ghana	1,200	-	87	2012
	Namiele	Togo	-	1,250	-	-
	Wakuti	Togo	-	1,350	-	-
Mango	Arli	Burkina Faso	-	-	0.92	-
Lower Volta						
Senchi	Asantekwaa	Ghana	-	200	-	-
	New Longoro	Ghana	-	200	-	-
	Buipe	Ghana	-	200	-	-
	Yapei	Ghana	-	200	-	-

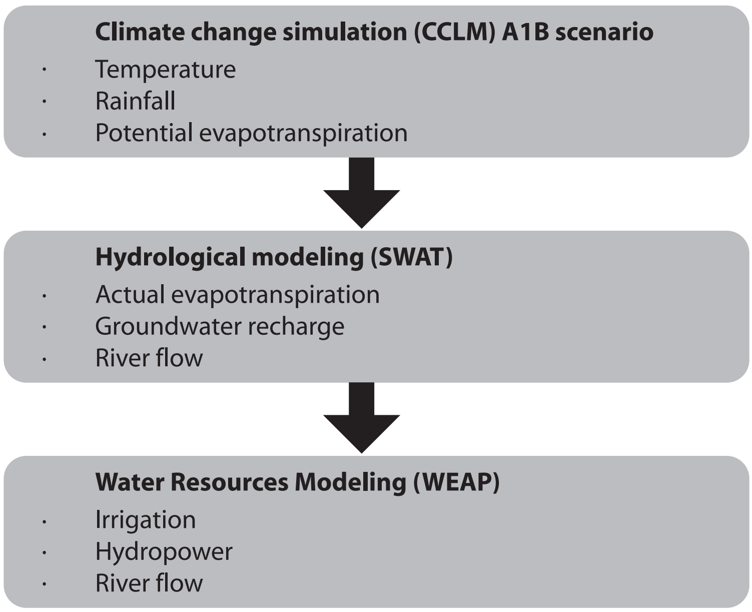
Source: Ministry of Water Resources, Works and Housing, Ghana; National Investment Brief, 2008, Burkina Faso; Pre-water audit for the Volta River Basin, West Africa, 2005; and GIDA.

Note: [1] Live storage volume.

Method

Three models were used in combination to assess the implications of the A1B CC scenario on the water resources of the Volta Basin (Figure 2). A dynamic regional climate model, COSMO-CLM (CCLM), was used to determine climate projections for the basin for the period 1983-2100. The outputs generated from CCLM (i.e., rainfall, temperature and potential evapotranspiration) were used as input to a hydrological model (SWAT) which was setup, calibrated and validated with observed climate and hydrological data. Finally, the WEAP model was used to determine the water resources implications of the changes in climate. Results of the SWAT modeling (i.e., projections in river flow and groundwater recharge) in conjunction with projected water demands, were used as input to the WEAP model. Where applicable, the future water demand was estimated considering the assumptions of the A1B emissions scenario. The sections below provide detailed descriptions of each of the models.

FIGURE 2. Schematic illustrating the methodological approach used in the study.

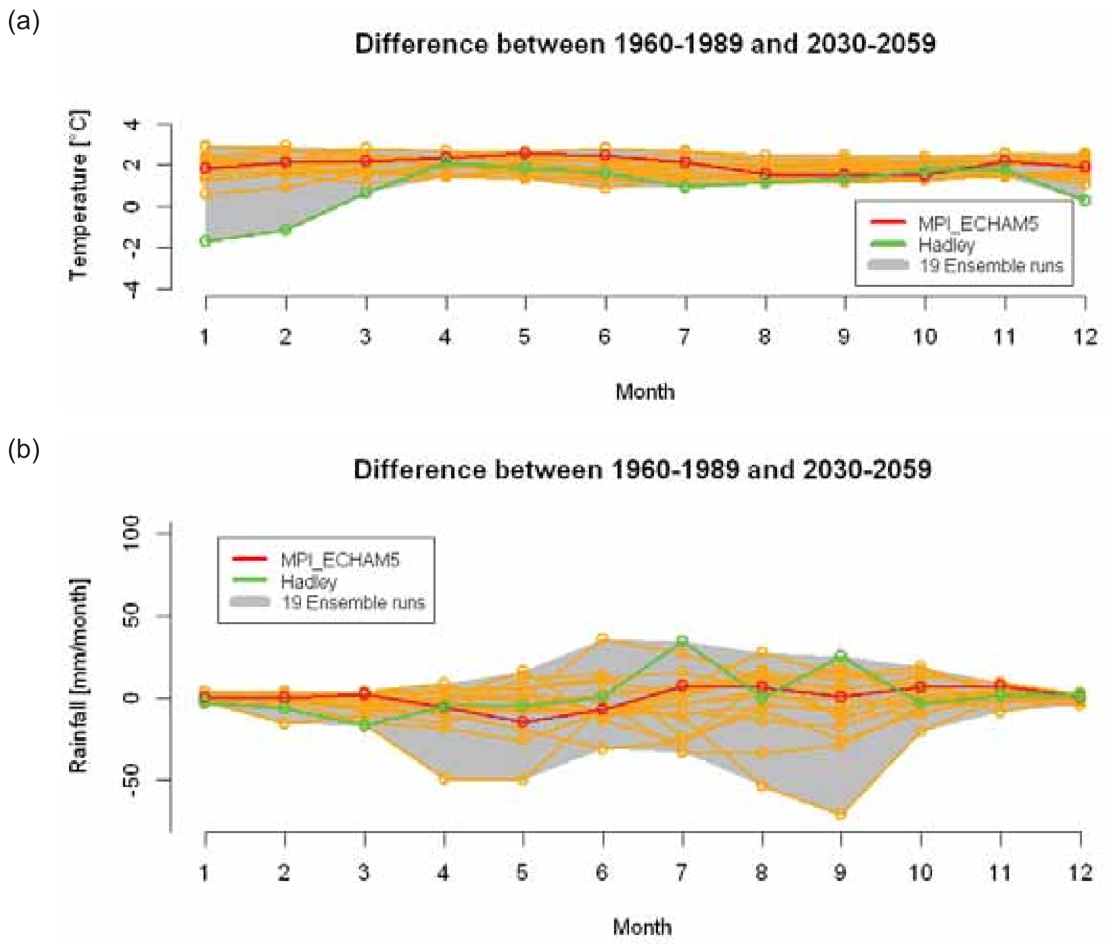


Climate Projections

Although variable-resolution global atmospheric General Circulation Models (GCMs) are increasingly being used, most GCMs provide projections of CC at the global to continental scale with a resolution of 2.5^{o} (i.e., grid squares of approximately 250 kilometers (km) at the equator). This resolution is not fine enough to resolve small-scale atmospheric circulation and GCMs are not normally applicable at the scale of river basins. Consequently, GCM outputs have to be downscaled to provide information useful for hydrological and water resource studies. Two broad classes of downscaling approaches exist: i) dynamic methods, which involve the explicit solving of the process-based physical dynamics of the system (Giorgi and Mearns 1991; Jones et al. 1995); and ii) statistical methods that use identified system relationships from observed data (Wigley et al. 1990; Wilby 1995). Statistical approaches assume that observed relationships between climate variables and local weather will be the same in the future even under conditions of CC. Because in reality these relationships may change, physical methods ought to be able to reproduce regional climate better than statistical methods, especially under conditions of CC. However, the physics of the atmosphere and its feedback effects (e.g., on surface processes) are highly complex and dynamic methods still lack the full inclusion of some of these processes. Furthermore, the numerical simulation of regional climate is extremely time-consuming. As a result, there are currently few climate realizations generated by regional climate models, and previous studies of CC in the Volta Basin have been based predominantly on statistical downscaling methods (Andah et al. 2004; de Condappa et al. 2009; Leemhuis et al. 2009).

In the current study, we used a dynamic regional climate model to determine future climate projections in the basin. The model used (CCLM) has 32 vertical layers and 10 soil layers. It was run for the whole African continent with grid dimensions of 165 x 162 and grid spacing of 0.5°. For scenario simulations, the boundary conditions are normally taken from GCM outputs. Rather than using the results from a number of GCMs, we used the output from the model which best quantified the current temperature and rainfall regime in the region. This was the ECHAM-5 model (Roeckner et al. 1999, 2003), which over the wider region of West Africa produces results that lie approximately in the middle of the set of projections produced by a total of 21 GCMs (Figure 3).

FIGURE 3. Comparison of changes in a) temperature, and b) rainfall from 21 GCMs for West Africa, illustrating that ECHAM-5 results lie broadly in the middle of the set of projections.



Current climate, of which data for the Volta Basin is rarely available without gaps, was reconstructed using runs of CCLM forced by ERA-40 re-analysis data, generated by the European Centre for Medium-range Weather Forecasts (ECMWF) (http://www.ecmwf.int/products/data/archive/descriptions/e4/index.html) in combination with observed data converted to a grid (Hattermann 2011). A bias correction was performed for simulated temperature and precipitation using Climatic Research Unit data (Mitchell and Jones 2005) as reference and comparing it against the simulated data on a monthly time step for the 30-year reference period 1971-2000. For each grid cell, the long-term observed data were compared to the simulated data and the average bias was computed to derive a vector of twelve correction factors (i.e., one per month) for each cell. The climate projections were corrected by this bias for each simulation day and at each grid cell using the monthly correction factors (Hattermann 2011).

To provide the basis of the CC analyses, a number of different scenarios could have been evaluated. However, in this study, only the IPCC SRES-AR4 A1B emissions scenario (IPCC 2000) was used. This scenario describes a future world of very rapid economic growth, global population that peaks at 8.7 billion in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. It is distinguished from other scenarios by the technological emphasis on a balance between fossil-intensive and non-fossil energy sources (IPCC 2000). As such, it provides a broadly middle impact scenario with changes that, at the global level, lie between extremes produced by other emission scenarios (i.e., A2 - extensive fossil fuel use, and B2 - moderate increase in greenhouse gas concentrations). The simulations comprised 30 years of daily control runs (1971-2000) and 100 years of transient scenario runs using the A1B climate scenario (2001-2100).

Flow Simulation

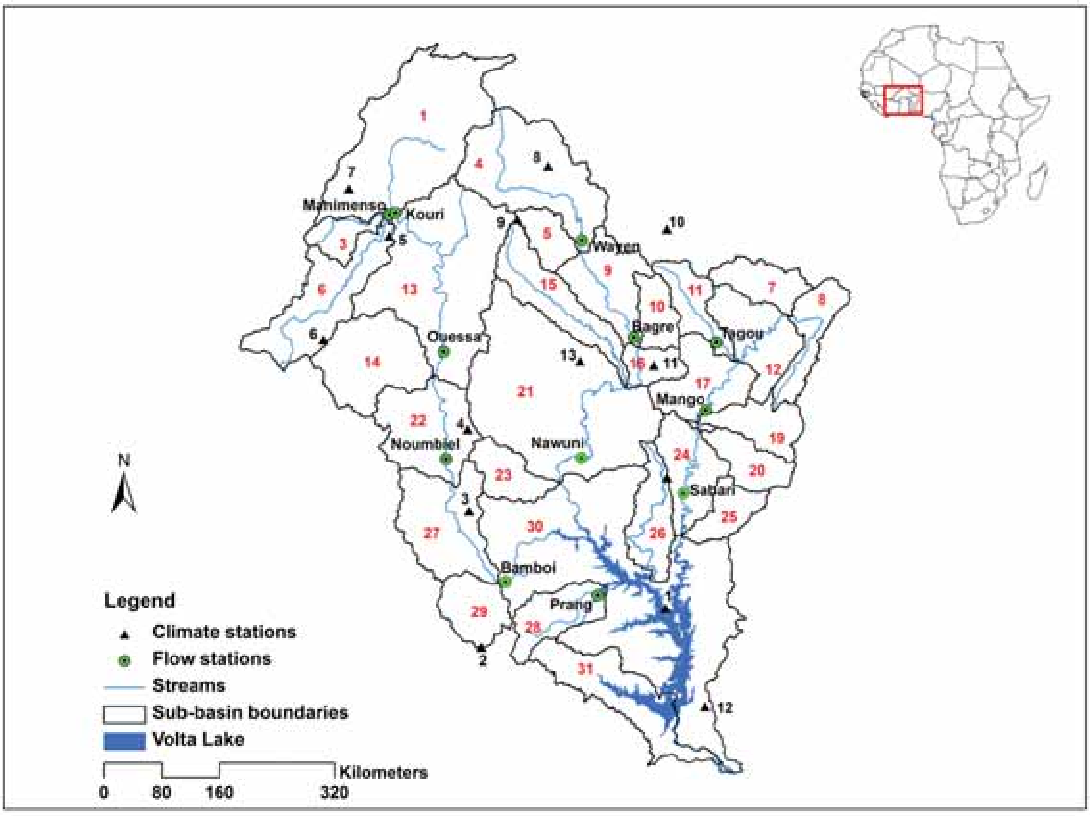
SWAT was used to simulate the hydrology of the Volta Basin with results of the CCLM simulation as input. SWAT is a rainfall-runoff model (Arnold et al. 1998) which operates on a daily time step. Data input to SWAT is grouped into five categories: topography, land use, soil, land use management and climate. Similar land use, soil characteristics and slope within identified sub-basins are lumped together into smaller hydrological response units (HRUs). In this study, topographic data were obtained from the Shuttle Radar Topography Mission (SRTM) (Rabus et al. 2003), land use from the European Space Agency's GlobCover Portal (Arino et al. 2007) and soil data from the Digital Soil Map of the World of the Food and Agriculture Organization of the United Nations (FAO) (Batjes 1997). The physical characteristics of the soils, required by the SWAT model, were extracted for each soil texture class from the MapWindow Interface for SWAT (MWSWAT) database (http://swat.tamu.edu/software/mwswat/).

SWAT uses an automated procedure, based on an area 'threshold' set by the user, to delineate sub-basins. In this study, the area threshold was set as 3,061 km^2, which created 31 sub-basins (Figure 4). The area threshold was selected by trial and error in an attempt to match the SWAT sub-basins as closely as possible to those used in the WEAP model. It was not possible to get an exact match and, consequently, some of the catchments in the WEAP model comprise more than one SWAT sub-basin. In addition, 78 HRUs were created.

The model was set up using observed daily climate data for the period 1968-1980 derived from 14 meteorological stations located within the basin (Figure 4). Five climate-related inputs (i.e., precipitation, solar radiation, wind speed, minimum and maximum temperature, and relative humidity) were used.

The SWAT Calibration and Uncertainty Program (SWAT-CUP2) (Abbaspour 2009) was used to calibrate the model. Historic monthly flows from eight hydrological stations (i.e., those with sufficient data, spanning a common period) were used over the period January 1970 to December 1980. In this study, the Sequential Uncertainty Fitting (SUFI-2) was employed. This aims to quantify and minimize the uncertainty in the model

FIGURE 4. Map showing the sub-basins simulated within SWAT, the location of the climate stations used for input data and the flow-gauging stations used for model calibration.



simulation (i.e., the uncertainty arising from the model and model parameters). Two quantitative measures, P-factor and R-factor, were used as indicators for the model uncertainty. The P-factor indicates the percentage of observed data that falls within 95% of prediction uncertainty (95PPU) while the R-factor is the average thickness of the 95PPU band divided by the standard deviation of the observed data. The Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970) and Coefficient of Determination (R^2) were also used to evaluate the calibration. Model validation was carried out for the period 1980 to 1985. Only six stations, 3, 6, 7, 9, 10 and 23, had observed data for this period. This included station 23 which had no data in the calibration period.

The indicators reveal a mixed performance from SWAT. The model calibrated and validated well for some stations, but less well for others (Table 4). Overall, the results were good for four stations and poor for four others. The poor results can partly be attributed to the scarcity of input data. For example, although it covers a large area (ca. 36,500 km^2, about 8% of the total basin), the catchment of gauging station 7 is represented in the model by just one land use class (i.e., agriculture); there are no data on other land uses in the catchment and no management practices have been defined for the agricultural land use. Furthermore, no dams, reservoirs or ponds are simulated in the model.

After calibrating and validating, daily climatic variables derived from CCLM (i.e., rainfall, temperature, potential evapotranspiration) were used as input to the SWAT model. SWAT uses climate data from a weather station closest to the centroid of each sub-basin, so the gridded weather data from CCLM were first converted to point data. To do this, the centroid of each sub-basin was considered a virtual weather station and the Inverse Distance Weighting (IDW) method (Bartier and Keller 1996) was used to interpolate

TABLE 4. Calibration and validation results obtained for the SWAT model.

Gauging station	Description	Longitude	Latitude	Data period	Catchment area (km^2)	Calibration				Validation	
						P-factor (x 100)	R-Factor	NSE	R^2	NSE	R^2
3	Station Bagre, White Volta, Burkina Faso	-0.43	11.20	1974-1990	36,579	0.45	0.77	0.74	0.75	0.03	0.47
6	Station Kouri, Black Volta, Burkina Faso	-3.48	12.73	1955-1982	3,873	0.76	3.54	0.29	0.40	-0.69	0.4
7	Station Manimenso, Black Volta, Burkina Faso	-3.40	12.75	1956-1984	36,532	0.52	2.71	-0.17	0.17	-0.79	0.02
9	Station Noumbiel, Black Volta, Burkina Faso	-2.77	9.68	1975-1985	115,742	0.71	1.4	0.81	0.83	0.69	0.84
10	Station Ouessa, Black Volta, Burkina Faso	-2.8	11.02	1969-1986	85,936	0.11	0.44	0.29	0.53	0.3	0.41
17	Station Mango, Oti River, Togo	0.47	10.29	1953-1974	40,358	0.8	0.66	0.79	0.79	-	-
21	Station Prang, River Pru, Black Volta, Ghana	-0.88	7.98	1957-1967	7,894	0.23	3.02	0.65	0.68	-	-
22	Station Tagou, Kompienga, Oti River, Burkina Faso	0.60	11.14	1980-1988	6,342	0.68	0.96	0.15	0.16	-	-
23	Station Wayen, White Volta, Burkina Faso	-1.078	12.38	1955-1988	21,374	-	-	-	-	0.1	0.44

data from grid points to the virtual weather station. Using these data, SWAT simulated river flows, groundwater recharge and actual evapotranspiration for the period 1983-2100. It was assumed that there were no changes in land use patterns.

To determine hydrological changes arising from CC, standard analyses were applied to the simulated 30 years of flow data in each of the three periods 1983-2012, 2021-2050 and 2071-2100 at key locations in the basin. This included the derivation of flow duration curves and flood frequency curves. A flow duration curve shows the relationship between any given discharge and the percentage of time that flow is equaled or exceeded (Shaw 1984). As such, it illustrates not only the range of discharges experienced, but also the general flow variability at a site (Smakhtin 2001).

Flood frequency analysis entails the estimation of the peak discharge that is likely to be equaled or exceeded, on average, once in a specified period, T years. This is the T-year event and the peak, Q_T, is said to have a return period or recurrence interval of T years. The return period, T years, is the long-term average interval between successive exceedances of a specified flood magnitude, Q_T. Analysis of flood frequency involves fitting a statistical distribution to the series of annual maximum flows, ranked by the magnitude of flow. In this study, we did the analyses using the maximum daily discharges derived from SWAT and used the General Extreme Value (GEV) distribution, fitted using the method of probability weighted moments (Shaw 1984). In all cases, the curves were extrapolated to T=100 years. No allowance was made for anthropogenic impacts on flows.

The simulation of the historic period indicated that SWAT was, in principle, able to reproduce the hydrological response of several sub-basins in the Volta Basin. However, for some locations there was still a distinct bias to the observed data. Consequently, before using the flow series in the WEAP model, the bias of simulated flows was corrected using the available observed data at each gauging station. This was achieved using the same approach as for the bias correction of the simulated climate data. For each station, the observed and simulated data were compared on a monthly basis and the average bias per month was calculated. The simulated future monthly flows were corrected using the twelve monthly correction factors.

Water Resources Simulation

The WEAP model (SEI 2007) was used to assess the impacts of CC on water resource availability in the Volta Basin. The WEAP model calculates a mass balance of flow sequentially down a river system, making allowance for human-induced abstractions and inflows. It is typically used to simulate alternative scenarios comprising different development and management options. For each scenario, the model allocates water use in the catchment using an iterative Linear Programming algorithm, the objective of which is to "optimize coverage of demand site and instream flow requirements, subject to demand priorities, supply preferences, mass balance and other constraints" (SEI 2007). The demand priorities are set by the user. When water is limited, the algorithm is formulated to progressively restrict water allocation to those demand sites given the lowest priority.

In this study, we refined a WEAP model that had been configured for the basin by de Condappa et al. (2009). The model was configured to simulate the 18 major sub-basins of the Volta Basin (Figure 5; Table 5). The model was modified to include several additional large dams. In addition, small reservoirs in each sub-basin were modeled by aggregating their total storage (estimated using the methodology described in Liebe et al. 2005) and simulating it as a single reservoir. This was an improvement on the earlier version of the model, which simulated the small reservoirs simply as a fixed demand (de Condappa et al. 2009). The time step for the modeling was monthly.

For each sub-basin, the available water resources (head-flow) were derived from the output of the SWAT modeling. SWAT flow was generated in 31 sub-basins, so a simple method of area-weighting was used to convert them to the 18 sub-basins simulated in the WEAP model. Rainfall and potential evapotranspiration data, required for irrigation schemes and reservoirs, were obtained directly from the CCLM output and varied depending on which sub-basin they were located. Net evaporation from reservoirs (i.e., open water evaporation minus rainfall directly onto a reservoir surface) was estimated from the rainfall and potential evaporation data, and averaged over each sub-basin.

In the model, spatially and seasonally disaggregated water demand was simulated for four sectors: domestic, livestock, irrigation and hydropower. Temporal variation in demand is mainly a function of differing water demand due to climate-related seasons in agriculture and varying electricity demand over the year. The priorities for the demand sites were set within each sub-basin assuming priority in the order given above (i.e., domestic the highest priority and hydropower the lowest). However, recognizing the reality that there is currently no upstream-downstream cooperation, allocation priorities were also progressively decreased with increasing distance downstream. Environmental water needs were not explicitly included in the model.

FIGURE 5. Schematic of the Volta Basin as configured within the WEAP model for the current situation.

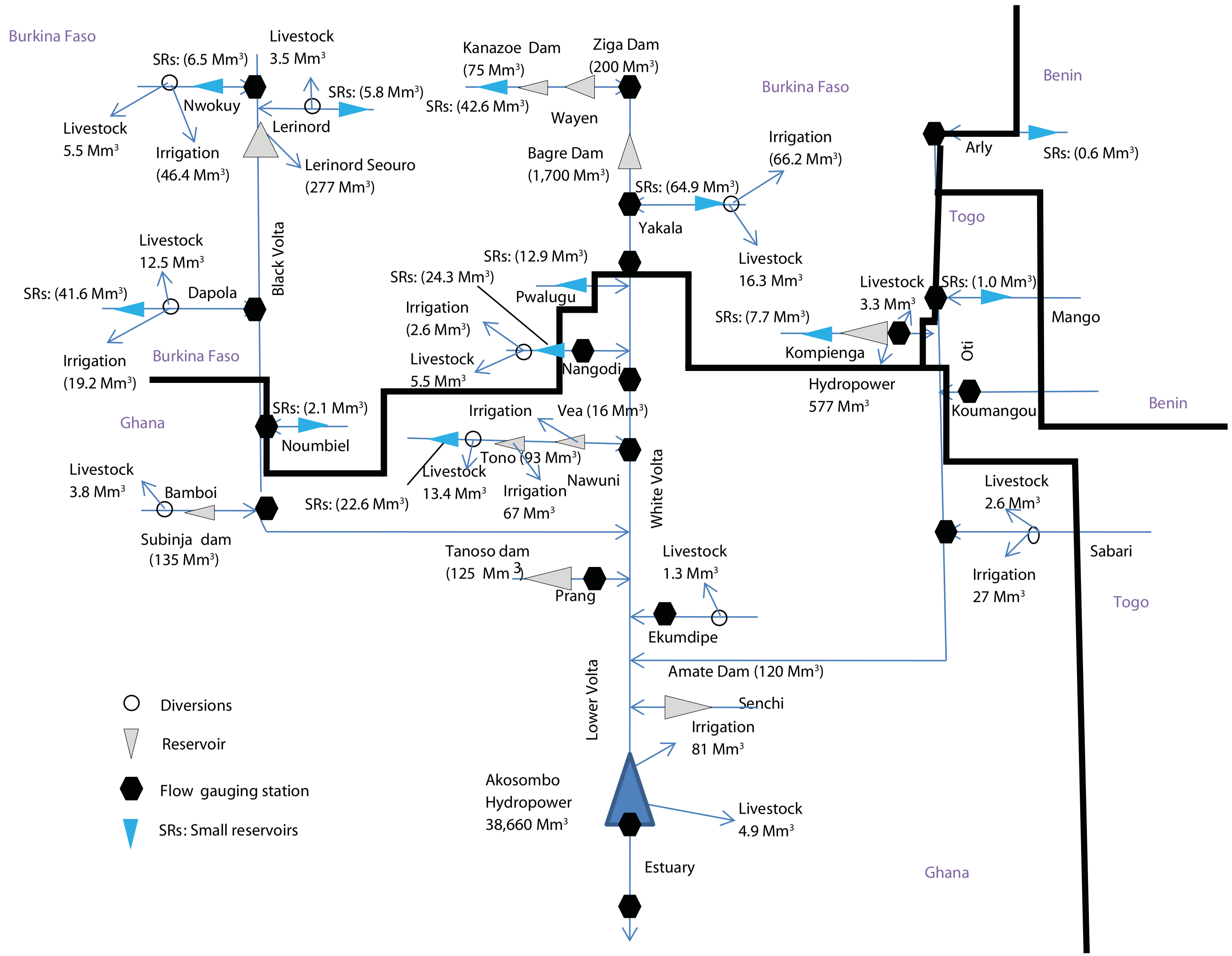


TABLE 5. Summary of the 18 sub-basins simulated in the WEAP model.

Basin ID	Name	Area (km^2)	Observed average annual flow (Mm^3)*	Total area of formal irrigation (ha)	Total installed hydropower capacity (MW)	Small reservoir storage (Mm^3)
1	Lerinord	32,505	-	-	-	5.8
2	Nwokuy	15,289	820	3,291	-	6.5
3	Dapola	53,367	3,195	11,007	-	41.6
4	Noumbiel	14,582	2,643	230	-	2.1
5	Bamboi	22,627	-	110	-	-
6	Wayen	21,374	231	5,319	-	42.6
7	Yakala	15,206	931	4,695	10	64.9
8	Nangodi	11,355	746	184	-	24.3
9	Pwalugu	8,718	-	-	-	12.9
10	Nawuni	43,908	-	3,790	-	22.6
11	Arly	7,052	188	-	-	0.6
12	Kompienga	6,343	292	-	14	7.7
13	Mango	26,964	-	-	-	1.0
14	Koumangou	6,843	1,939	-	-	-
15	Sabari	15,960	-	1,915	-	-
16	Prang	7,895	1,056	129	-	-
17	Ekumdipe	8,208	1,752	-	-	-
18	Senchi	84,647	-	308	1,020	-

Note: * Observed average annual flow is based on the total length of the record that is available at the most downstream station in each sub-basin.

Domestic demand was determined by estimating population per sub-basin and multiplying it by the average per capita water consumption of the basin (35 liters (l) d^{-1}). The average per capita consumption was assumed not to change over time. A gridded population dataset from the Socioeconomic Data and Applications Center (SEDAC) (http://sedac.ciesin.columbia.edu/gpw/documentation.jsp) at 2.5' resolution was aggregated to derive population per sub-basin for the year 2010. Using a decay function and a population growth rate of 2.6% and 2.4%, respectively, the equivalent population for 1983 (base year) and 2000 were derived. In accordance with the A1B scenario, it was assumed that population growth would gradually decline with no further increases after 2050 (Table 6).

Regional livestock data for Ghana and Burkina Faso were analyzed to estimate livestock demand per sub-basin. Average annual livestock growth rate (2.5%) for the basin was inferred from regional time-series data obtained for the two countries (Ministry of Food and Agriculture, Ghana) (Table 6). Livestock numbers per sub-basin were multiplied with livestock per capita water consumption (50 ld^{-1}) to determine livestock demand. Within the WEAP model, the water required to meet both domestic and livestock demand was assumed to come from rivers or groundwater, with rivers being given the higher supply preference.

TABLE 6. Estimated human and livestock populations in each sub-basin.

Sub-catchment	Human population				Livestock population			
	1983	2000	2025	2050	1983	2000	2025	2050
Arly	98,809	156,834	261,174	280,111	265,317	460,874	748,458	1,387,599
Bamboi	454,843	721,947	1,238,867	1,289,426	339,004	515,835	956,329	1,772,980
Dapola	1,549,051	2,458,723	4,219,186	4,391,374	238,043	362,211	671,518	1,244,957
Ekumdipe	138,692	220,138	377,758	393,175	153,275	233,226	432,388	801,623
Kompienga	141,566	224,700	385,587	401,323	200,117	304,502	564,529	1,046,605
Koumangou	164,723	261,455	448,659	466,969	155,176	236,119	437,751	811,565
Lerinord	399,361	633,884	1,087,750	1,132,142	578,174	879,760	1,631,026	3,023,831
Mango	540,283	857,562	1,471,582	1,531,639	511,193	887,978	1,442,073	2,673,522
Nangodi	428,415	680,000	1,166,885	1,214,507	766,530	1,166,366	2,162,377	4,008,927
Nawuni	841,009	1,334,888	2,290,677	2,384,161	1,487,520	2,263,438	4,196,287	7,779,681
Noumbiel	247,896	393,471	675,199	702,755	575,904	876,306	1,624,622	3,011,959
Nwokuy	490,166	778,014	1,335,078	1,389,563	529,936	806,360	1,494,947	2,771,548
Prang	241,763	383,737	658,495	685,369	88,652	153,996	250,089	463,652
Pwalugu	483,612	767,611	1,317,226	1,370,983	610,034	1,059,672	1,720,903	3,190,452
Sabari	501,664	796,264	1,366,395	1,422,158	364,086	553,999	1,027,085	1,904,158
Senchi	2,104,437	3,340,258	5,731,905	5,965,829	1,897,202	2,886,817	5,351,998	9,922,305
Wayen	1,236,666	1,962,892	3,368,336	3,505,801	693,123	1,054,669	1,955,297	3,625,011
Yakala	1,214,798	1,928,182	3,308,774	3,443,808	1,063,234	1,617,836	2,999,378	5,560,679
TOTAL	11,277,754	17,900,560	30,709,533	31,971,093	10,516,520	16,319,964	29,667,055	55,001,054

Data on irrigation water demand (per hectare) were not available for all irrigation schemes in the basin. However, data were available for six schemes in Ghana. Using these data, a regression relationship between annual water demand and developed irrigation area was derived. This relationship was used to estimate annual irrigation water demand for all the formal irrigation schemes in the basin. For each month of simulation, irrigation demand (m^3ha^{-1}) in each sub-basin was estimated from a second empirical relationship that linked irrigation demand to net rainfall (i.e., rainfall-potential evapotranspiration). The key assumption in this analysis was that, in relation to per-hectare demand, differences between schemes predominantly reflect differences in rainfall and potential evapotranspiration rather than differences in crops or water management practices. This is a simplification, but without more information on either crops or water management it was not possible to conduct a more sophisticated analysis. The regression equation enabled estimates of modified future irrigation demand, arising from changes in rainfall and potential evapotranspiration (as predicted in CCLM), to be computed. For all simulation runs, irrigated crops and agronomic practices were assumed to remain constant in the future. Within the WEAP model, irrigation water was assumed to come from rivers or, in a few cases, directly from reservoirs (e.g., the Tono and Vea reservoirs).

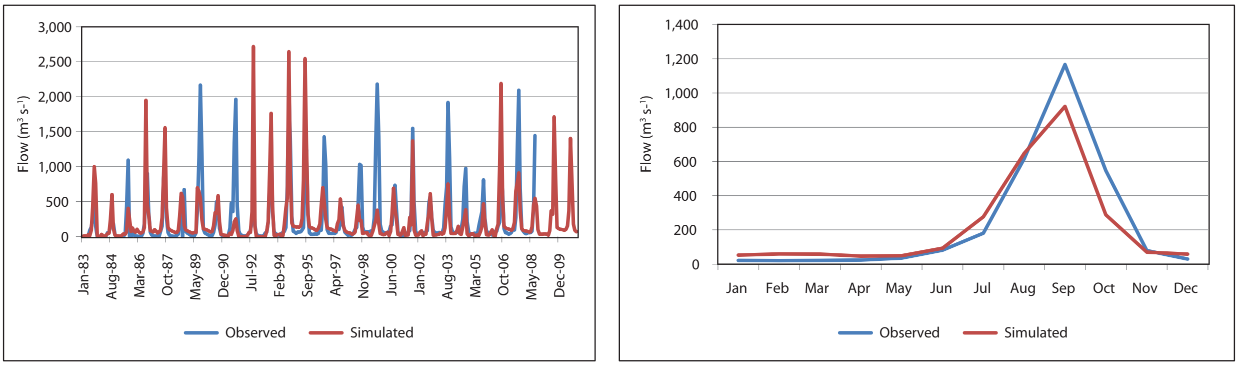
Hydropower demand was built into reservoirs that generate electricity in the basin. For all hydropower schemes (current and future), the WEAP model requires the current or proposed power-generating characteristics (i.e., maximum and minimum turbine flow, plant factor (i.e., proportion of time the power station is operating) and generating efficiency). For larger schemes (e.g., Akosombo, Bui, Sabari), some data were available from the Engineering Department of the VRA and the Bui Power Authority. Where data were not available, particularly for planned schemes, it was necessary to make assumptions based on the overall generating capacity (MW) of the proposed schemes. The WEAP model converts the energy demand into an equivalent volume of water that must be released from the reservoir every month to satisfy that demand. For all simulation runs, future reservoir operational rules were assumed to remain constant.

The WEAP model requires volume-elevation relationships for all reservoirs in order to compute changes in volume as a consequence of evaporation. For hydropower reservoirs, these relationships are also required to determine the drop in elevation (i.e., ‘head’) of water passing through the turbines. This information was available for many of the larger reservoirs, but for many small and large reservoirs, especially those of the planned schemes, the curves were not available. However, the Ministry of Works and Housing, Ghana (MWH 1998) provided information on tail-water elevation, dam height, minimum reservoir operating level, full supply level, storage capacity, live storage and daily average discharge for many of the official dams. From these data, assumed volume elevation curves for the reservoirs were constructed. The same analysis was carried out for the reservoir that simulated the combined storage of all the small reservoirs in each catchment.

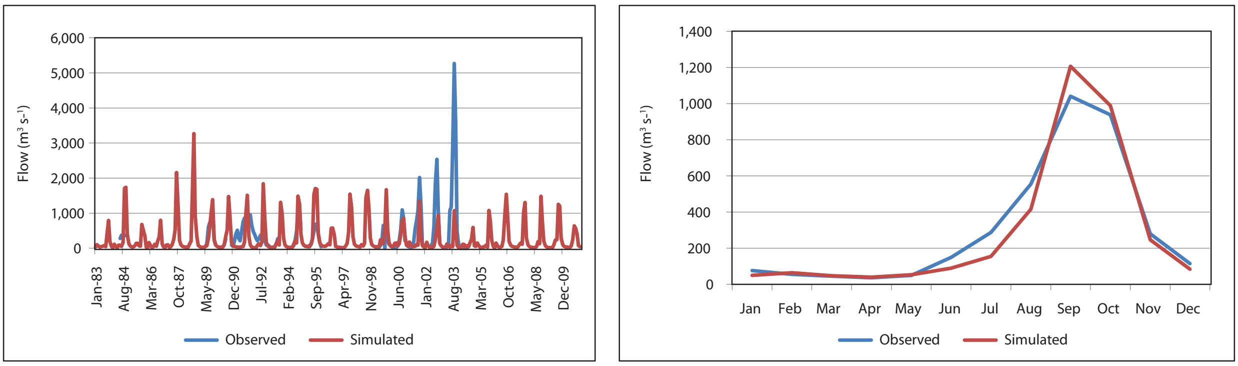
The WEAP model was validated by simulating the recent past (1983-2010) and comparing simulated and observed flows at the most downstream stations on the Black Volta, White Volta and Oti River (i.e., Bamboi, Nawuni and Sabari, respectively). In addition, comparison was made between observed and simulated water levels in Lake Volta. The results effectively show the combined effect of all the model simulations (Figure 6). They indicate that the simulated flow hydrographs are reasonable and that the models have performed well in relation to mean monthly flows. However, although the broad pattern of water-level fluctuations in Lake Volta is reasonable, the timing of changes is poor. This is primarily due to error in the timing of high and low flows in each of the major tributaries. Furthermore, the mean monthly water levels are over-estimated in all the months. The error in the simulated mean monthly values varies from 1.0 to 1.6 m and the percentage error in the mean annual water level is 1.3%. With respect to mean annual volume, this translates into an error of 16.1%. Although there is little observed data for comparison, in relation to electricity generated the error in mean annual electricity production is 5% (i.e., 4,636 $GWhy^{-1}$ observed compared to 4,425 $GWhy^{-1}$ simulated). The fact that the model simulates slightly less electricity than the actual value generated, despite over-estimating the volume of water stored, is most likely a consequence of error in the power-generating characteristics entered into the WEAP model for Akosombo or because the dam has not been operated exactly as simulated in the WEAP model. Overall, results of the calibration suggest that, although the model simulations could inevitably be improved, they are sufficiently robust to provide an indication of the possible changes that might occur in the future and enable comparison between scenarios.

FIGURE 6. Simulation of time series and mean monthly flows at key locations in the basin: a) Nawuni on the White Volta, b) Bamboi on the Black Volta, c) Sabari on the Oti River, and d) water levels in the Akosombo Reservoir.

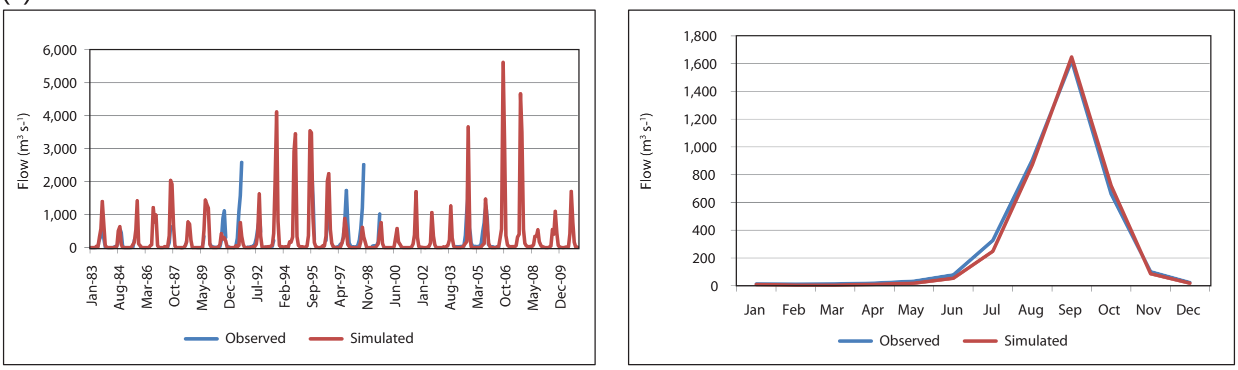
(a)



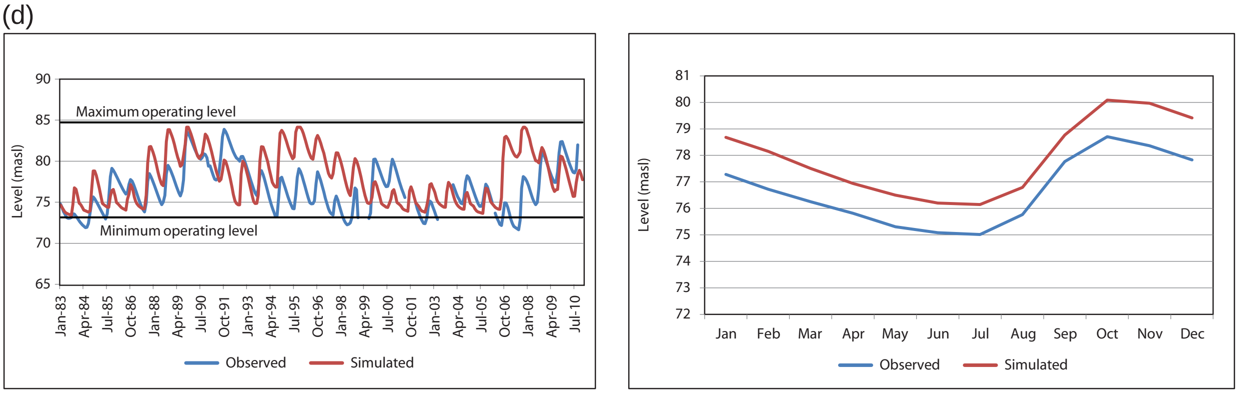
(b)



(c)



(d)



Note: masl = meters above sea level

Development Scenarios

The trajectory of future water resources development in the basin is not clear; many development schemes are being considered but it is unclear which will go ahead and which will not. Consequently, in order to systematically assess the combined impact of growing water demand and CC on the basin's water resources, four scenarios, reflecting different degrees of development, were elaborated and modeled. In essence, the scenarios serve to explore the effects of CC in conjunction with increasing human and livestock populations on different levels of water resources development in the basin. A brief description of each development scenario is given below.

- No development – this scenario simulated the basin in its natural condition without any development. It provided a baseline to enable the impact of only CC to be assessed.
- Current development – this scenario simulated present water withdrawals/demand. In this scenario, irrigation and hydropower schemes were the ones that are currently operating.
- Intermediate development – this simulated possible expansion of existing irrigation schemes, as well as new hydropower and irrigation schemes that are likely to start by approximately 2025.
- Full development – this simulated expansion of the near-future schemes and additional new schemes that may start by 2050.

Table 7 compares total reservoir storage, irrigated area and installed hydropower generating capacity for the four scenarios. The period of simulation for each scenario spanned the full period of CC simulation (i.e., 1983-2100). To facilitate comparison between the scenarios:

- results were summarized over three evaluation intervals: 1983-2012, 2021-2050 and 2071-2100; and
- the assumptions made about demand priorities for the current development scenario (see section, *Water Resources Simulation*) were maintained in the intermediate and full development scenarios.

Basin average results were computed from sub-basin results by computing the area-weighted mean of the results from individual basins.

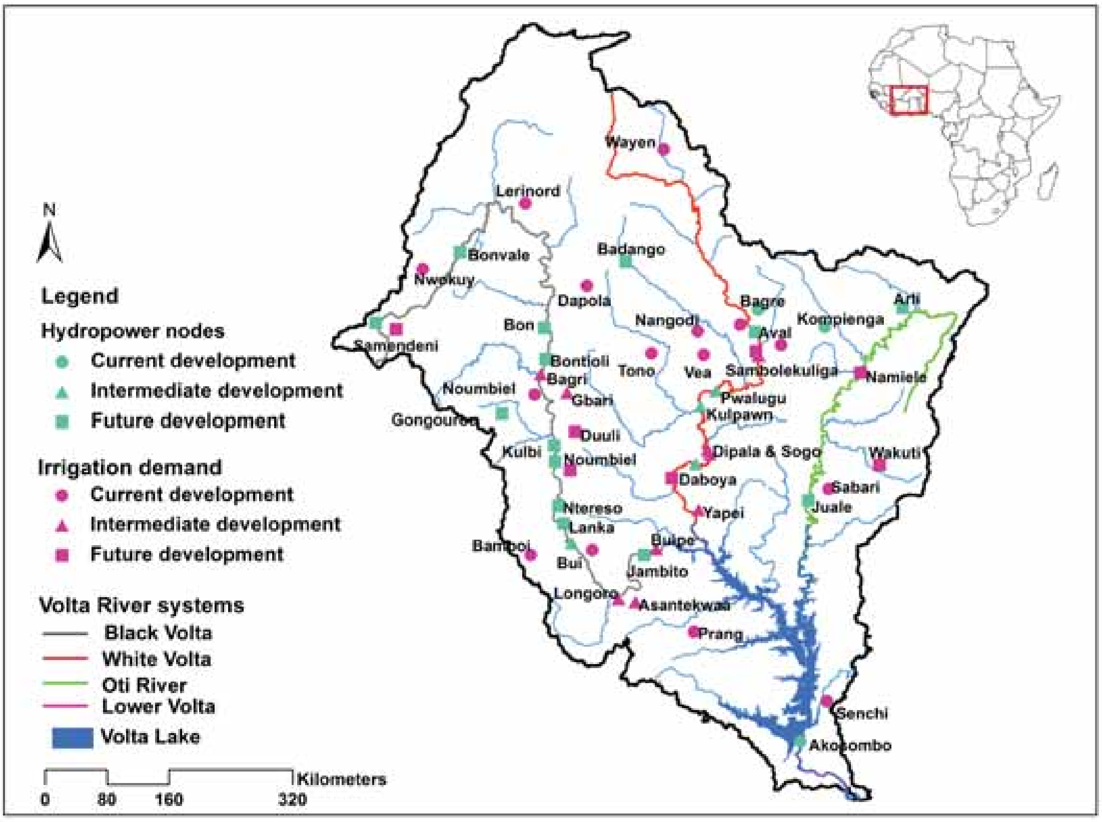
The study focused on formal irrigation and hydropower schemes. Informal irrigation, which is becoming increasingly widespread and gaining prominence in the basin (Barry et al. 2010; Namara et al. 2010), was not considered. Figure 7 shows the irrigation and hydropower schemes considered for the current, intermediate and full development scenarios.

The implications for irrigation and hydropower, as well as domestic and livestock demand, were evaluated for each of these three development scenarios. The volume of water delivered to irrigation schemes as well as the unmet demand was determined for each of the 30-year evaluation periods. Similarly, the amount of hydropower

TABLE 7. Comparison of total reservoir storage, irrigated area and installed hydropower generating capacity for the four development scenarios.

Scenario	Total reservoir storage (Mm^3)	Irrigated area (ha)	Installed hydropower generating capacity (MW)
No development	0	0	0
Current development	153,124	30,468	1,044
Intermediate development	180,124	63,253	1,547
Full development	203,437	78,007	2,031.6

FIGURE 7. Map showing irrigation and hydropower development in the current, intermediate and future development scenarios.



generated was compared to the potential (i.e., the total possible with the installed generating capacity, if flows did not change) for each evaluation period. The amount of water delivered and the unmet demand were computed for domestic supplies and livestock.

The impact of CC and changes in infrastructure development on indices of reliability, resilience and vulnerability (RRV) (Hashimoto et al. 1982b; Fowler et al. 2003) of selected reservoirs was determined for each of these three development scenarios, over each of the 30-year evaluation periods. These indicators provide insight into system performance and are defined as follows:

- *Reliability* is a measure of the frequency of the reservoir to fail to supply water for all irrigation and hydropower demands.
- *Resilience* is a measure of the speed of recovery of the reservoir from failure.
- *Vulnerability* is a measure of the cumulative maximum extent of failure (i.e., cumulative supply deficits).

To calculate these indices, a criteria, C, was defined for each reservoir, which indicates whether the reservoir is in a satisfactory or unsatisfactory state. A satisfactory value occurs when the reservoir can meet all the demands. An unsatisfactory value occurs when the reservoir is unable to meet the specified hydropower and irrigation demand (i.e., the reservoir yield is insufficient). In all cases, C was defined as the top of the *buffer zone*, which, in the WEAP model, is the reservoir water level at which restrictions are imposed to conserve the reservoir's dwindling supplies. The time series of simulated average monthly water levels (X_t), derived from the WEAP model, were then classified as being in either a satisfactory state (S) or a state of failure (F), depending on whether or not water levels exceeded C (equation (1)):

$$\text{If } X_t \geq C \text{ then } X_t \varepsilon\, S \text{ and } Z_t = 1$$
$$\text{Else } X_t \varepsilon\, F \text{ and } Z_t = 0 \qquad (1)$$

Thus, Z_t is a generic indicator of satisfaction or failure.

Another indicator, W_t, which represents a transition from a state of failure to a satisfactory state, was defined as shown in equation (2).

$$W_t = \begin{cases} 1, X_t \varepsilon\, F \text{ and } X_t + 1\ \varepsilon\, S \\ 0, \text{Otherwise} \end{cases} \qquad (2)$$

If the periods of unsatisfactory X_t are then defined as U_1, U_2,…, UN then reliability, resilience and vulnerability are defined as shown in equations (3), (4) and (5), respectively (Hashimoto et al. 1982a, 1982b).

Reliability

$$C_R = \frac{\sum_{i=1}^{T} Z_t}{T} \qquad (3)$$

Resilience

$$C_{RS} = \frac{\sum_{i=1}^{T} W_t}{T - \sum_{i=1}^{T} Z_t} \qquad (4)$$

Vulnerability

$$C_V = \max\left\{\sum C\text{-}X_t, \quad i=1\ldots..N\right\} \qquad (5)$$

Results

Changes in Climate

Figure 8 and Table 8 summarize changes in key meteorological time series (i.e., temperature, basin average rainfall, and potential and actual evapotranspiration) on an annual time-step over the period 1983 to 2100, as derived from the CCLM model for the A1B scenario. The A1B scenario anticipates a basin-wide increase in annual average temperature of up to 3.6 ^{o}C and a decrease in annual average rainfall of approximately 20% by the end of the twenty-first century. As a consequence of the rise in temperature, basin-wide annual potential evapotranspiration increases by approximately 22%. However, due to the reduction in rainfall, basin-wide actual evapotranspiration decreases by approximately 15%. There is considerable spatial variation in the magnitude of changes across the basin with some sub-basins showing much greater changes than others, but there is no apparent pattern in the observed spatial changes (i.e., no north-south or east-west relationship) (Figure 9).

TABLE 8. Basin averaged meteorological variables for the periods 1983-2012, 2021-2050 and 2071-2100.

	Temperature (^{o}C)	Rainfall (mm)		Potential evapotranspiration (mm)	Actual evapotranspiration (mm)
		Mean	CV		
1983-2012	30.3	835	0.12	2,729	717
2021-2050	31.3	757	0.11	2,813	668
2071-2100	33.9	666	0.15	3,323	606

FIGURE 8. Basin average annual climate variables (1983-2100): a) temperature, b) rainfall, c) potential evapotranspiration, and d) actual evapotranspiration.

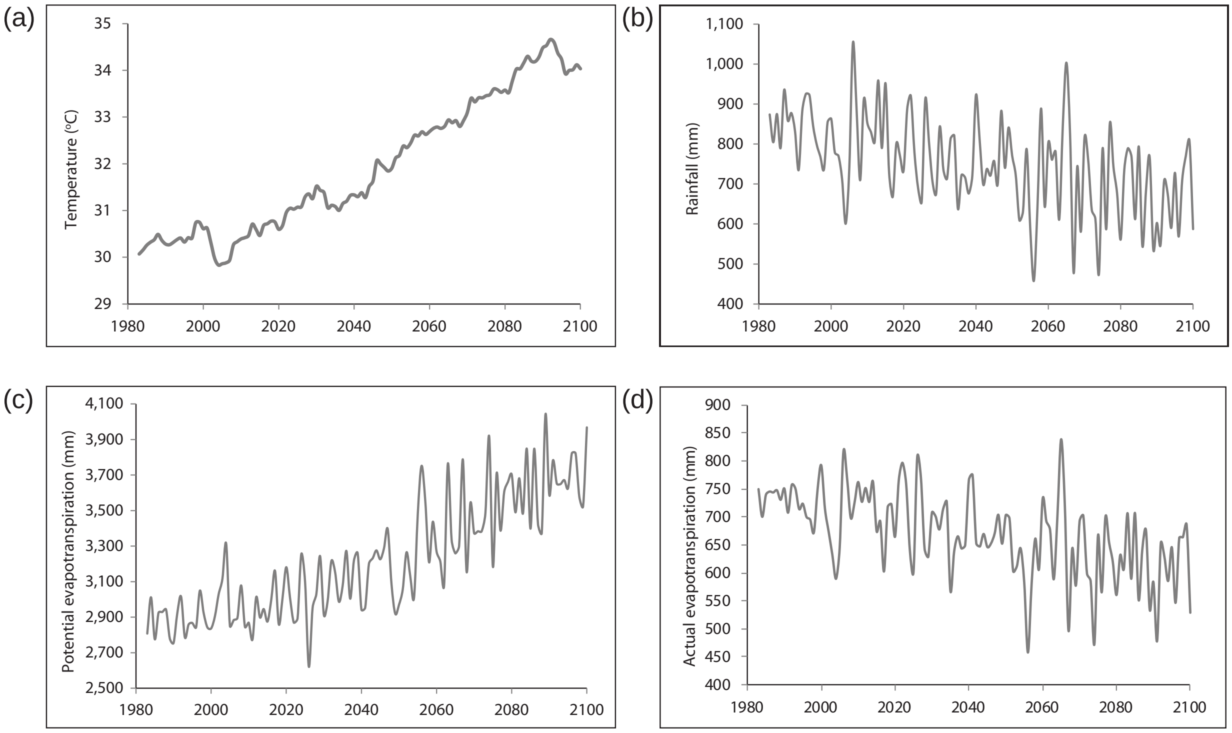
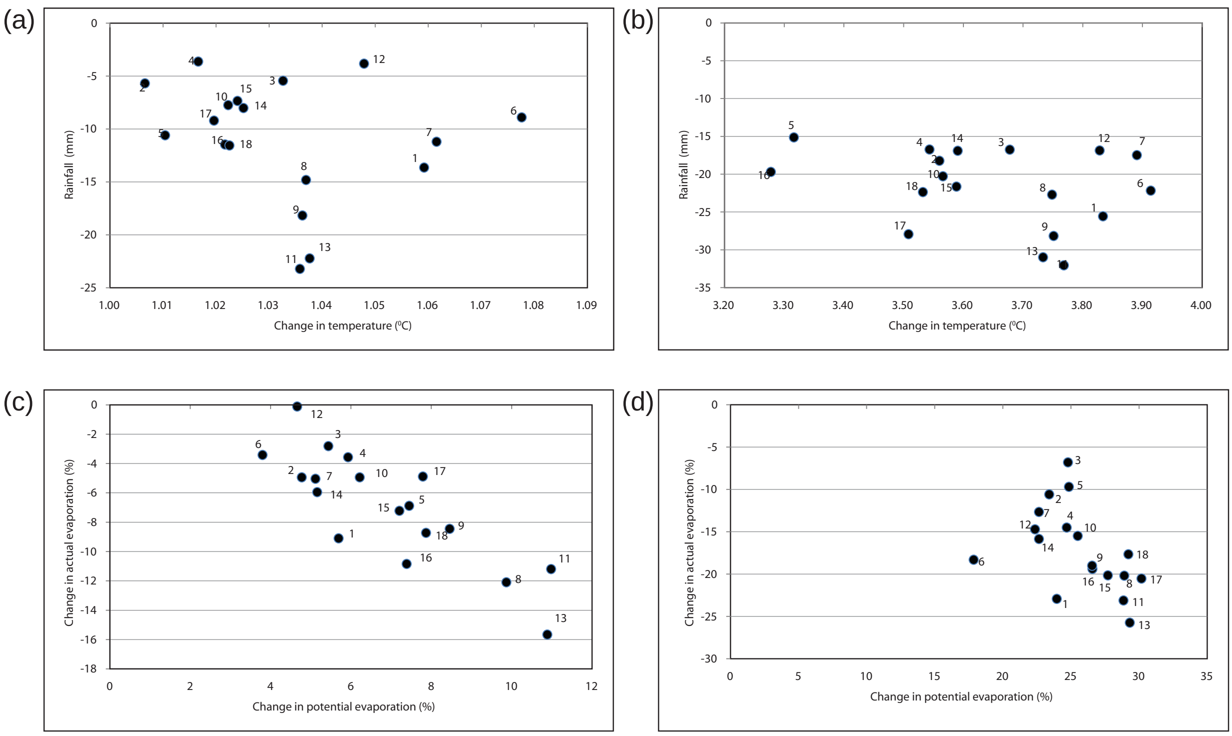


FIGURE 9. CC as projected for the A1B scenario using the CCLM model for the 18 sub-basins. Long-term average means for changes in annual rainfall (%) and increases in temperature (°C) for a) 2021-2050, and b) 2071-2100. Long-term means for changes in potential and actual evaporation (%) for c) 2021-2050, and d) 2071-2100.



Changes in Hydrology

Figure 10 shows the impact of the A1B climate scenario on total basin river flow (m^3s^{-1}) and basin-average groundwater recharge (mm) (i.e., the 'no development' scenario). Both these show a downward trend as a consequence of the changes in climate projected in the A1B scenario. By the end of the century, average annual discharge and groundwater recharge decrease by approximately 45% and 53%, respectively. The CV of both these also increases significantly (Table 9). Flow duration curves, derived downstream of Akosombo for the 'no development' scenario for the same three periods, confirm the decrease in flows of between 40% and 60% at all percentiles (Figure 11).

FIGURE 10. a) Simulated annual discharge (downstream of Akosombo), and b) average basin-wide groundwater recharge.

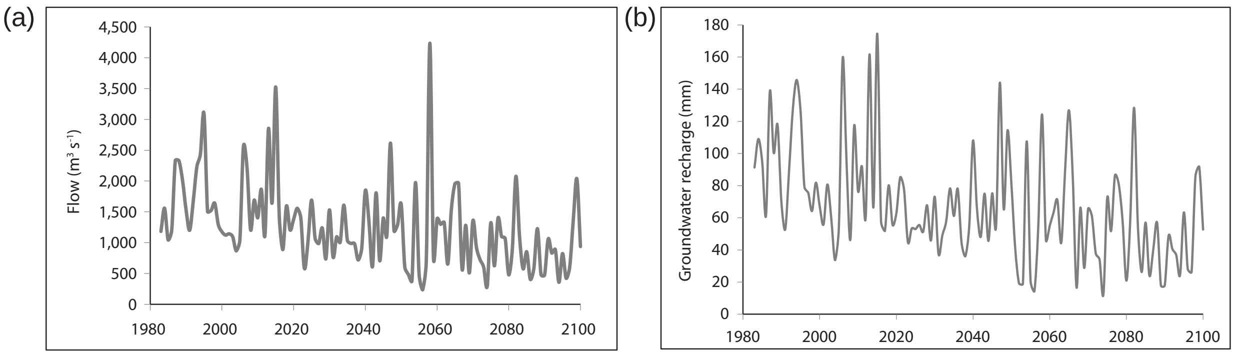
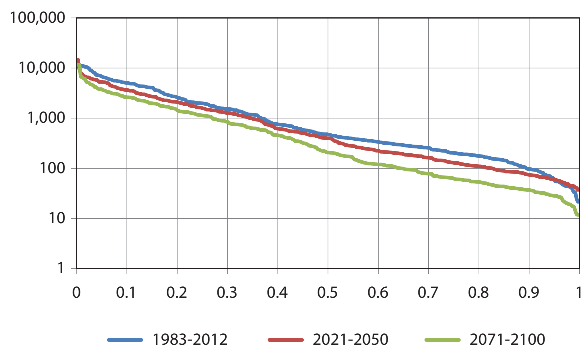


TABLE 9. Mean annual flow and groundwater recharge in the absence of any development for the periods 1983-2012, 2021-2050 and 2071-2100.

	Flow (m^3s^{-1})		Groundwater recharge (mm)	
	Mean	CV	Mean	CV
1983-2012	1,610	0.34	76	0.47
2021-2050	1,217	0.49	53	0.46
2071-2100	885	0.67	36	0.62

FIGURE 11. Comparison of flow duration curves downstream of Akosombo (derived from monthly data) for the 'no development' scenario for the three periods 1983-2012, 2021-2050 and 2071-2100.

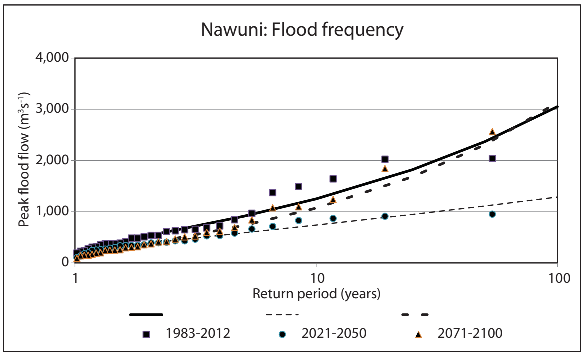


Percentile	Flow (m^3s^{-1})		
	1983-2012	2021-2050	2071-2100
99	33	42	14
95	57	60	28
90	97	74	37
75	203	128	62
50	468	395	206
25	1,967	1,562	1,124
10	5,048	3,624	2,610
5	6,565	5,228	3,601
1	11,022	7,574	6,601

Analyses of the frequency of flood flows (i.e., annual peak discharges) and how they change over time in sub-basins, highlights a complex situation (Figure 12). The magnitude of low-return period (i.e., frequent) floods decreases from 1983-2012 to 2021-2050 and from 2021-2050 to 2071-2100 in all sub-basins. However, the magnitude of the higher-return period floods (i.e., less frequent) increases in some sub-basins (e.g., Lerinord) and decreases in others (e.g., Wayen). In other sub-basins (e.g.. Nawuni), the floods with the higher-return period initially decrease (i.e., between 1983-2012 and 2021-2050) and then increase (i.e., between 2021-2050 and 2071-2100). These results further highlight both the complexity of possible changes occurring as a consequence of CC and also the significant spatial variability in those changes.

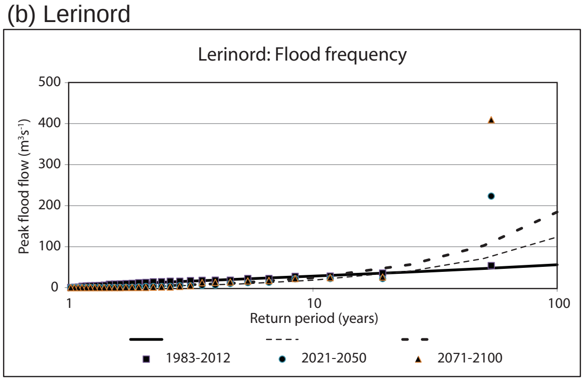
FIGURE 12. Comparison of flood frequency curves in (a) Nawuni, (b) Lerinord and (c) Wayen sub-basins for the periods 1983-2012, 2021-2050 and 2071-2100.

(a) Nawuni



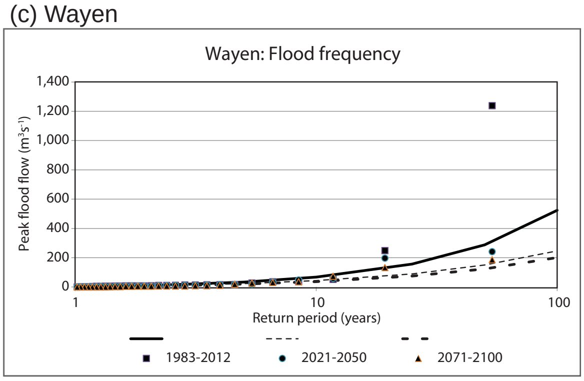
Return period	1983-2012	2021-2050	2071-2100
1.5	410	304	272
2	529	382	376
5	911	590	731
10	1,252	741	1,072
25	1,819	947	1,680
50	2,368	1,112	2,036
100	3,051	1,288	3,129

(b) Lerinord



Return period	1983-2012	2021-2050	2071-2100
1.5	7.8	0.9	0.8
2	11.3	2.4	2.6
5	20.9	9.1	11.6
10	28.1	18.1	24.1
25	38.3	40.3	56.3
50	46.7	71.0	102.6
100	55.9	123.4	184.3

(c) Wayen



Return period	1983-2012	2021-2050	2071-2100
1.5	5.1	3.3	2.7
2	9.8	7.0	6.0
5	33.4	23.2	19.9
10	67.4	43.5	37.0
25	156.5	89.8	75.1
50	287.9	149.9	123.8
100	523.9	246.7	200.8

Combined Impacts of CC and Water Resources Development

Table 10 shows the impacts of CC and water resources development on the flows at four major gauging stations in the basin for the four development scenarios. All stations indicate significant changes in flow. In Table 10, changes in flow in the horizontal direction are attributable to effects of CC while changes in the vertical direction are attributable to developmental effects. It can be seen that the effects of CC on flows are much greater than those of development. This observation is in line with the results obtained by previous studies (de Condappa et al. 2009; Leemhuis et al. 2009). In the 'full development' scenario, the average flow downstream of Akosombo is anticipated to decline, as a consequence of the combined impacts of CC and upstream development, by 48% (i.e., from the current 1,207 to 626 m^3s^{-1}) and 80% (i.e., from the current 1,207 to 261 m^3s^{-1}) by 2050 and 2100, respectively.

Implications for Water Resources Development

Figure 13(a) shows how the average annual irrigation demand (m^3ha^{-1}) across the entire basin changes as a consequence of changes in rainfall and potential evapotranspiration anticipated in the A1B scenario (Figure 7). Figure 13(b) shows how this increasing per-hectare demand, combined with increased irrigated area, translates into a total increase in demand for the current, intermediate and full development scenarios. Table 11 summarizes the increased demand and the unmet demand in each of these three development scenarios.

TABLE 10. Changes in river flows (m^3s^{-1}) at four locations in the basin for the four development scenarios.

Scenario	River	1983-2012	2021-2050	2071-2100
No development	Bamboi	301	263	171
	Nawuni	237	168	152
	Sabari	307	178	173
	Akosombo	1,610	1,217	885
Current development	Bamboi	288	251	160
	Nawuni	218	155	140
	Sabari	300	173	167
	Akosombo	1,207	808	408
Intermediate development	Bamboi	243	217	136
	Nawuni	182	111	94
	Sabari	300	173	167
	Akosombo	1,140	739	346
Full development	Bamboi	161	155	84
	Nawuni	179	100	93
	Sabari	300	174	168
	Akosombo	1,028	626	261

FIGURE 13. a) Predicted average irrigation demand for the basin, and b) total annual irrigation demand for the current, intermediate and full development scenarios.

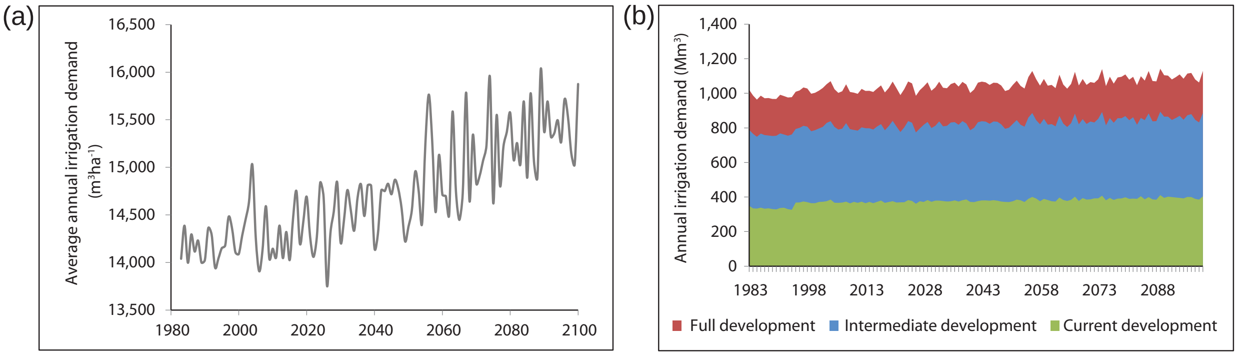


TABLE 11. Changes in total irrigation demand, satisfied demand, unmet demand and percentage of demand delivered in each of the three development scenarios considered.

		1983-2012	2021-2050	2071-2100
Basin average irrigation demand (m^3ha^{-1})		14,234	14,527	15,328
Current development	Water demand (Mm^3)	356	376	394
	Satisfied demand (Mm^3)	323	322	250
	Unmet demand (Mm^3)	33	54	144
	Demand delivered (%)	91	86	59
Intermediate development	Water demand (Mm^3)	786	817	855
	Satisfied demand (Mm^3)	726	605	342
	Unmet demand (Mm^3)	60	212	513
	Demand delivered (%)	92	74	40
Full development	Water demand (Mm^3)	1,005	1,040	1,091
	Satisfied demand (Mm^3)	910	782	349
	Unmet demand (Mm^3)	95	258	742
	Demand delivered (%)	91	75	32

Figure 14 shows the simulated hydroelectricity generated each year in the current, intermediate and full development scenarios, and Table 12 presents the average for each of these three scenarios over the three periods 1983-2012, 2021-2050 and 2071-2100. These results indicate a significant increase in hydroelectricity produced as a consequence of the increased generating capacity between the current and full development scenarios. The results also show that reduced river flows, arising as a consequence of CC, will reduce the amount of hydroelectricity generated in comparison to the potential in the second half of the century. The results for CV indicate that inter-annual variability in hydropower production increases significantly as a consequence of CC, but as the volume of storage increases (i.e., with increasing water resources development) the variability is reduced.

FIGURE 14. Simulated hydroelectricity generated each year (1983-2100) for the current, intermediate and full development scenarios.

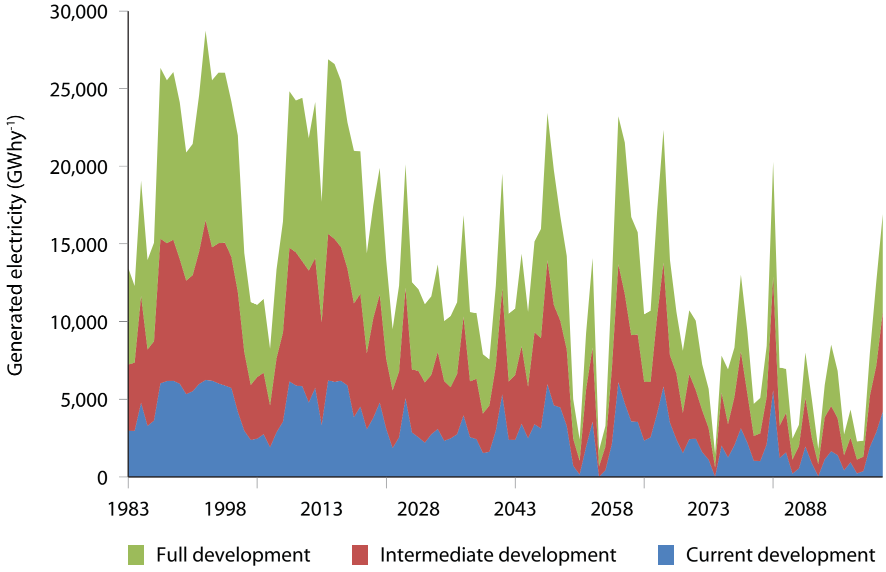


TABLE 12. Changes in average annual hydroelectricity generated and percentage of the total potential in the current, intermediate and full development scenarios.

	Current development			Intermediate development			Full development		
	Hydro-electricity generated (GWhy^{-1})	Percentage of total potential (%)	CV	Hydro-electricity generated (GWhy^{-1})	Percentage of total potential (%)	CV	Hydro-electricity generated (GWhy^{-1})	Percentage of total potential (%)	CV
1983-2012	4,678	77	0.32	6,975	80	0.31	8,467	74	0.28
2021-2050	3,159	48	0.35	4,779	53	0.30	5,673	48	0.25
2071-2100	1,569	24	0.78	2,599	30	0.61	2,701	24	0.58

Table 13 presents indices of reliability, resilience and vulnerability for the Akosombo, Bui and Noumbiel reservoirs, under the current, intermediate and full development scenarios. These results are indicative of the performance of other reservoirs in the basin, and highlight the impacts of both CC and water resources development on reservoir performance. The Bui Dam starts operating in the 'intermediate development' scenario and the Noumbiel Dam in the 'full development' scenario, so results are available only for the appropriate scenarios. The results indicate the following:

- For all the reservoirs, their reliability and resilience decrease and their vulnerability increases as a consequence of CC.
- The reliability and resilience of the Akosombo Dam decrease and vulnerability increases as a consequence of increasing upstream water resources development (i.e., moving from the current development to the full development scenario).
- Conversely, for the Bui Reservoir, reliability and resilience increase as a consequence of upstream water resources development,

and vulnerability declines until 2050 though it increases significantly at the end of the century.

Table 14 summarizes the increased domestic and livestock water demand, both of which increase over time but neither of which vary between the current, intermediate and full development scenarios. The unmet demand in each of these three scenarios is also presented. The results indicate that, because they were given the highest priority, both domestic and livestock water demand are almost fully met in all the scenarios.

TABLE 13. Technical performance of dams in each of the current, intermediate and full development scenarios.

Dam		Current development			Intermediate development			Full development		
		C_R	C_{RS}	C_v	C_R	C_{RS}	C_v	C_R	C_{RS}	C_v
Akosombo	1983-2012	0.86	0.24	5	0.81	0.22	4	0.72	0.18	11
	2021-2050	0.56	0.14	18	0.35	0.09	33	0.31	0.07	47
	2071-2100	0.23	0.05	106	0.10	0.02	122	0.06	0.01	365
Bui	1983-2012	-	-	-	0.71	0.15	15	0.98	0.22	6
	2021-2050	-	-	-	0.34	0.11	51	0.79	0.17	30
	2071-2100	-	-	-	0.13	0.05	285	0.24	0.06	407
Noumbiel	1983-2012	-	-	-	-	-	-	0.86	0.08	39
	2021-2050	-	-	-	-	-	-	0.53	0.04	159
	2071-2100	-	-	-	-	-	-	0.04	0.01	629

TABLE 14. Changes in domestic and livestock water demand and unmet demand in each of the current, intermediate and full development scenarios.

		Domestic			Livestock		
		1983-2012	2021-2050	2071-2100	1983-2012	2021-2050	2071-2100
	Water demand	220	400	409	278	702	2,240
Current development	Satisfied demand	219	398	407	275	690	2,217
	Unmet demand	1	2	2	3	12	23
	Delivered (%)	99.5	99.6	99.5	98.9	98.3	99.0
Intermediate development	Satisfied demand	219	398	407	275	689	2,217
	Unmet demand	1	2	2	3	13	24
	Delivered (%)	99.4	99.6	99.5	98.8	98.1	99.0
Full development	Satisfied demand	219	400	409	275	689	2,214
	Unmet demand	1	0	0	3	14	26
	Delivered (%)	99.5	100.0	100.0	98.8	98.1	98.8

Discussion

Increased water storage, predominantly behind large dams, is central to development plans in the Volta Basin. The governments of the riparian sates (particularly Ghana and Burkina Faso) plan to significantly increase large reservoir water storage in order to support national food security and industrial development (Biney 2010). The planned increases in water storage will facilitate significant increases in hydropower generation and irrigation. If all planned development occurs, large reservoir water storage will exceed 203,000 Mm^3 (i.e., approximately 1.3 times the present levels and 5 times the current mean annual flow of the river), irrigation will exceed 78,000 ha (i.e., 2.6 times the present levels) and installed hydropower generating capacity will be in excess of 2,030 MW (i.e., 1.9 times the present levels).

The results from this study illustrate a single representation of the possible consequences of one particular CC scenario (A1B) derived from one set of models. Each of the models is allied with particular error and uncertainty. The lack of hydrological data in the basin made it difficult to calibrate and validate aspects of the modeling. For example, there were no groundwater data against which to calibrate the groundwater recharge estimates. Hence, an assumption had to be made that, if the SWAT model was simulating river flows reasonably, this meant that it was also providing plausible estimates of groundwater recharge. In reality, this may not have been the case and SWAT may have been simulating flow adequately while misrepresenting the processes that generate runoff. Furthermore, it is likely that some errors have been compounded by the different models and others will have cancelled each other out. However, because of the complexity of using multiple models and lack of data for calibration/ validation, it was not possible to quantify the overall error in the simulation results.

The modeling in this study was greatly complicated by the attempt to combine SWAT with the WEAP model. The SWAT model was chosen because it was felt to be an appropriate physically based model that would be able to simulate the changing conditions arising as a consequence of CC. However, because SWAT and the WEAP model were two separate models without a formal method for coupling, this added significant complication to the modeling effort, not least because it was not possible to align the sub-catchments in each model (see section, *Water Resources Simulation*). Consequently, in future, until the SWAT and the WEAP models are formally combined within a single modeling framework, it would seem more practicable to utilize the hydrological function within the WEAP model rather than attempt to simulate the hydrology in a separate, albeit more sophisticated, model. The limitations in the modeling mean that the results of the study should be treated as suggestive, rather than absolute, indicators of the possible consequences of this particular A1B scenario.

Results from the modeling indicate that CC will affect the basin hydrology. There will be significant spatial variability, but under a mid-range CC scenario the CCLM model anticipates a decline in basin-wide mean annual rainfall of approximately 9% by 2050 and 20% by 2100. In conjunction with an anticipated rise in potential evapotranspiration, this translates into a decrease in average annual basin flow of approximately 24% and 45% by 2050 and 2100, respectively. Groundwater recharge is also anticipated to decrease. These are clearly very significant changes which will have serious consequences for the rural poor, food security and economic growth in the riparian countries.

Agriculture in the basin remains heavily reliant on rainfall and the rural poor rely almost exclusively on agriculture for sustenance. Diminished and less predictable rainfall will lead to increased drought and dry spells within the growing season, which is likely to reduce the resilience of farmers and increase poverty. Recent research has suggested a possible shift to groundwater for agriculture because of the unreliable nature of rainfall (Masiyandima and Giordano 2007; Tuinhof et al. 2011). However, the declining trend in groundwater recharge makes this a less viable option, especially for the shallow groundwater which is most usually accessed by rural communities.

The performance of both the existing and planned reservoirs is greatly undermined by the anticipated impacts of CC of the A1B scenario. The reliability and resilience of individual reservoirs decreases and the increased vulnerability to droughts is shown by the increases in cumulative supply deficits. The impact of increased water storage development is mixed, with the performance of some dams (e.g., Bui) broadly enhanced by upstream water resources development, but the performance of others (e.g., Akosombo) undermined. It was beyond the scope of the current study to evaluate in detail why the differences in changing performance occur for different reservoirs. However, it is likely that they reflect trade-offs between reliability, resilience and vulnerability that are specific to each dam, as well as differences in the nature of upstream water resources development (e.g., the relative ratio of irrigation and hydropower development) and particular geographic features (i.e., upstream basin characteristics) that are a function of the exact location of each reservoir within the basin.

Demand for domestic water supplies is anticipated to increase, largely as a consequence of increasing population within the basin. However, in contrast to both hydropower and irrigation, the volumes of water required remain relatively small in the future and, providing domestic water supply is given the highest priority, future demand will be met more than 99% of the time in the current, intermediate and full development scenarios (Figure 15).

The changes in hydrology, anticipated by the A1B scenario, will have impacts on both hydropower generation and irrigation. The model simulations indicate that currently approximately 91% (323 Mm^3) of formal irrigation demand is met and 77% (4,678 GWhy^{-1}) of the potential average annual hydroelectricity is generated. Increased water storage in large reservoirs, foreseen in the intermediate and full development scenarios, increases the area of land that can be irrigated and the amount of electricity that can be generated. In the absence of CC, both the irrigation demand and the hydroelectricity generated would increase significantly with only relatively minor changes in the reliability of water delivery for either (Figure 15).

CC greatly reduces river flow and hence the volume of water available in the current, intermediate and full development scenarios. With the additional storage provided in the intermediate development scenario, it is anticipated that, by the middle of the century, on average, 74% (605 Mm^3) of the total annual irrigation demand could be delivered and 53% (4,779 GWhy^{-1}) of the average annual hydroelectric potential could be generated. In the same scenario, it is anticipated that, on average, only 40% (342 Mm^3) of the total annual irrigation demand could be delivered and only 30% (2,599 GWhy^{-1}) of the average annual hydroelectric potential could be generated, by the end of the twenty-first century (Figure 15).

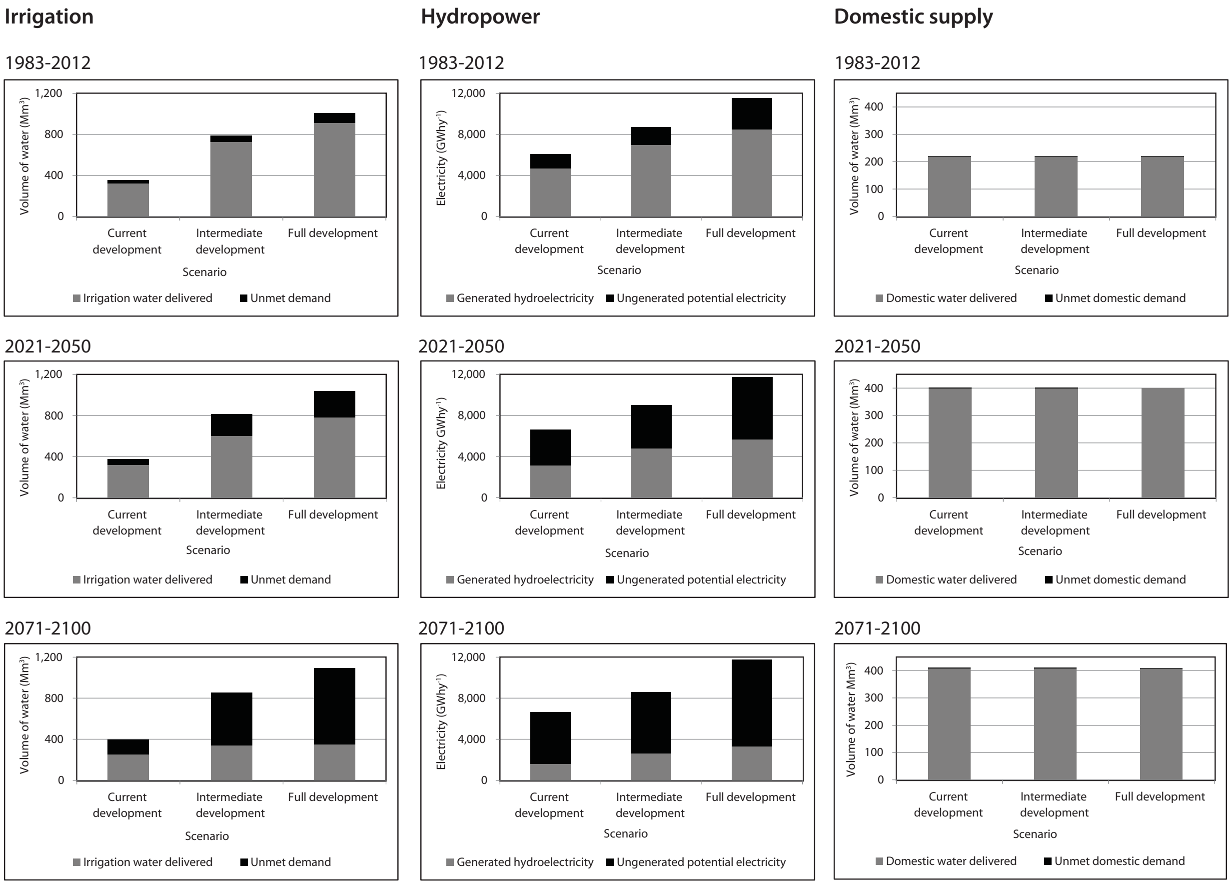
The even greater water storage associated with the full development scenario means that, in comparison to the intermediate scenario, in absolute terms more water could be delivered for both irrigation and hydroelectricity. However, there is a decrease in performance for both irrigation and hydropower (i.e., the ratio of water delivered relative to the potential). Until the middle of the century, the irrigation performance is approximately the same as in the intermediate scenario with, on average, 75% (782 Mm^3) of the total annual irrigation demand being delivered. By the end of the century, it is anticipated that this would be reduced to just 32% (349 Mm^3). It is anticipated that the performance of hydropower generation would be even more badly affected with reductions to just 48% (5,673 GWhy^{-1}) and 24% (2,701 GWhy^{-1}) of the average annual potential, by the middle and the end of the century, respectively (Figure 15).

The results indicate that the inter-annual variability in the ability to deliver water, particularly for hydropower generation, increases significantly as a consequence of CC. However, the additional storage in the intermediate and full development scenarios results in a significant reduction in the variability of hydropower production. This is important because it means that the firm energy that can be produced by hydropower (i.e., the amount of energy that can be guaranteed) is increased, thereby easing complications in the future planning and management of energy production.

Overall, investment in reservoir storage brings benefits, but these benefits are substantially reduced in comparison to those that would accrue in the absence of CC. The changes anticipated by the modeling conducted indicate that CC will most likely undermine the financial benefit-cost ratio of many planned dams. The changes are likely to drastically affect both the economies and food security of the riparian countries. Reduction in the production of hydroelectricity will be a major setback in the regions pursuit of increased industrialization. Notwithstanding the existence of the Volta Basin Authority (VBA), which is mandated to approve the development plans of member countries that could have a substantial impact on the basin's water resources, impacts of CC on water resources of the basin could increase the likelihood of transboundary disputes over increasingly scarce water resources.

In the face of the long time horizons and great uncertainties associated with CC, future water resources development in the basin requires integrated planning that bolsters resilience and water security. Cooperation between riparian states is essential, if the basin water resources are to be managed effectively and equitably. The key to success is the establishment of practical institutional arrangements that enable water resources to be planned and managed across the entire basin. It is to be hoped that such

FIGURE 15. Comparison of simulated water resources development – irrigation demand, hydropower generated and domestic water supplied – under each of the current, intermediate and full development scenarios, for the periods 1983-2012, 2021-2050 and 2071-2100.



arrangements can be developed within the context of the VBA.

Another essential requirement is the creation of a basin-wide water resources management strategy that explicitly incorporates a water storage development plan, clearly identifying objectives and priorities for investment in all water storage options, not just large dams. Such a plan would ensure that future water resources development is less fragmented and much better coordinated than in the past. Consideration should be given to integrated water storage "systems" that combine different water storage types and build on the complementarities that different water storage options provide (McCartney and Smakhtin 2010). In the case of the Volta Basin, such systems would most likely be much more effective if they were planned and managed as integrated systems, irrespective of national boundaries.

Surface water storage used conjunctively with groundwater is likely to be much more reliable and resilient and less vulnerable than surface water storage in isolation. Since natural groundwater recharge is likely to decline, one option that could be considered is managed aquifer recharge (i.e., the enhanced recharge of aquifers under controlled conditions, either by injection or infiltration). Managed aquifer recharge has been used in other arid and semi-arid climates (e.g., Australia and southern Europe) to store water for later abstraction and use. Other innovative options that could be considered are the use of sand dams and small farm ponds/tanks with roofs to reduce evaporation.

In addition to evaluation of more appropriate options for water storage, adaptation to CC also requires that future water resources management includes the reallocation of water between users and increasing water productivity wherever possible. For the electricity sector, research needs to be conducted to determine to what extent increasing energy demand can be satisfied by other renewable energy sources (i.e., wind and solar), and the most appropriate energy-mix for the changed circumstances that will arise as a consequence of CC.

Conclusion

Water resources development is vital for the well-being and livelihoods of the people living in the Volta River Basin and central to the economic development of the riparian countries. There remains great uncertainty about how CC will affect water resources of the basin. However, the results of this study have shown that anticipated reductions in rainfall, and increases in temperature and potential evapotranspiration, would affect both river flow and groundwater recharge, which in turn will impact the performance of existing and planned reservoirs and hence irrigation and hydropower schemes.

The planned additional surface water storage in the basin will enable larger areas to be irrigated (up to 78,000 ha) and more hydroelectricity to be generated (up to 11,749 $GWhy^{-1}$). However, CC as anticipated in this study (i.e., the A1B scenario) will mean that, overall, system performance will be significantly curtailed. If it is given the highest priority, domestic water supply is largely safeguarded but, even with greatly increased surface water storage (i.e., full development scenario), the performance of existing and planned irrigation and hydropower schemes is likely to be severely compromised. By 2050, on average, only 75% of annual irrigation water demand will be supplied and just 52% of potential hydroelectricity will be generated. By 2100, the situation will be even worse with, on average, just 32% of annual irrigation water demand being supplied and just 28% of potential hydroelectricity generated. One advantage of the planned increase in water storage is that it reduces the inter-annual variability in hydropower generation, ensuring greater levels of firm energy production.

The predicted water resource implications of CC are likely to have severe consequences for people and the economies of the riparian states. Harsher CC, which, based on current emissions trends is perhaps more likely than that anticipated in the A1B scenario, would have even more severe effects. To moderate the negative impacts of CC requires much better planning and management of water resources and, in particular, water storage. In the Volta Basin, this will necessitate much greater cooperation between riparian states with much more systematic planning of water resources development. In the absence of this more systematic planning, much of the currently planned investment in water storage will not be fit for purpose and will fail to deliver all the intended benefits. Careful consideration needs to be given to integrated, possibly transnational, storage 'systems' that maximize the benefits to be obtained from the complementarities of different storage options (e.g., surface water used conjunctively with groundwater) as well as innovative solutions, such as managed aquifer recharge. However, planning for CC requires going beyond water alone to consider other sectors in the water-energy-food nexus.

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