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LETTER

Attributing synergies and trade-offs in water resources planning and management in the Volta River basin under climate change

S Liersch[1,*], H Koch[1], J A Abungba[2], S Salack[3] and F F Hattermann[1]

[1] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, PO Box 60 12 03, D-14412 Potsdam, Germany
[2] Water Resources Commission, Accra, Ghana
[3] WASCAL Competence Center, Blvd Moammar El-Khadafi, 06BP 9507, Ouagadougou 06, Ouagadougou, Burkina Faso
[*] Author to whom any correspondence should be addressed.

E-mail: liersch@pik-potsdam.de

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Abstract

To feed the growing population, achieve the Sustainable Development Goals, and fulfil the commitments of the Paris Agreement, West African countries need to invest in agricultural development and renewable energy, among other sectors. Irrigated agriculture, feeding millions of people, and hydropower, generating clean electricity, depend on water availability and compete for the resource. In the Volta basin, the planned 105 000 ha of irrigated land in Burkina Faso and Ghana could feed hundreds of thousands of people. However, irrigation in the dry season depends on upstream dams that change the river's flow regime from intermittent to permanent, and at the same time irrigation water is no longer available for hydropower generation. Using an integrated eco-hydrological and water management model, we investigated the water demand and supply of three planned irrigation projects and the impacts of the planned Pwalugu multi-purpose dam on the hydropower potentials and water availability in the entire Volta basin. We found that future irrigation withdrawals would reduce the hydropower potential in the Volta basin by 79 GWh a^{-1} and the operation of Pwalugu by another 86 GWh a^{-1}. Hence, Pwalugu contributes only about 101 GWh a^{-1} of its potential of 187 GWh a^{-1}. Under climate change simulations, using an ensemble of eight bias-adjusted and downscaled GCMs, irrigation demand surprisingly did not increase. The higher evaporation losses due to higher temperatures were compensated by increasing precipitation while favouring hydropower generation. However, water availability at the irrigation site in Burkina Faso is clearly at its limit, while capacity in Ghana is not yet exhausted. Due to hydro-climatic differences in the Volta basin, the cost of irrigating one hectare of land in terms of lost hydropower potential follows a north-south gradient from the hot and dry north to the humid south. Nevertheless, food production should have priority over hydropower, which can be compensated by other renewables energies.

1. Introduction

Compared to other world regions, temperatures over large parts of Africa have risen faster in recent decades [1] and are already leading to more frequent extreme events such as droughts, heatwaves, heavy rains, and floods [2–4]. As a result, West African countries are already facing the consequences of climate change, as heat and rainfall extremes are far outside the historical climate worldwide [5]. The Volta River basin (VRB) located in the hot semi-arid and tropical wet savanna climate zones of West Africa covers an area of more than 400 000 km^2 and is shared by six riparian countries. The water resources are used to cultivate crops, generate hydropower, livestock, fisheries, mining, and domestic and industrial water supply [6]. About 30 million people depend on the basin's water resources for their livelihoods, which are under constant pressure due to population growth, climate change and variability [7], and other developments. In 2002 and 2003, for example, the city of Ouagadougou was affected by severe water shortages

[8], around the time when the Ziga Dam was repurposed to supply water only to Ouagadougou, and irrigation withdrawals ceased [9]. In 1998, Ghana accused Burkina Faso's water infrastructure developments of being mainly responsible for the low water level of Lake Volta, which reduced the hydropower potential in Akosombo by 50% [10]. According to Amisigo *et al* [11], the water resources of the VRB would not, even in a wet climate scenario, fully satisfy the municipal, agricultural, and hydropower water demands simultaneously. Therefore, water resources management must follow a basin or region-wide approach across sectors, taking into account climate change projections and socioeconomic trends.

Irrigated agriculture and hydropower are promising measures to support and improve food security and increase the share of renewables in the electricity mix. Both are dependent on available water resources and compete with each other. Gross revenues from irrigated agriculture are up to ten times higher than from rainfed crop production [12]. Yet, only about 6% of Africa's cultivated land area is irrigated [12, 13], but there is a large potential for expanding large-scale irrigation in Sub-Saharan Africa [14], specifically downstream existing dams, providing greater water security during the dry period.

To ensure future water supply, integrated transboundary river basin management requires reliable estimates of future spatio-temporal water availability and demands to prevent potential conflicts. Therefore, this study examines the water demand, supply, and deficits at the example of some current and major planned water management infrastructure in the VRB, focusing on synergies and trade-offs between irrigation and hydropower potentials. To illustrate the impact of today's infrastructure, we first compare simulated inflows to Lake Volta and hydropower potential at the Akosombo dam with simulations of natural flows. In the second step we investigate the impacts of planned infrastructure projects on the inflows to Lake Volta and the hydropower potential in the entire VRB. The projects are: (a) construction of the multi-purpose Pwalugu dam and its associated irrigation scheme downstream in northern Ghana, (b) extension of irrigation downstream the Bagré dam in Burkina Faso, and (c) establishment of irrigation downstream the Bui dam in western Ghana. The impacts are attributed to individual projects under current and future climatic conditions using eight bias-adjusted and downscaled global climate models (GCMs) and two climate scenarios (ssp126 and ssp370).

2. Materials and methods

2.1. Study area

The VRB covers an area of about 403 000 km^2 and is shared by six West African countries. About 85% of the basin area is in Burkina Faso and Ghana in roughly equal parts. The remaining 15% is located in Mali, Benin, Togo, and Côte d'Ivoire. The VRB extends across two climatic zones, with the northern parts, essentially Mali and northern Burkina Faso, characterized by a hot, semi-arid climate (BSh) and the central and southern parts by a tropical humid savanna climate (Aw) [15].

The main tributaries to the main Volta River, nowadays covered by Lake Volta, are the Black Volta (Mouhoun) in the west, the White Volta (Nakambé), Dakar and Red Volta draining the northern and central region, and the Oti River draining the eastern parts.

2.2. Infrastructure projects

The information and data collected from various sources was sufficient to implement and parameterize ten dams and reservoirs plus the planned Pwalugu dam. Due to missing information, the list (table 1) is incomplete but captures the major water management infrastructure. The three planned irrigation projects considered are located downstream of the dams Bagré (BAG: extension by 52 000 ha to 58 000 ha [16]), about 40 km downstream Pwalugu (PWA: 25 000 ha [17]), and Bui (BUI: 28 000 ha [18]), abbreviations explained in table A1. Moreover, hundreds of small reservoirs exist in Burkina Faso and northern Ghana for irrigation, livestock, and domestic water use [19, 20]. These were included as 12 aggregate water users, see appendix B.4. All infrastructure projects are shown in figure 1.

2.3. Data

The spatio-temporal data used to set up, calibrate, and validate the hydrological model are described in appendix A.

Future climate projections are represented by eight bias-adjusted and downscaled CMIP6 GCMs from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) [21, 22], see table A2. The bias-adjustment and downscaling method using WFDE5 as reference climate is explained in Lange [23, 24]. The two climate scenarios ssp126 (based on RCP 2.6, low radiative forcing) and ssp370 (based on RCP 7.0, high radiative forcing) were selected to cover an extensive range of projections.

2.4. Methods

2.4.1. Hydrological modelling

The Soil and Water Integrated Model (SWIM) [25, 26] is a spatially semi-distributed and process-based eco-hydrological and water management model that operates on a daily time step. It integrates physics-based and conceptual approaches to simulate hydrological process, vegetation growth, nutrient cycling, and sediment transport. It uses a three-level spatial disaggregation scheme from river basin to sub-basins and hydrological response units (HRUs). HRUs represent units with the same properties (soil

Table 1. Dams, reservoirs, and planned irrigation sites used in this study.

Dam	Catchment	Country	Commissioned	Max. area (km^2)	Max. capacity (Mm^3)	Inst. capac. (MW)	Purpose	Intake	Planned irrigation [ha]
Bagré	White Volta	BF	1993	260	2300	16	HP, fish, irr	From reservoir	58,000
Kanozoe	White Volta	BF	—	—	90				
Lac Bam	White Volta	BF			41		natural lake		
Loumbila	White Volta	BF	1935		42		irr, sup, lst	From reservoir	
Pwalugu	White Volta	GH	Planned	439	5,000	59	HP, flood, irr, fish	Downstream	25,000
Ziga	White Volta	BF	1971		200		irr, sup, lst	From reservoir	
Kompienga	Oti	BF	1984	210	2025	14	HP, irr	From reservoir	
Bui	Black Volta	GH	2013	440	12,700	400	HP, irr	Downstream	28,000
Leri	Black Volta	BF	1976		360		irr, lst	From reservoir	
Akosombo	Volta	GH	1965	8,500	155,500	1,020	HP, irr, sup, fish	From reservoir	
Kpong	Volta	GH	1982	Run-of-river	—	160	HP	Not considered	

HP = hydropower; irr = irrigation; flood = flood protection; fish = fishing; sup = public water supply, lst = livestock

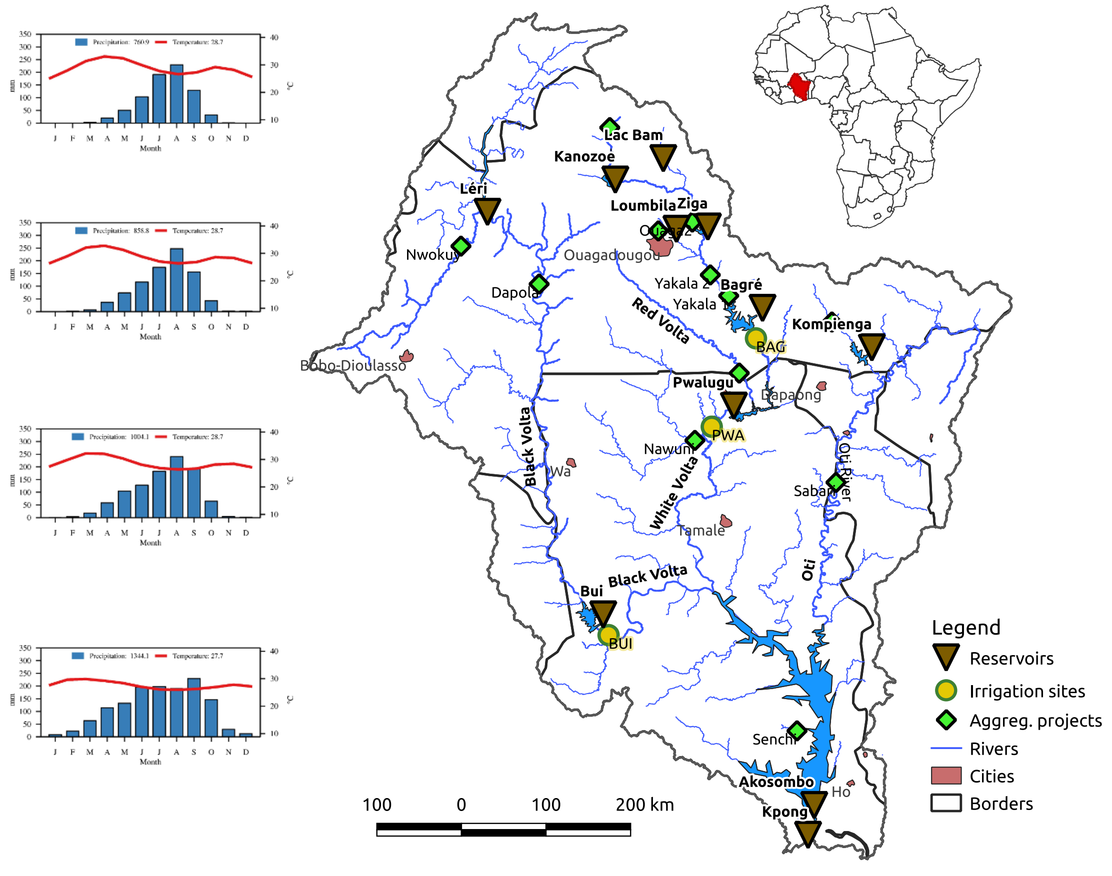

Figure 1. Map of the Volta basin, dams/reservoirs, planned irrigation sites, and small aggregate projects considered in this study. Figures in left panel show average climatology from north to south.

Table 2. Scenario settings.

Scenario	Natural (QNAT)	Baseline (BL)	Full development (FD)
Dams			
White Volta			
– Kanozoe	—	x	x
– Lac Bam	x	x	x
– Loumbila	—	x	x
– Ziga	—	x	x
– Bagré	—	x	x
– Pwalugu	—	—	x
Black Volta			
– Bui	—	x	x
– Léri	x	x	x
Oti			
– Kompienga	—	x	x
Lower Volta			
– Akosombo	x	x	x
– Kpong	—	x	x
Irrigation			
White Volta			
– BAG_2000: 6,000 ha	—	x	—
– BAG_cr3: 58,000 ha	—	—	x
– PWA_cr3: 25,000 ha	—	—	x
Black Volta			
– BUI_cr3: 28,000 ha	—	—	x
Aggregate small projects	—	x	x

and land use/cover) regarding biophysical processes. To assess the synergies and trade-offs between existing and planned water management infrastructure (reservoirs, hydropower, water allocation, and irrigation), SWIM is equipped with sophisticated modules described in appendix B. Model calibration results are shown in section appendix B.5.

2.4.2. Irrigation

Each of the three irrigation sites was implemented as an irrigated unit in the model, composed of several irrigated HRUs selected to closely match the respective areas of the planned irrigation sites. In contrast to the BUI and PWA irrigation sites being planned, a small area of about 6000 ha was already irrigated in the year 2000 at the BAG site (BAG_2000), with plans to expand to 58 000 ha. At the BUI and PWA sites, water is withdrawn from the river, while for BAG it is taken from the Bagré reservoir, constituting a trade-off with hydropower generation.

The daily water demand for irrigation at the three sites is computed by the SWIM model in a process-based way (appendix B.2) using user-defined crop rotation scenarios (appendix B.3). It depends on the current crop development status, water availability in the soil, and weather conditions. For example, in a dry year, irrigation water demand is higher than in a wet year.

The crop rotation scenario *cr*3 was chosen and applied to all sites that represents the current observed monthly withdrawal patterns from the Bagré reservoir. This has the advantage that simulations of water demand and deficits for the three sites are directly comparable under recent as well as projected climate. The disadvantage is that other crop rotations may be preferred at the PWA and BUI sites.

2.4.3. Simulation periods

The period 1984–2014 represents the reference period (P0) around the year 2000, the period 2035–2065 the medium future (P1) around 2050, and the period 2065–2095 the far future (P2) around 2080.

2.4.4. Water management scenarios

The QNAT scenario represents a simulation assuming unmanaged or natural flow conditions. Lac Bam and Léri were included to consider their natural retention function and the Akosombo dam, impounding Lake Volta, to serve as a basis for estimating the impacts of recent developments on the flow regime and hydropower potential at Akosombo.

In the baseline (BL) scenario, 10 existing dams are implemented (table 2). The only irrigation project considered is the BAG_2000 site downstream the Bagré dam. Furthermore, the monthly withdrawals of 12 aggregated small projects were considered, see appendix B.4.

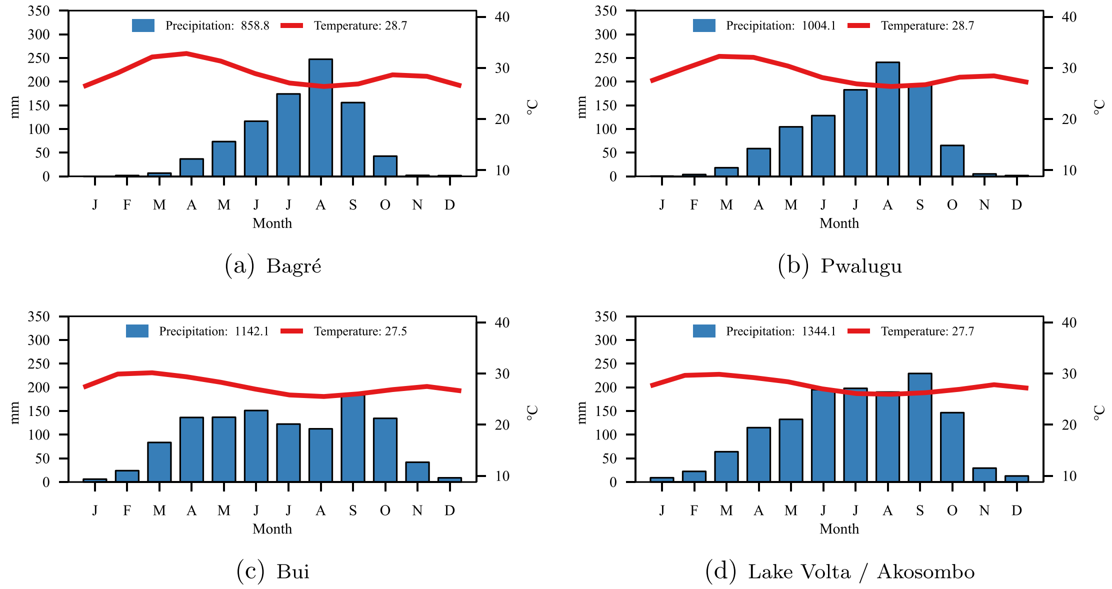

Figure 2. Precipitation and temperature regime at reservoirs, WFDE5 in P0 (1984–2014).

The full development (FD) scenario considers all developments in the BL scenario. It includes the planned multi-purpose Pwalugu dam, and the three planned irrigation sites (BAG, PWA, BUI) downstream of the associated dams. To account for an increased demand due to population growth, withdrawals for the supply of Ouagadougou from the Ziga and Loumbila dams were assumed to be about 2 m^3s^{-1} higher than in the BL scenario.

To allow comparability between simulations and periods, all infrastructure projects existed from the first year of the simulations, even if individual projects were established later. To attribute impacts to single projects, some sub-scenarios were simulated, e.g. BAG_cr3 without Pwalugu in the FD scenario, to estimate inflow changes to Lake Volta solely based on withdrawals at the BAG_cr3 site.

3. Results

3.1. Current climate

The BAG irrigation site is located in the driest and hottest zone. At the BUI irrigation site, about 350 km south and 180 km west of Bagré, mean annual precipitation was about 280 mm higher and temperatures 1.2 °C lower (figure 2 and table A3). The different climates affected the simulated crop water requirements at the three irrigation sites.

3.2. From natural conditions to baseline

Compared to natural conditions (QNAT), developments in the BL scenario reduced the inflows to Lake Volta by 60 m^3s^{-1} (4.4%) and the hydropower potential of Akosombo by 249 GWh a^{-1} (4.5%), see figure 3. About 46% of the changes were attributed to developments on the White Volta, 41% to the construction of the Bui dam on the Black Volta, and 12% to the Kompienga dam on the Oti River. About 89% of this was due to large infrastructure and the remaining 11% due to aggregated small projects (table C1). Note that only about 44% (6.8 m^3s^{-1}) of the total demand of small projects (15.6 m^3s^{-1}) was met, indicating water shortages in the drier parts of the VRB.

Our simulations revealed an interesting phenomenon of increased transmission losses. The establishment of the Bagré dam transformed the intermittent flow regime of the White Volta to a permanent regime [27]. While there used to be about a hundred days a year without discharge, water now flows downstream of Bagré every day (figure B5), exposing the 350 km river section to additional riverbed infiltration and evaporation during the dry season. The reduction of discharge downstream BAG_2000 (without additional withdrawals from aggregate small projects) was 15.5 m^3s^{-1} but 22.1 m^3s^{-1} in the sub-basin draining into Lake Volta. The gap of 6.6 m^3s^{-1} can be solely attributed to transmission losses. This phenomenon was also simulated downstream of the Bui dam to a lower extent. Together, increased transmission losses due to the transformation from intermittent to permanent flow regime alone accounted for about 24% of reduced inflows into Lake Volta. Appendix B.6 explains how transmission losses are computed in SWIM.

3.3. Planned irrigation projects

Future irrigation water demand at the BAG_cr3 site was simulated at 586 mm a^{-1} or 344 Mm^3 a^{-1} (table 3). Due to the different climatic conditions (figure 2, table A3), the relative irrigation demand at the PWA_cr3 (480 mm a^{-1}) and BUI_cr3

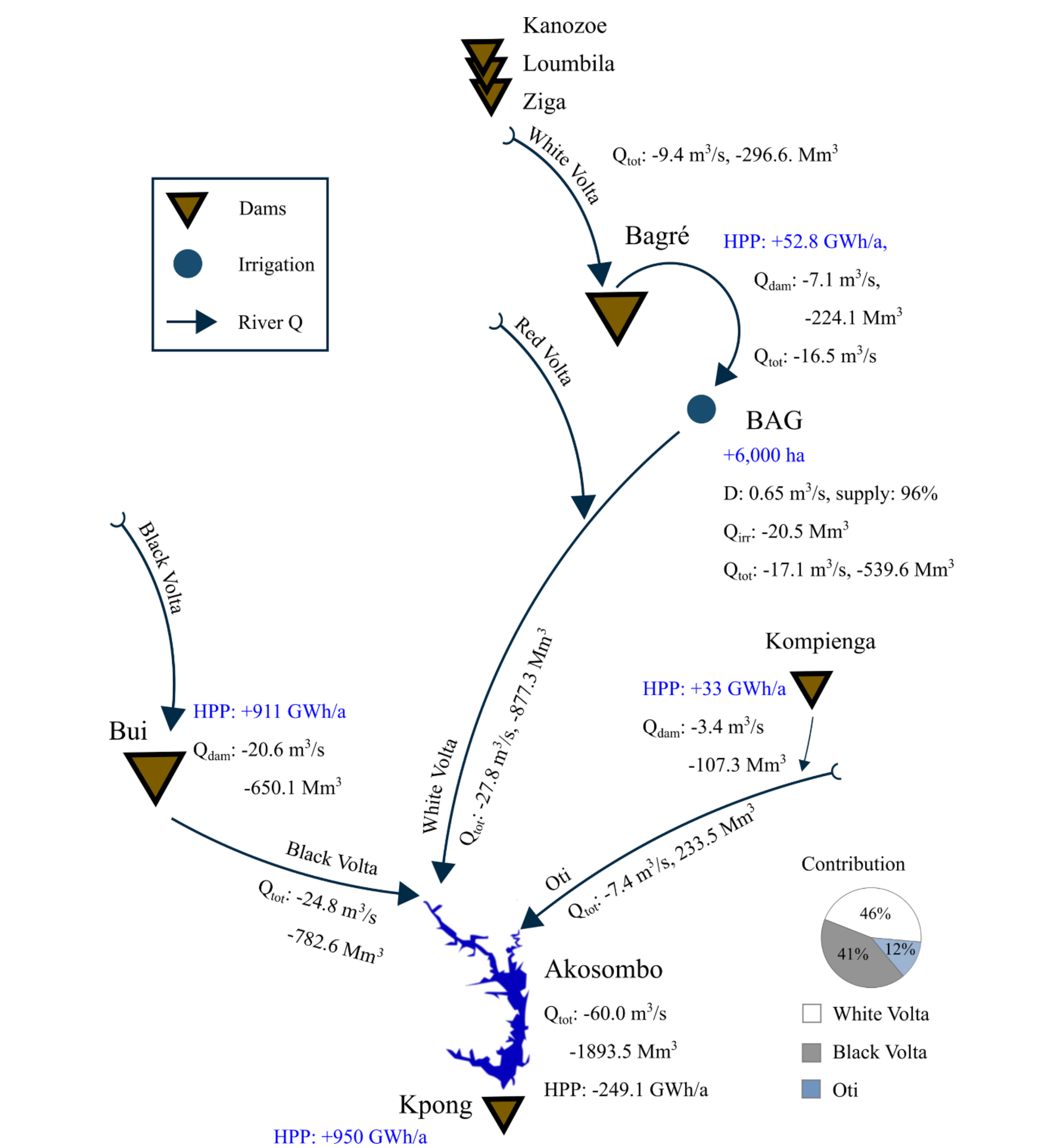

Figure 3. Impacts of developments in the BL scenario, WFDE5 in P0 (1984–2014). Q_{tot} = cumulative discharge reduction; Q_{dam} = discharge reduction by dam; HPP = hydropower potential; D = irrigation demand.

Table 3. Irrigation demand and supply at BAG, PWA, and BUI, WFDE5 in P0 (1984–2014).

Irrigation scenario	$m^3 s^{-1}$	$Mm^3 a^{-1}$	$mm a^{-1}$	Irrigated area (ha)	Demand as % of reservoir input	% supplied
BAG_2000	0.65	20.5	295	6952	1	96
Simulated irrigation demand						
BAG_cr3	10.9	344	586	58 738	18	72.9
PWA_cr3	3.6	115	480	23 948	2.9	97
BUI_cr3	2.8	87	314	27 927	1.4	99.9

Reservoir input = inflow and precipitation.

($314 mm a^{-1}$) sites was much lower than at the BAG_cr3 site (figure 4), representing 81% and 53% of the demand at BAG_cr3, respectively. The higher total irrigation water demand at the BAG_cr3 is a result of the larger irrigated area and the drier climatic conditions.

At the BAG_cr3 site, the highest mean irrigation deficits (>25%) occurred between April and July,

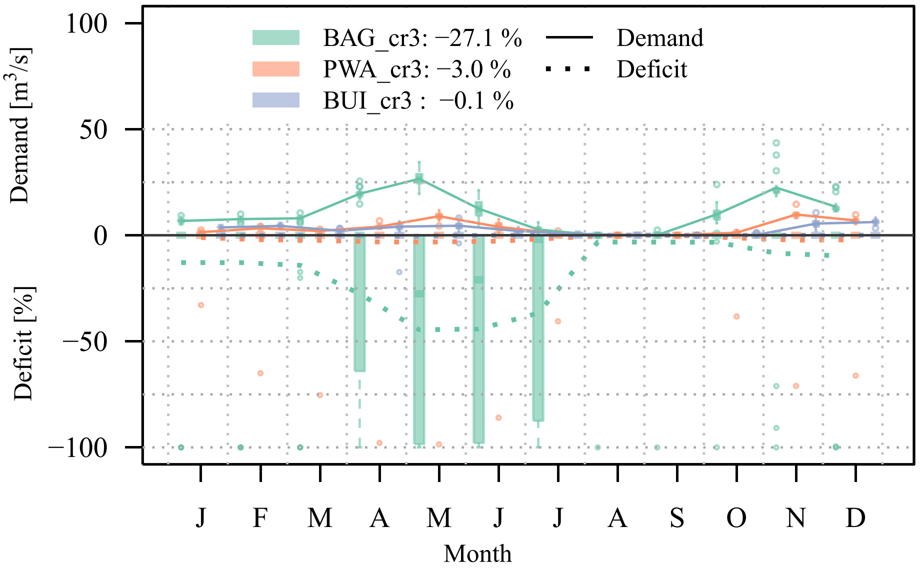

Figure 4. Mean monthly irrigation demand and deficit at the three sites, crop rotation scenario *cr_3* (FD scenario), WFDE5 in P0 (1984–2014). Numbers in the legend indicate the average annual deficit in %. Lines connect the medians of monthly boxplots. Dots indicate very dry outlier years.

exceeding 40% on average in May and June at the end of the dry season and the onset of the rainy season (figure 4). With the Pwalugu dam in place, irrigation deficits at the PWA_cr3 site were only 3% on average. Irrigation at the BUI_cr3 site is normally not jeopardized by water availability from the Black Volta, because the Bui dam usually releases enough water during the dry season to potentially support irrigation. Only in exceptionally dry years, like 1984, shortages occurred.

To demonstrate the importance of upstream dams to irrigation performance, we conducted theoretical examples assuming the upstream dams were not present. At the BAG_cr3 site, dry-season irrigation would be impossible because the deficits would be almost 100% (figure C1). At the PWA_cr3 site, the average deficit was about 31% and was above 25% from February to June (figure C2). During the peak demand season (April and May), deficits were substantial in many years. Irrigation deficits at the BUI_cr3 site would be 16% on average and around 25% between February and April (figure C3). Depending on the situation, upstream dams are either a prerequisite for irrigation or have a supporting effect.

3.4. Impact attribution of development projects

3.4.1. Irrigation

The withdrawals at the BAG_cr3 site for the additional 52 000 ha irrigated land reduced the mean discharge downstream by 12% or 6.6 m^3s^{-1} compared to the BL scenario (figure 5 and table 4). The differences between the irrigation water demand of 10.9 m^3s^{-1} and the actual discharge reduction of 6.6 m^3s^{-1} can be explained by the fact that only 73% of the demand was available and withdrawn from the Bagré reservoir and supplied to the fields and that higher excess water return flows to the river system (surface, subsurface and groundwater flows) were simulated. Irrigation at the BAG_cr3 site represents a clear trade-off with hydropower in the VRB. In total, it reduced the hydropower potential by 53.5 GWh a^{-1} (−11.9 GWh a^{-1} at Bagré, −7.9 GWh a^{-1} at Pwalugu, and −33.7 GWh a^{-1} at Akosombo and Kpong). Irrigation at the PWA_cr3 site reduced the discharge by 3 m^3s^{-1} resulting in a loss of 15.3 GWh a^{-1} at Akosombo and Kpong. The BUI_cr3 site reduced the inflows into Lake Volta by 1.9 m^3s^{-1} and the downstream hydropower potential by 10.2 GWh a^{-1}.

Due to differences in hydro-climatic conditions and the number of hydropower stations affected, each irrigation site has an individual hydropower reduction footprint, equivalent to 117 Watts ha^{-1} (BAG_cr3), 70 Watts ha^{-1} (PWA_cr3), and 42 Watts ha^{-1} (BUI_cr3), respectively.

3.4.2. Hydropower

The planned Pwalugu dam adds 186.6 GWh a^{-1} hydropower potential to the system, but reduces the downstream discharges by 12.4 m^3s^{-1} due to evaporation and seepage. An additional 4.4 m^3s^{-1} of transmission losses can be attributed to the operation of the Pwalugu dam, reinforcing the White Volta's permanent flow regime. In total, the 16.8 m^3s^{-1} discharge reduction resulted in a loss of 85.8 GWh a^{-1} at Akosombo and Kpong.

All developments in the FD scenario reduced the hydropower potential by 125 GWh a^{-1} (2.4%) at Akosombo and 20 GWh a^{-1} at Kpong (figures 6(d) and C4). About 93% are attributable to developments in the White Volta and 7% to the BUI_cr3

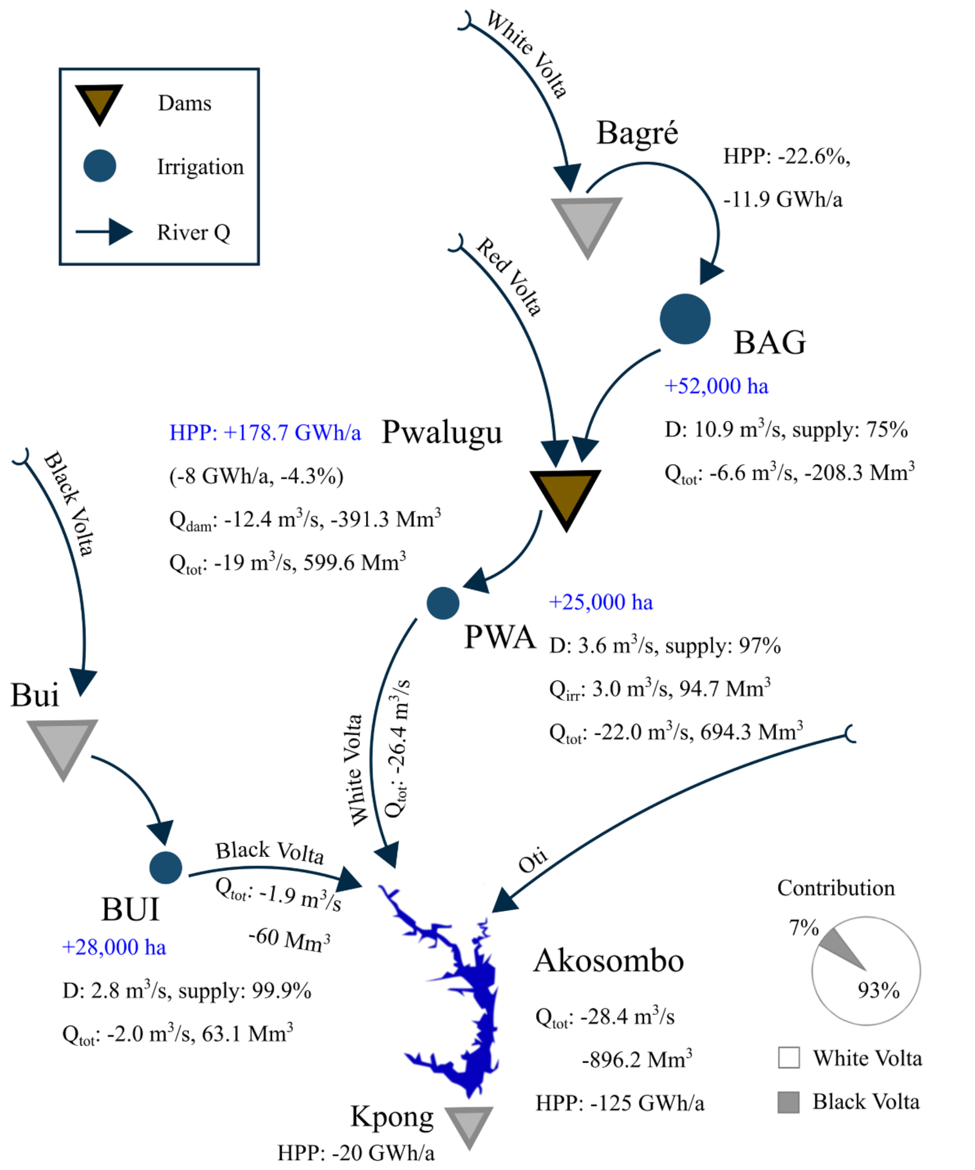

Figure 5. Synergies and trade-offs (gains and losses), changes between BL and FD scenario, WFDE5 in P0 (1984–2014). Q_{tot} = cumulative discharge reduction, Q_{irr} = discharge withdrawn for irrigation; Q_{dam} = discharge reduction by dam; HPP = hydropower potential; D = irrigation demand.

irrigation site at the Black Volta (table 4). About 60% of the reduced hydropower potential is due to the operation of Pwalugu and 40% due to irrigation withdrawals at BAG_cr3, PWA_cr3, and BUI_cr3.

The largest relative reduction in hydropower potential occurred at the Bagré dam, where the capacity factor dropped from 38% (BL scenario) to 29% (FD scenario), see table C2.

3.5. Climate change and its impacts

3.5.1. Meteorological projections

Until about 2040, precipitation and temperature trends in the ssp126 and ssp370 scenarios differ little. Compared to P0, mean air temperature is projected to increase by 1.2 °C (ssp126) and 1.7 °C (ssp370) and mean annual rainfall to increase by around 3% and 8%, respectively (figure 7). After 2040 substantial differences become apparent, with mean temperature increasing by either 1.4 °C (ssp126) or 3.1 °C (ssp370) and rainfall either returning to a level slightly below P0 (−2.4%) under ssp126 or remaining at 9% a higher level than in P0. Depending on the scenario and future period, 10–60% of the simulations project a drier future.

The spatial distribution of projected precipitation changes over the VRB shows figure C5, while figure C6 compares the ISIMIP3b projections with the entire CMIP6 ensemble.

3.5.2. Irrigation under climate change

Based on the ISIMIP3b ensemble median, the future irrigation water demand at the three sites did not change substantially in ssp126 and remained

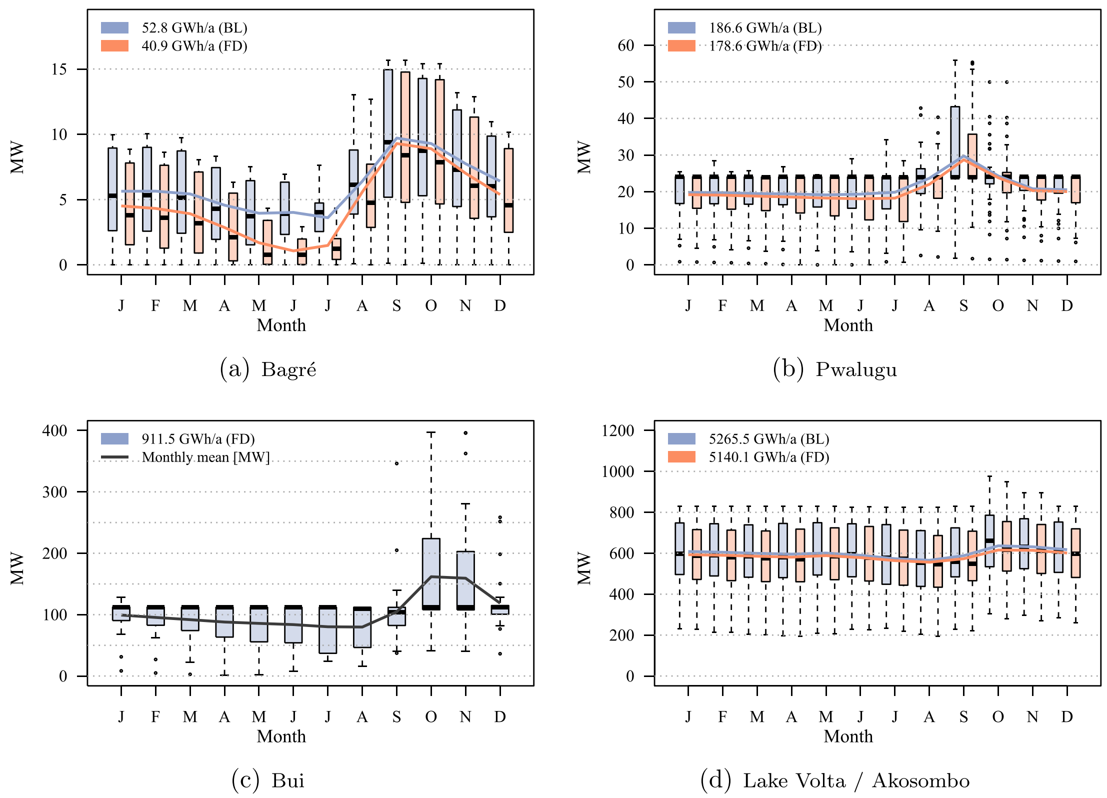

Figure 6. Hydropower generation potentials at the four dams for the BL and FD scenarios, WFDE5 in P0 (1984–2014).

in the range of P0 (figure 8). Under ssp370 the water demand decreases at all sites, specifically at BAG_cr3 and PWA_cr3. This is interesting because the projected temperature rise was expected to increase demand, but the increase in precipitation compensates for the higher evaporative losses.

At the PWA_cr3 and BUI_cr3 sites, the ensemble median projects no irrigation deficits. At the BAG_cr3 site, deficits in P1 were at a relatively low level in both climate scenarios. In P2 the climate scenario matters, where in ssp126 irrigation deficits returned to a fairly high level, comparable to P0, but in ssp370 the ensemble median shows only a few years where deficits occurred at all.

Analyzing the highest and lowest irrigation demands and deficits reveals that not always the same GCM showed the highest or lowest values at the three irrigation sites (figure C7). In the driest simulation, irrigation at Bagré would be severely impacted.

3.6. Hydropower under climate change

Generally, the projected hydropower potentials are consistent with precipitation projections under the two climate scenarios. Compared to P0, in P1 around the year 2050, the ensemble median hydropower potential increased between 9% and 30% in ssp126 and ssp370, respectively. In P2, it either returned to the levels of P0 under ssp126 or remained at a higher level of +25% under ssp370 (figure 9). Despite the general increase in ensemble median annual hydropower potential, all future periods contained years in which it was below the minimum of P0. This indicates a higher variability in the future with values outside the range of experience in P0. The future hydropower potentials of the six dams shows table 5 and figure C8.

4. Discussion

West African countries face the challenge of supplying their rapidly growing populations with food and electricity, where the agricultural and energy sectors often compete for water resources. However, there is not only competition but also synergy. Often, decision-makers require synergies and trade-offs to be expressed in monetary terms, like the monetary benefits and costs of joint reservoir operation and irrigation [6, 7]. In this study, we take another perspective by showing that irrigating one hectare of land reduces hydropower potential between 42 and 117 Watts, depending on the location's hydro-climatic conditions and the number of hydropower stations affected. This is approximately the electricity consumption of an old-fashioned light bulb. Taking a perspective of 'real' values allows to decouple the impacts of interventions from monetary values, which are subject to economic uncertainties such as inflation and price volatility for water, electricity, and agricultural products. We do not claim that this approach is superior to monetary perspectives

Table 4. Impact attribution of single development projects (FD − BL), WFDE5 in P0 (1984–2014).

	BAG_cr3	White Volta Pwalugu	PWA_cr3	Black Volta BUI_cr3	Cumulative Values
Bagré					
BAG_cr3 (ha)	52 000	—	—	—	52 000
Irrigation ($m^3\,ha^{-1}\,a^{-1}$)	−4005	—	—	—	
Q reduction ($m^3 s^{-1}$)	−6.6	—	—	—	−6.6
Q reduction (%)	−12.0	—	—	—	
HPP Bagré ($GWh\,a^{-1}$)	−11.9	—	—	—	−11.9
HPP total ($Watts\,ha^{-1}$)	−117.4	—	—	—	—
HPP total ($MWh\,ha^{-1}\,a^{-1}$)	−1028.8	—	—	—	—
Pwalugu					
HPP ($GWh\,a^{-1}$)	−7.9	186.6	—	—	166.8
Q_{dam} reduction ($m^3 s^{-1}$)	—	−12.4	—	—	−19.0
Q_{dam} reduction (%)	—	−11.0	—	—	—
$TL_{downstr}$ ($m^3 s^{-1}$)	—	−4.4	—	—	−23.4
PWA_cr3 (ha)	—	—	25 000	—	77 000
Irrigation ($m^3\,ha^{-1}\,a^{-1}$)	—	—	−3787	—	—
Q reduction ($m^3 s^{-1}$)	—	—	−3.0	—	−26.4
Q reduction (%)	—	—	−2.1	—	—
HPP total ($Watts\,ha^{-1}$)	—	—	−69.9	—	—
HPP total ($MWh\,ha^{-1}\,a^{-1}$)	—	—	−612.7	—	—
Bui					
BUI_cr3 (ha)	—	—	—	28 000	105 000
Irrigation ($m^3\,ha^{-1}\,a^{-1}$)	—	—	—	−2254	—
Q reduction ($m^3 s^{-1}$)	—	—	—	−2.0	−28.4
Q reduction (%)	—	—	—	−1	—
HPP total ($Watts\,ha^{-1}$)	—	—	—	−41.6	—
HPP total ($MWh\,ha^{-1}\,a^{-1}$)	—	—	—	−364.7	—
Akosombo & Kpong					
HPP ($GWh\,a^{-1}$)	−33.7	−85.8	−15.3	−10.2	−145.0
Inflow ($m^3 s^{-1}$)	−6.6	−16.8	−3.0	−2.0	−28.4
Contribution to HPP reduction (%)	23.2	59.2	10.6	7.0	100
Total HPP contribution ($GWh\,a^{-1}$)	−53.5	100.8	−15.3	−10.2	21.8

but rather complementary by adding a more deterministic view on interventions and their benefits and consequences.

According to Dossou-Yovo *et al* [28], farmers' yields in Sub-Saharan Africa are low, 2.2 $t\,ha^{-1}$ compared to the world average of 4.6 $t\,ha^{-1}$. Poor soil fertility and low soil clay contents are major constraints for crop productivity [29], but nitrogen and phosphorus fertilizer applications increase yields considerably [28, 30, 31], particularly if combined with improved seeds [32] and irrigation [12].

The irrigation demand simulated in this study was based on assumptions of conveyance efficiency (70%) and irrigation efficiency (75%, sprinkler) derived from FAO [33]. Gadédjisso-Tossou *et al* [34] found that controlled deficit irrigation in northern Togo ranges from 0–600 $mm\,a^{-1}$ and that supplemental irrigation for rainfed maize is only beneficial up to 150 $mm\,a^{-1}$. This is exactly the amount we simulated for maize crop requirements in the dry season at the Pwalugu irrigation site, located in a similar climate and latitude. The total irrigation demand, including losses in the irrigation system at the PWA site, was about 245 $mm\,a^{-1}$. Therefore, irrigation water savings can be achieved mainly by increasing the efficiencies (e.g. sealed canals), irrigation practice (e.g. drip irrigation), and optimized timing of crop schedules [30], rather than by deficit irrigation.

The water demand in our baseline scenario (BL) is within the range of the study by Amisigo *et al* [11], who claim that water resources in the VRB do not fully meet user needs. In our FD scenario, we have probably assumed a slightly lower expansion of planned irrigated area than Amisigo *et al* [11]. However, our analysis also reveals that the use of water resources in the northern part of the VRB, mainly in Burkina Faso, is reaching its limits. The estimated increased future freshwater demand for Ouagadougou around the year 2050, might not be fully met by the supply from the Loumbila and Ziga dams in dry years. The irrigation potential downstream of the Bagré dam at the White Volta is clearly

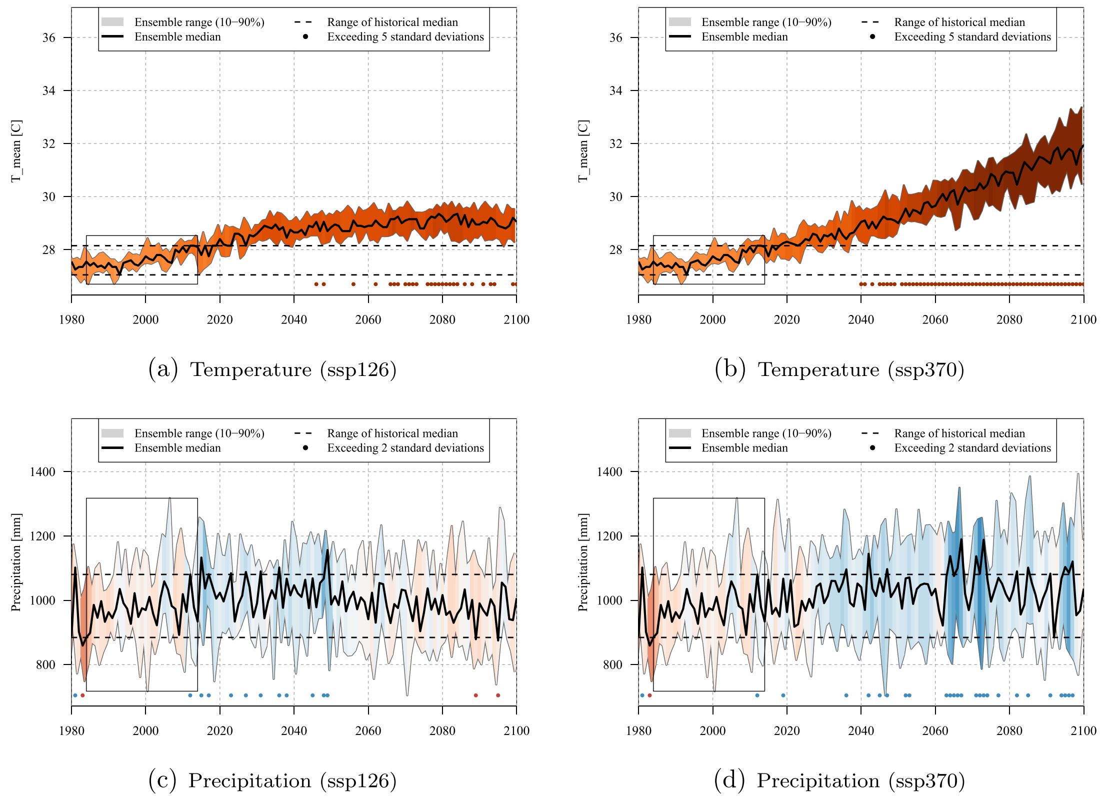

Figure 7. Temperature and precipitation projections averaged over the entire Volta basin, ISIMIP3b ensemble. Box represents the extents of P0 in time and value range.

at a water availability limit with a total envisaged area of about 58 000 ha, meeting on average about 73% of the demand and consuming 12% of mean annual discharge. In the Ghanaian part of the VRB, the situation is different. The planned Pwalugu dam on the White Volta in northern Ghana and the Bui dam on the Black Volta would enable the planned irrigation schemes of 25 000 and 28 000 ha downstream, respectively, with the capacity not yet exhausted.

These results show clear synergies between upstream dams altering the flow regime towards increased dry-season flows and irrigation. Interestingly, the change in flow regime from intermittent to permanent flow, e.g. caused by the Bagré dam, substantially increased transmission losses. The 350 km river section of the White Volta downstream of Bagré was subject to additional evaporation and seepage on a hundred days a year when no water would flow under natural conditions. While ecological consequences downstream of large dams are discussed in many studies [27, 35, 36], to our knowledge, the phenomenon of increased transmission losses has not yet been addressed in the literature. However, it should be considered, especially in environmental impact studies. The finding as such also underlines the need to apply process-based simulation models, as we would not have discovered this phenomenon with a conceptual approach.

The planned infrastructure investigated in this study reduces the hydropower potential in the VRB by 165 GWh a^{-1} (153 GWh a^{-1} in Ghana and 12 GWh a^{-1} in Burkina Faso). Of this, 79 GWh a^{-1} are due to the 105 000 ha irrigated land and 86 GWh a^{-1} are caused by evaporation and seepage from the Pwalugu dam. While Pwalugu's hydropower potential of 187 GWh a^{-1} compensates these losses, it adds only another 22 GWh a^{-1} (11% of its potential) to the grid. Basin-wide, there is a plus on both sides, an additional irrigated area of 105 000 ha and a plus of 22 GWh a^{-1}.

Country-wise, only the irrigation site at Bagré causes trade-offs between Burkina Faso and Ghana. However, the reduction in Ghanaian hydropower from the BAG_cr3 site amounts to 41.6 GWh a^{-1} (27% of the total reduction in Ghana), but is equivalent to only 0.6% of total Ghanaian hydropower generation in 2020 [37]. In Burkina Faso itself, the BAG_cr3 site reduces the country's hydropower potential by 12 GWh a^{-1}, or about 11% of the total hydropower generation [37], while adding 52 000 ha irrigated land. Ghana invests 187 GWh a^{-1} hydropower potential and receives in total 34 GWh a^{-1} while increasing its irrigated area by 53 000 hectares.

Accounting for climate change in impact studies remains a challenge. The reasons are manifold, e.g. uncertainties in the cascade from climate to

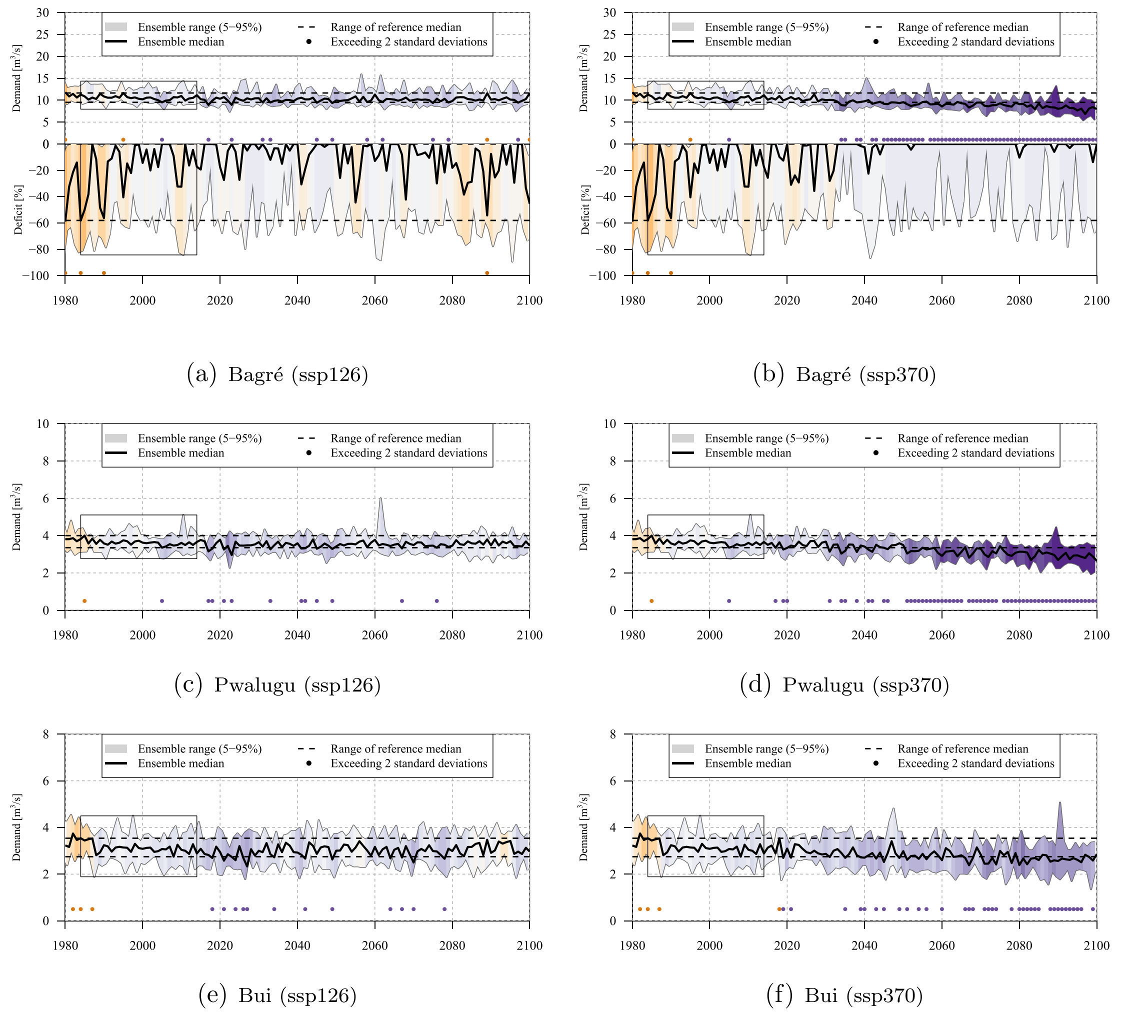

Figure 8. Irrigation water demand and deficits at the three planned irrigation sites, ISIMIP3b ensemble. Box represents the extents of P0 in time and value range.

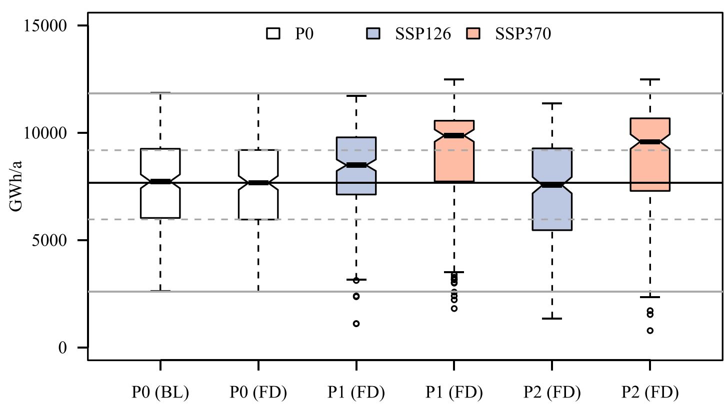

Figure 9. Combined hydropower potential of the six dams in the FD scenario under climate change, ISIMIP3b.

impact models [38, 39] or simply the choice of the baseline period used to compare future periods [40]. Specifically, a certain accuracy of (climate) input data is required in the context of water resources management, but is not always guaranteed [41]. The eight ISIMIP3b GCMs showed a good performance in the baseline period and adequately represent mean annual precipitation projections of the CMIP6 ensemble. However, precipitation projection uncertainties in the VRB are high [42]. Some models tend to simulate a wetter future, others a drier one, but both show an increase in rainfall intensity [43].

Table 5. Hydropower potentials (GWh a^{-1}) in the VRB under climate change, ISIMIP3b.

Dam	P0 (BL)	P0 (FD)	P1 (126)	P1 (370)	P2 (126)	P2 (370)
Bagré	54.1	43.9	49.1	61.7	44.9	65.1
Kompienga	33.8	33.8	38	51.9	36.2	58.9
Bui	980.3	980.3	999.7	1290.1	970.8	1223
Pwalugu	210.3	208.7	210.3	228.3	210.1	232.8
Akosombo	5459.5	5421.6	5973.8	7065.6	5373.5	6826.1
Kpong	990.9	981.8	1071	1233.9	975.9	1195.8
Sum	7728.9	7670.1	8341.9	9931.5	7611.4	9601.7

P0 columns show management impacts between BL and FD.
Columns P1 and P2 indicate climate change impacts compared to P0 (FD).

The ensemble median projections favour future hydropower potential and irrigation. The hydropower potential increases and the irrigation demand decreases, because evaporative losses due to higher temperatures in the future are compensated by higher precipitation. The only exception constitutes ssp126 in the far future. However, the projected increase in precipitation intensity is a severe threat that can trigger increased flooding [44] and erosion and cause crop damage. Multi-purpose dams can contribute to flood protection and storing excess rainfall for use in the dry season.

5. Conclusions

As presented in this study, analyzing synergies and trade-offs between water users within a river basin accounting for future developments and climate change can help identify and mitigate potential conflicts. However, solutions to these problems cannot always be found at the river basin scale but must be externalized to a higher level, especially when food and energy security are at stake.

Due to the drier and hotter climate in the northern parts of the VRB, the irrigation requirements in Burkina Faso (586 mm a^{-1} at Bagré) are almost twice as high as in southern parts of Ghana (314 mm a^{-1} at Bui). Therefore, the trade-offs between irrigation and hydropower and the fraction of available water resources per hectare of irrigated land show a north–south gradient. From the perspective that regions should be as self-sufficient as possible, food crops should have priority over hydropower generation. Alternatives to compensate for food shortages through imports depend on world market prices, which hit the poorest hardest. Hydropower losses due to increased irrigation withdrawals, on the other hand, can easily be compensated by other renewable energies such as solar and wind power. Furthermore, a combination of increased interconnections in the West African Power Pool, exploitation of spatio-temporal hydro-solar-wind complementarities, and large-scale deployment of storage options could help countries meet their increasing power demand by integrating a high share of renewables [45, 46].

Integrating all sectors in the VRB and beyond its boundaries and addressing environmental, social, and economic aspects remains a challenge, as institutional frameworks in many countries are still highly sectoral. Sixteen years ago, Taylor *et al* [47] noted that no comprehensive hydrological model represented the entire VRB. Since then, several simulation studies have been conducted, proving progress at the scientific level. The increasing number of interdisciplinary research projects in the VRB is also encouraging. However, future projects need to be more transdisciplinary and involve researchers, decision-makers, and society representatives from all disciplines more equally.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

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Appendix A. Data

A.1. Spatial data

To set up the hydrological model, the SRTM Digital Elevation Model in 90 m horizontal resolution [48] was used to delineate the VRB and its sub-basins. Soil properties were derived from the harmonized world soil database [49] and information on land use/cover was taken from GLC2000 [50].

A.2. Meteorological data

The daily gridded weather dataset WFDE5 [51] was used to calibrate and validate the eco-hydrological model, to conduct the baseline simulations, and

Table A1. Abbreviations.

Abbreviation	Explanation
BAG	Irrigation site downstream Bagré dam
BAG_2000	BAG irrigation site and withdrawals according to year 2000
BAG_cr3	BAG irrigation site with crop rotation *cr*32
BL	Baseline (scenario)
BUI	Planned irrigation site downstream Bui dam
BUI_cr3	BUI irrigation site with crop rotation *cr*32
FD	Full development (scenario)
GCM	Global Climate Model
$GWh\ a^{-1}$	Gigawatt hours per year
HPP	Hydropower production
HRU	Hydrological response unit
ISIMIP	Inter-sectoral Model Intercomparison Project
P0	Reference period around 2000, 1984–2014
P1	Future period around 2050, 2035–2065
P2	Future period around 2080, 2065–2095
PWA	Planned irrigation site downstream Pwalugu dam
PWA_cr3	PWA irrigation site with crop rotation *cr*32
Q	River discharge
QNAT	Simulation under natural conditions
RCPs	Representative concentration pathways
ssp126	Climate scenario based on RCP 2.6
ssp370	Climate scenario based on RCP 7.0
SWIM	Soil & Water Integrated Model (eco-hydrological model)
VRB	Volta River basin
WFDE5	Watch ERA5 climate data, reference climate

Table A2. ISIMIP3b GCMs.

ID	GCM	Used in this study
1	CNRM-CM6-1	Yes
2	CNRM-ESM2-1	Yes
—	CanESM5	No
—	EC-Earth3	No
3	GFDL-ESM4	Yes
4	IPSL-CM6A-LR	Yes
5	MIROC6	Yes
6	MPI-ESM1-2-HR	Yes
7	MRI-ESM2-0	Yes
8	UKESM1-0-LL	Yes

www.isimip.org/.

Table A3. Climate at reservoirs, WFDE5 and ISIMIP3b in P0 (1984–2014).

	Precipitation ($mm\ a^{-1}$)		Temperature (°C)		Solar radiation ($J\ cm^{-2}$)	
Reservoir	WFDE5	ISIMIP3b	WFDE5	ISIMIP3b	WFDE5	ISIMIP3b
Bagré	859	850	28.7	28.7	2121	2110
Pwalugu	1004	996	28.6	28.6	2049	2038
Bui	1142	1137	27.5	27.5	1876	1863
Lake Volta	1344	1337	27.7	27.7	1853	1841

ISIMIP3b columns represent the ensemble median (eight GCMs).

served as basis for downscaling and bias-adjustment [23, 24] of the ISIMIP3b GCMs.

Originally, the ISIMIP3b ensemble consists of ten GCMs (table A2). Two models (CanESM5 and EC-Earth3) were omitted in this study, because they projected an extreme increase of more than 50% in annual rainfall over the north-eastern part of the VRB. This decision was made taking into consideration the expert judgement of West African climate scientists.

A.3. Discharge data

The eco-hydrological model SWIM was calibrated and validated at 31 gauges. Observed daily discharge time series were available from the Global Runoff Data Centre (GRDC) for 22 gauges. In addition, monthly mean discharges were available from GRDC for three gauges. Some complementary time series were provided by the CIREG project partner West African Science Service Centre on Climate Change and Adapted Land Use. The time periods covered by the observations were very heterogeneous. While some covered the period 1960 to 2018, others included only a few years. Many of the daily and monthly time series contain gaps that span months or even years.

Appendix B. Eco-hydrological modelling

SWIM is equipped with sophisticated features to account for various reservoir operations, e.g. hydropower, flood protection, and water supply [52], water allocation, and irrigation. SWIM is therefore well suited to assess the impacts of existing and planned human interventions, such as the construction of new dams and the expansion and establishment of irrigation schemes on the water availability under climate change.

B.1. Reservoir module

The reservoir module, developed by Koch *et al* [52], simulates various influences of natural and artificial lakes in river basins. It offers sophisticated functions to model storage effects, to estimate hydropower potentials, to provide water resources for different users, and to simulate flood protection.

Three operation rules are implemented to manage reservoir processes. The first option allows operating a reservoir to release daily minimum discharges to meet environmental targets downstream. In the second option, the daily release is based on targets of firm energy yields of a hydropower plant where the release to produce the targeted energy is calculated depending on the actual water level. The third option was implemented to simulate discharges from a natural lake where the release depends on the current water level of the lake assuming a static outlet at a given elevation.

The actual reservoir area, volume and water levels are changing daily depending on inflows, reservoir release and losses due to evapotranspiration, seepage and withdrawals. Reservoir release is determined by operation rules that are defined separately for the filling period and regular operation. Actual evapotranspiration from the reservoir area is determined by the area-weighted sums of the lake's open water surface evaporation and actual evapotranspiration from the land area (not permanently inundated reservoir area). Both depend on the actual filling state of the reservoir. The daily seepage rate is computed as a user-defined fraction of the current total storage volume. A share of the seepage volume can either contribute to shallow groundwater flows downstream of the reservoir or the total volume is allowed to percolate into the deep groundwater storage.

B.2. Irrigation

The water management module in SWIM provides different approaches to implement water allocation and agricultural irrigation. Water can be transferred from a source to a destination. A source can be reservoir, a sub-basin's river section, or an external source (outside the river basin). A destination can be a reservoir, a sub-basin's river section, an agricultural field (HRU), or an external water user. Water transfer from a source to a destination can be based on a predefined daily, monthly, mean monthly, or annual time series or a daily demand can be created from irrigation demands during the simulation.

The latter approach (plant demand) was used to determine crop and irrigation water demands. The crop growth model of SWIM is based on the EPIC crop growth model [53] and was used to simulate daily crop processes from sowing and growing to harvesting. At each day of their growing cycle, the plants have different demands for water and nutrients depending preceding and current soil and weather conditions and on their current stage of development, e.g. a young and small plant usually requires less water than a mature plant. If the soil water content is sufficiently high, the plants may not need any additional irrigation on certain days and thus generate no demand.

The daily irrigation water demand I_{wd} was computed from crop water requirements C_{wr} simulated by SWIM and the efficiency of the irrigation scheme E_{scheme}. The C_{wr} in mm were computed as the difference between water uptake by the crop C_{up} and its transpiration C_{tr} at each time step (B.1).

$$C_{\mathrm{wr}} = \begin{cases} C_{\mathrm{up}} - C_{\mathrm{tr}} & \text{if } C_{\mathrm{tr}} > C_{\mathrm{up}} \\ 0 & \text{if } C_{\mathrm{tr}} \leqslant C_{\mathrm{up}} \end{cases} \tag{B.1}$$

where E_{scheme} was estimated based on the irrigation efficiency E_{irr} depending on the irrigation practice and the efficiency of water transport in canals (conveyance efficiency E_{conv}). According to FAO (1989), an E_{irr} value of 60% represents surface irrigation, 75% sprinkler irrigation, and 90% drip irrigation. To compute the irrigation water demand, we assumed an E_{irr} value of 75% (sprinkler irrigation) and an E_{conv} of 70%. E_{scheme} was computed as follows (B.2):

$$E_{\mathrm{scheme}} = \frac{E_{\mathrm{irr}} \cdot E_{\mathrm{conv}}}{100}. \tag{B.2}$$

The total irrigation water demand I_{wd} or water to be withdrawn from the source accounting for estimated losses due to irrigation practice and conveyance efficiency, was computed according to (B.3).

$$I_{\mathrm{wd}} = C_{\mathrm{wr}} + \frac{C_{\mathrm{wr}} \cdot (100 - E_{\mathrm{scheme}})}{100}. \tag{B.3}$$

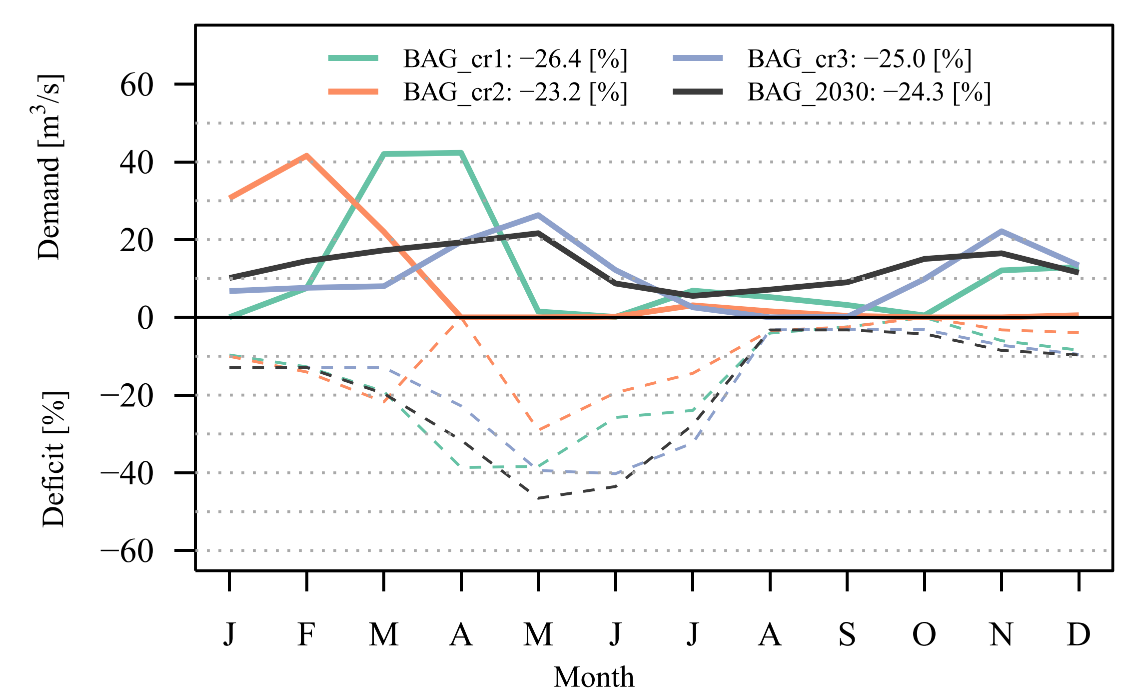


Figure B1. Irrigation water demand and deficits of different crop rotation scenarios.

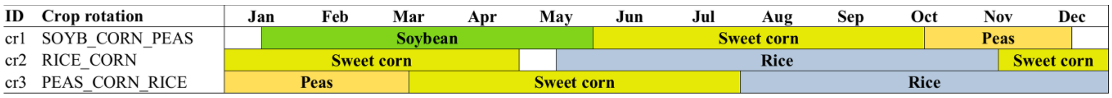


Figure B2. Crop rotation scenarios.

The actual Supply depends on the water availability of the source and can be either equal or lower than I_{wd}. The Supply was added as rainfall to the fields (HRUs), imitating sprinkler irrigation and thereby accounting for evaporative losses, canopy interception, surface runoff, infiltration, and percolation to the shallow groundwater aquifer. Excess water is simulated as return flows (surface, sub-surface, and groundwater) to the corresponding river section.

Irrigation deficits D were computed by subtracting daily I_{wd} from simulated Supply or water availability from the respective source (B.4). The deficits as percentage D_{PC} of I_{wd} were computed according to (B.5).

$$D = \text{Supply} - I_{wd} \tag{B.4}$$

$$D_{PC} = \frac{D}{I_{wd}} \cdot 100. \tag{B.5}$$

B.3. Crop rotation scenarios

The National Electricity Company of Burkina Faso (SONABEL), provided an observed monthly time series of irrigation withdrawals from the Bagré reservoir from 2000 to 2018. In the year 2000, withdrawals were about 0.65 m^3s^{-1} or 20.5 million m^3 per year (Mm^3a^{-1}) and increased almost linearly to 8.5 m^3s^{-1} (267 Mm^3a^{-1}) in 2018. This linear trend of withdrawals and associated irrigated area was extrapolated into the future until it reached the planned maximal irrigated area of 57 800 ha downstream Bagré [16] around the year 2040. According to the extrapolation, withdrawals are projected to increase to 13 m^3s^{-1} (410 Mm^3a^{-1}) by 2030 and to 17.2 m^3s^{-1} (543 Mm^3a^{-1}) by 2040.

However, the extrapolated time series was used only as a proxy to evaluate the seasonal pattern of simulated irrigation water demand with SWIM. For example, the extrapolated time series for 2030 (BAG_2030) shows demand peaks in May and October/November, generally lower demand during the rainy season (June to September), and the highest deficits at the end of the dry season around May and June (figure B1). The figure also shows the simulated demand and deficit patterns of the three crop rotation scenarios shown in figure B2. The FAO crop calendar was used as a guidance to develop the crop rotation scenarios, assuming typical crops for Burkina Faso and Ghana. To develop a crop rotation scenario with monthly demand and deficit patterns comparable to the extrapolated scenario, some adjustments were made to the timing of sowing and harvesting.

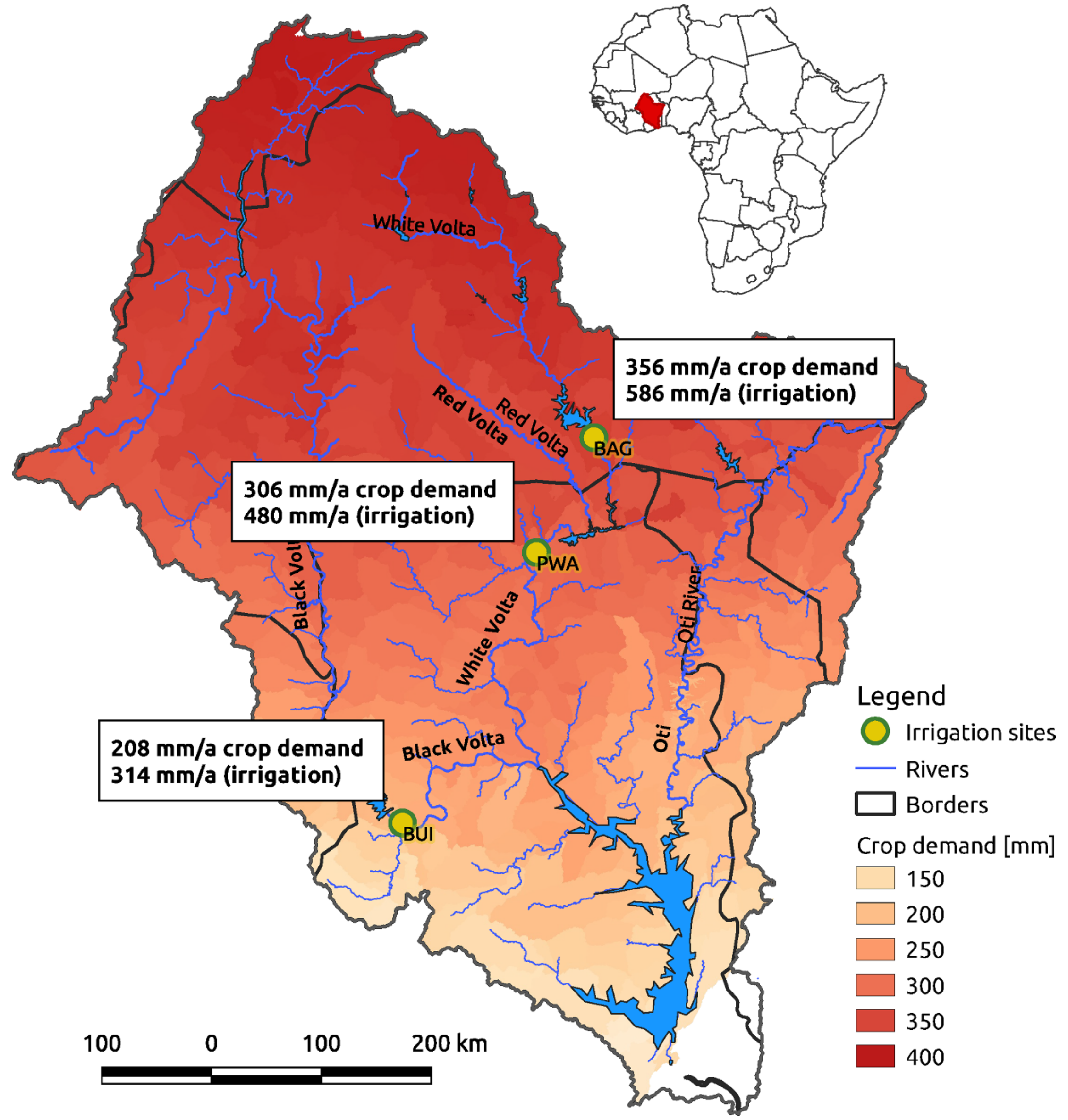
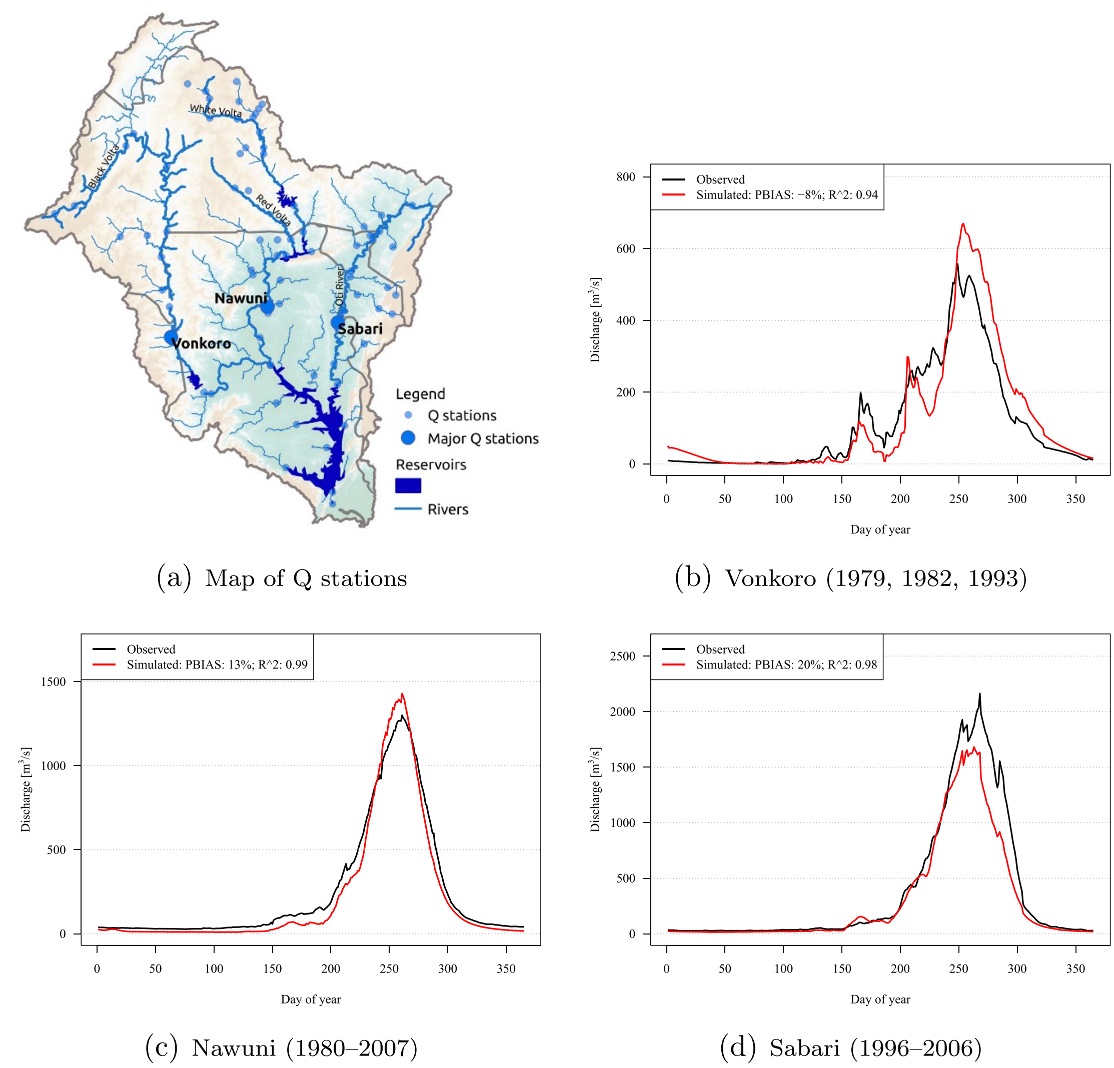


Figure B3. Theoretical crop water demand in the Volta basin using crop rotation scenario *cr*3.

Table B1. Withdrawals of aggregated water users in ($m^3 s^{-1}$).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wayen	0.0	0.0	0.0	0.0	0.0	0.0	2.0	6.0	3.1	1.0	0.0	0.0
Yakala 1	0.0	0.0	0.0	0.0	0.0	0.0	3.0	9.1	4.7	1.5	0.0	0.0
Yakala 2	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Kompienga	0.0	0.0	0.0	0.0	0.0	0.4	0.7	1.1	0.8	0.4	0.0	0.0
Sabari	1.4	1.5	1.4	1.4	0.3	0.4	0.3	0.3	0.4	0.3	1.4	1.4
Senchi	4.0	4.5	4.0	4.2	1.0	1.0	1.0	1.0	1.0	1.0	4.2	4.0
Nangodi	0.0	0.0	0.0	0.0	0.0	0.0	1.6	4.9	2.5	0.8	0.0	0.0
Nawuni	4.1	4.5	4.1	4.2	1.0	2.0	2.9	3.9	4.0	2.9	5.2	4.1
Nwoky	3.1	3.4	3.1	3.2	0.8	0.8	0.8	0.8	0.8	0.8	3.2	3.1
Dapola	1.3	1.5	1.3	1.4	0.6	0.6	1.9	3.2	4.7	3.2	2.7	1.3
Ouaga 1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ouaga 2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Sum												
$m^3 s^{-1}$	14.8	16.3	14.8	15.3	4.7	6.2	15.3	31.2	22.9	12.9	17.6	14.8
million m^3	39.6	39.5	39.6	39.6	12.6	16.1	40.9	83.6	59.3	34.5	45.6	39.6



(a) Map of Q stations (b) Vonkoro (1979, 1982, 1993)

(c) Nawuni (1980–2007) (d) Sabari (1996–2006)

Figure B4. Calibration results of selected major gauges.

As figure B1 shows, the temporal demand patterns of the crop rotation scenarios *cr*1 and *cr*2 are peaking in February (*cr*2) and March/April (*cr*1). Scenario *cr*3, on the other hand, represents the temporal behaviour of demand and deficit of the extrapolated time series much better. It was therefore used to simulate and compare irrigation water demand and deficit under current and future climate conditions at the three irrigation sites. The advantage of using the same crop rotation scenario at all sites is that the water demand and deficit simulations for the three sites are directly comparable under both the current and predicted climates. The disadvantage is that other crop rotations may be preferred at the PWA and BUI sites. However, the primary interest of this study was to determine future water demands and deficits for irrigation rather than crop yields. Thus, the hydrological impacts of irrigation was more important in this context then possible dietary or agricultural preferences. The map in figure B3 shows the average annual crop water demand if the *cr*3 crop rotation scenario was applied to the entire VRB. In the hot and semi-arid north the crop water requirements of *cr*3 was around 400 mm a^{-1} and in the tropical savanna in the south around 150 mm a^{-1}.

B.4. Water allocation (aggregate small projects)

The water allocation module was used to account for the water demand and consumption of small water users such as for irrigation, livestock, and households. Since there are hundreds of water users in the VRB who take water either directly from rivers or from small dams, we grouped them by region and river into a total of 12 aggregated water users. The Tono and Vea dams are, for example, considered in the Nawuni site. Table B1 shows the monthly water demand of the aggregated water users. Their combined demand is 15.6 m^3s^{-1} or 490 million m^3a^{-1}.

The information on the lump sums of the aggregated water users was mainly collected from the stakeholders during several model training workshops in the context of the CIREG project. Each aggregated water user was assigned in the model to a specific river section from which the respective demand was taken,

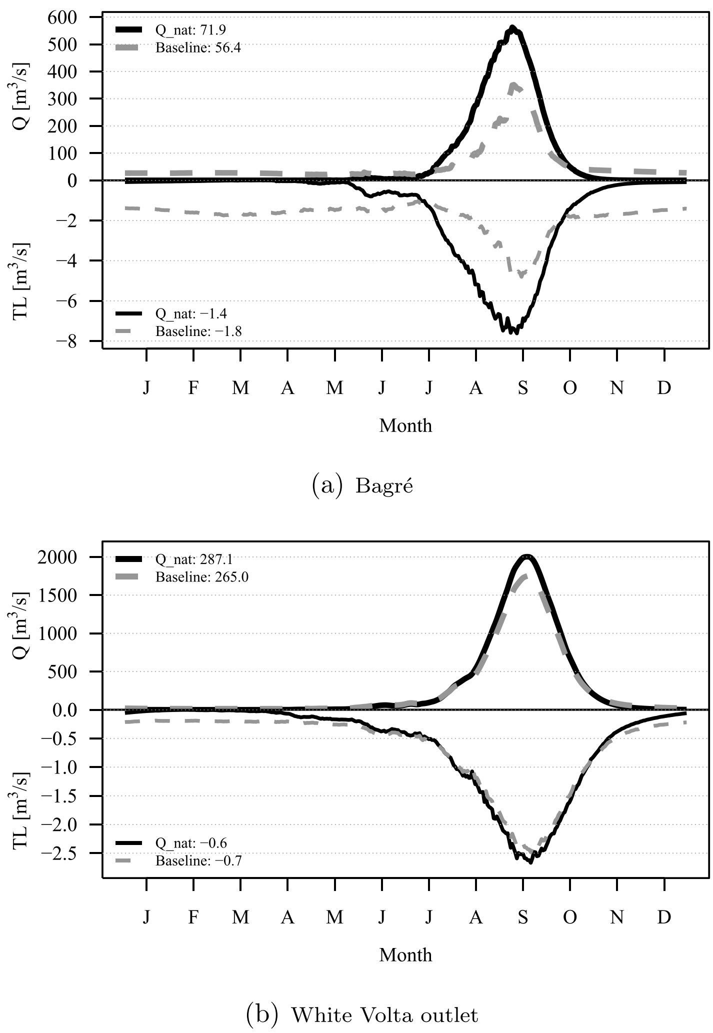


Figure B5. Flow regime and transmission losses (TL) in QNAT and BL scenario at the sub-basin downstream Bagré (a) and the sub-basin at the White Volta draining into Lake Volta, WFDE5 in P0 (1984–2014).

if enough water was available in the corresponding river section.

A small mistake was made with the water user Senchi. The water intake is not from Lake Volta, as assumed in the model, but the water is taken downstream of the Akosombo dam [54]. Thus, the reduction in hydropower potential actually affects only Kpong, not Akosombo Dam. However, due to the comparably small impact of this one water user, no correction was made in the model.

B.5. Calibration

SWIM was set up to the VRB, including 578 sub-basins and 9880 HRUs. Depending on data availability, it was thoroughly calibrated and validated to observed discharges at 31 gauging stations during the period between 1970 and 2016.

Even though the number of discharge stations in the VRB is spatially representative, data availability is strongly limited. Many of the daily and monthly time series contain gaps, lasting over months or even years. Model calibration was therefore limited to periods without long data gaps. The figure B4 shows the calibration results at the three gauges representing discharges into Lake Volta from the Black Volta (gauge Vonkoro), the White Volta (gauge Nawuni), and from the Oti River (gauge Sabari).

The observed and simulated discharges shown in the figure B4 represent mean daily discharges averaged over the period with available data. For the gauge Vonkoro, the time series represented only full records for the years 1979, 1982, and 1993. For the other two gauges the available time series were much longer.

B.6. Transmission losses

Transmission losses in rivers are computed during the river routing process based on some static parameters, e.g. channel length, some dynamic variables, e.g. water depth, wetted perimeter of the channel, water surface area, and a correction factor. The correction factor was set to 1.05, increasing the computed seepage to the riverbed by 5%. At each time step (day), the transmission losses from both seepage to the riverbed and the evaporation losses at the river's surface area are computed.

The evaporation losses are calculated by multiplying the potential evapotranspiration $[\mathrm{mm} * 10^{-3}]$ for a given day and sub-basin with the actual water surface area $[\mathrm{m}^2]$ of the same sub-basin's channel.

Seepage to the riverbed depends on the sub-basin's hydraulic conductivity $[\mathrm{mm} * \mathrm{h}^{-1}]$ of the riverbed and the actual wetted perimeter of the channel. The seepage-part of the transmission losses can be added either to the shallow or the deep groundwater aquifer or to both in equal shares. In the simulations of this study, the seepage was added to the deep groundwater aquifer.

Figure B5(a) shows the impact of the Bagré dam on the simulated flow regime and transmission losses before (Q_nat) and after (Baseline) its construction. Due to the storage and filling process of the Bagré dam during the high-flow season (July to September), the managed discharges (baseline) are significantly lower than those of the natural simulations (Q_nat). On the other hand, water is released on average every day of the year and the White Volta has become a permanent river as a result of this intervention. During the dry period (November to April), where under natural conditions no transmission losses occur, losses of about 1.8 $\mathrm{m}^3\,\mathrm{s}^{-1}$ are simulated with the Bagré dam in place (Baseline). During the high-flow season, the transmission losses in the Baseline are lower than those of the natural simulation because less water flows downstream the dam.

The patterns of flow regime and transmission losses in the river section about 350 km downstream of the Bagré dam, before the White Volta drains into Lake Volta, are comparable to those downstream of the Bagré dam, figure B5(b). However, due to the generally higher discharges and the contributions of other tributaries at this river section, the impacts of the flow regime change due to the upstream Bagré are much weaker.

Appendix C. Results

Table C1. Attribution of impacts on Akosombo (BL − QNAT), WFDE5 in P0 (1984–2014).

	Inflow ($m^3 s^{-1}$)	HPP ($GWh\ a^{-1}$)	Contribution (%)
Akosombo	**−60**	**−249.1**	—
White Volta	−27.8	−115.4	46.3
Black Volta	−24.8	−102.6	41.2
Oti	−7.4	−30.7	12.3
Large projects	−53.2	−220.9	88.7
Aggregate projects	−6.8	−28.2	11.3

Note : The bold value indicates that the sum of reductions from the three rivers or the sum of large and aggregate projects

Table C2. Capacity factors, six dams, WFDE5 in P0 (1984–2014).

	Installed capacity		HPP (BL)		Cf	HPP (FD)		Cf
Dam	(MW)	($GWh\ a^{-1}$)	(MW)	($GWh\ a^{-1}$)	(%)	(MW)	($GWh\ a^{-1}$)	(%)
Bagré	16	140.3	6.0	52.9	37.7	4.7	40.9	29.2
Bui	400	3506.4	104.1	912.2	26.0	104.1	912.2	26.0
Pwalugu	59	517.2	21.6	189.3	36.6	20.4	178.7	34.6
Akosombo	1020	8941.3	601.1	5269.1	58.9	586.8	5143.6	57.5
Kpong	160	1402.6	108.5	951.1	67.8	106.2	931.0	66.4
Kompienga	14	122.7	3.8	32.9	26.8	3.8	32.9	26.8

Cf = capacity factor as % of installed capacity.
HPP = hydropower potential.

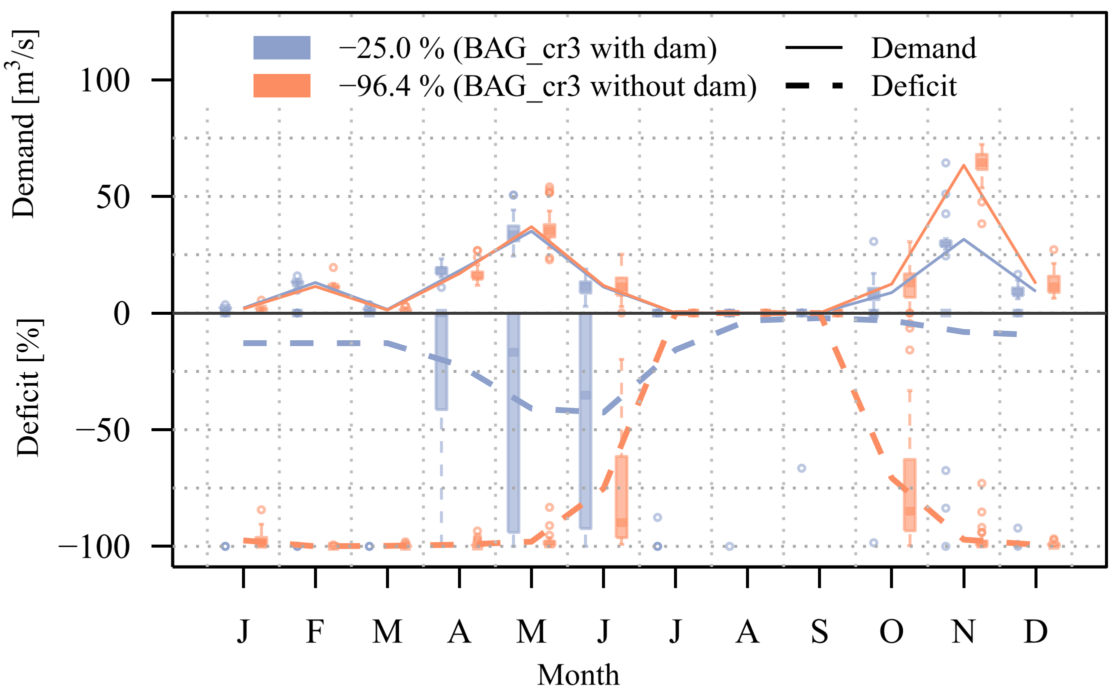


Figure C1. Mean monthly irrigation demand (top) and deficit (bottom) for *cr3* crop rotation scenario at the Bagré site, assuming the Bagré dam in place or not in place (theoretical example, because the dam exists in reality). Numbers in the legend indicate the percent deficit, WFDE5 in P0 (1984–2014). Rainy season: May/June to September.

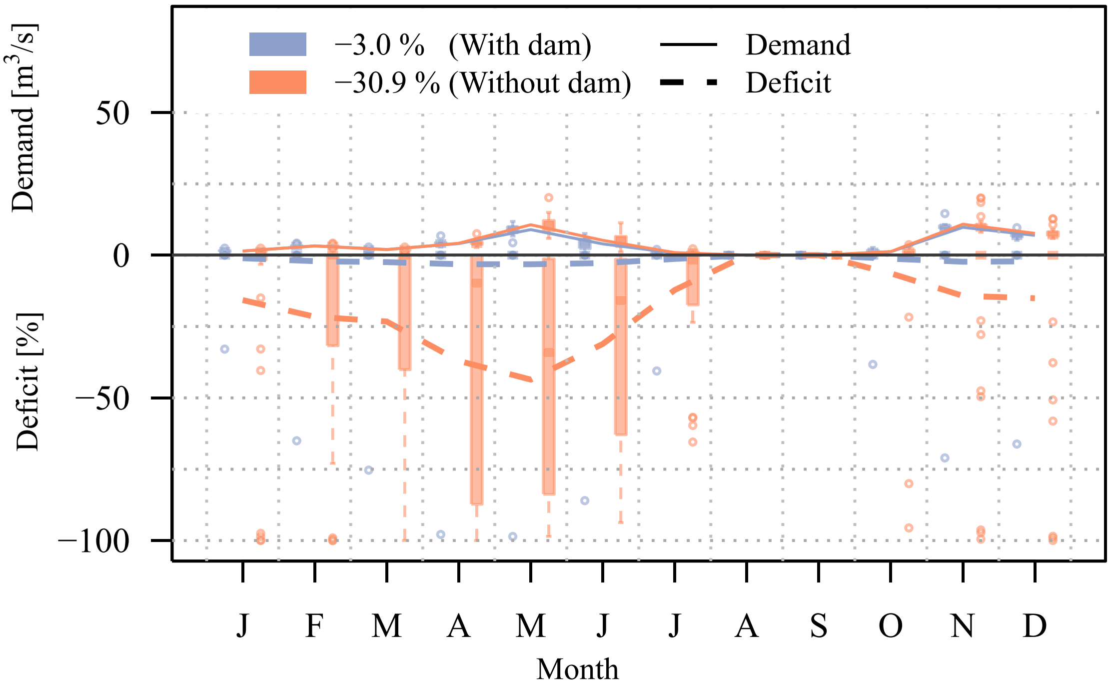


Figure C2. Mean monthly irrigation demand (top) and deficit (bottom) for *cr*3 crop rotation scenario at the Pwalugu site assuming the dam in place or not in place. Numbers in the legend indicate the percent deficit, WFDE5 in P0 (1984–2014). Rainy season: April/May to September.

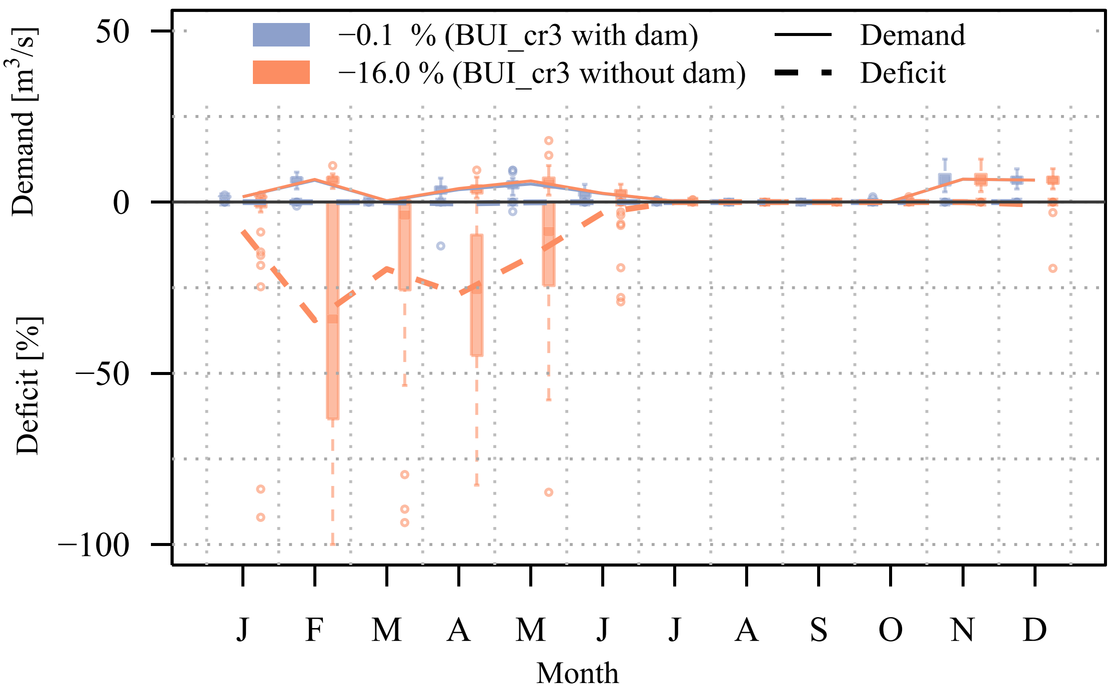


Figure C3. Mean monthly irrigation demand (top) and deficit (bottom) for *cr*3 crop rotation scenario at the Bui site assuming the dam in place or not in place (theoretical example, because the dam exists in reality), WFDE5 in P0 (1984–2014). Rainy season: March to October.

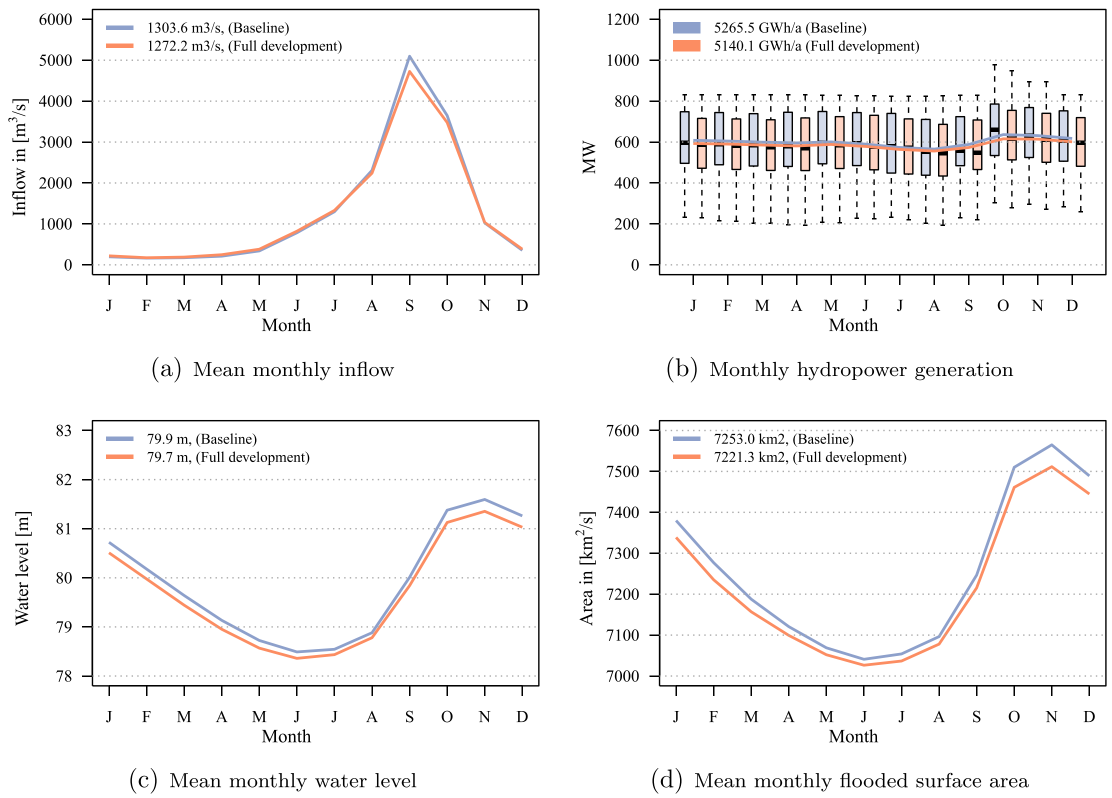


Figure C4. Differences of selected variables at Akosombo (Lake Volta) between FD and BL scenario, P0, WFDE5.

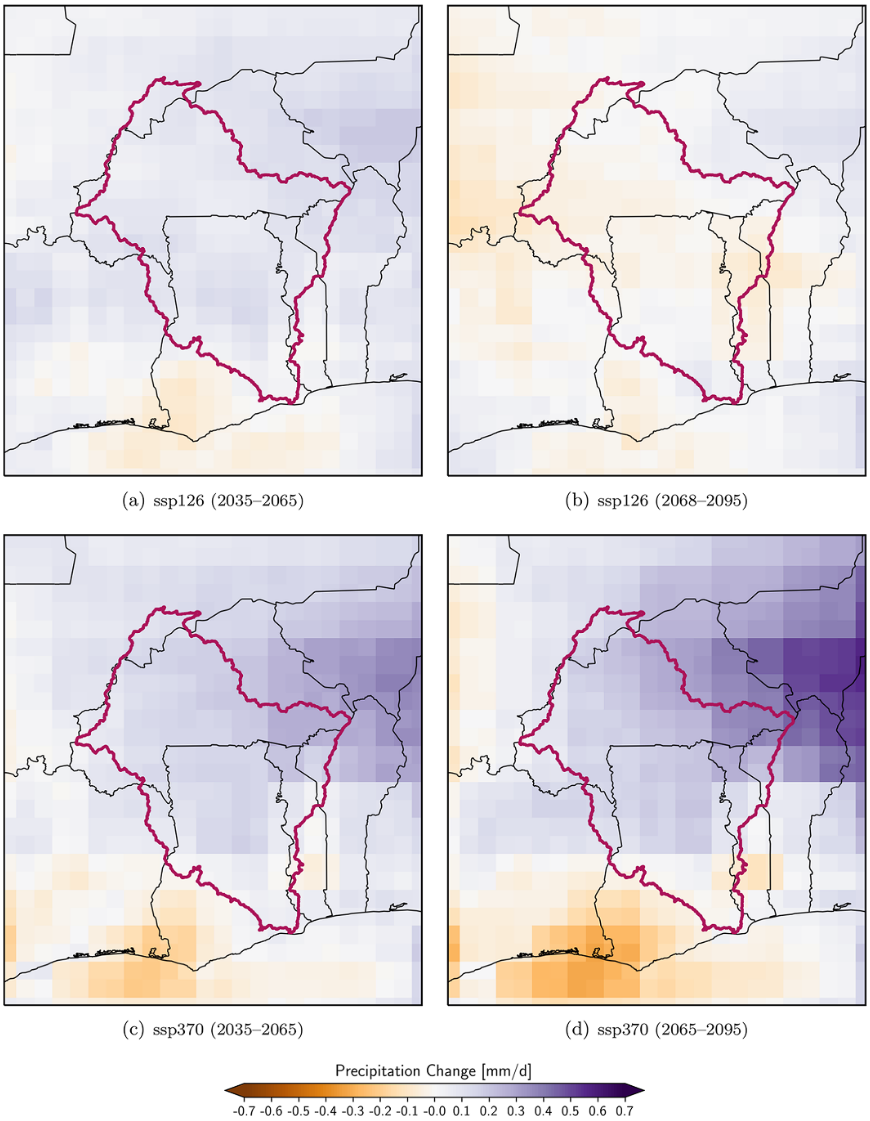


Figure C5. Precipitation change relative to reference period P0 (1984–2014), ensemble median of 8 ISIMIP3b GCMs.

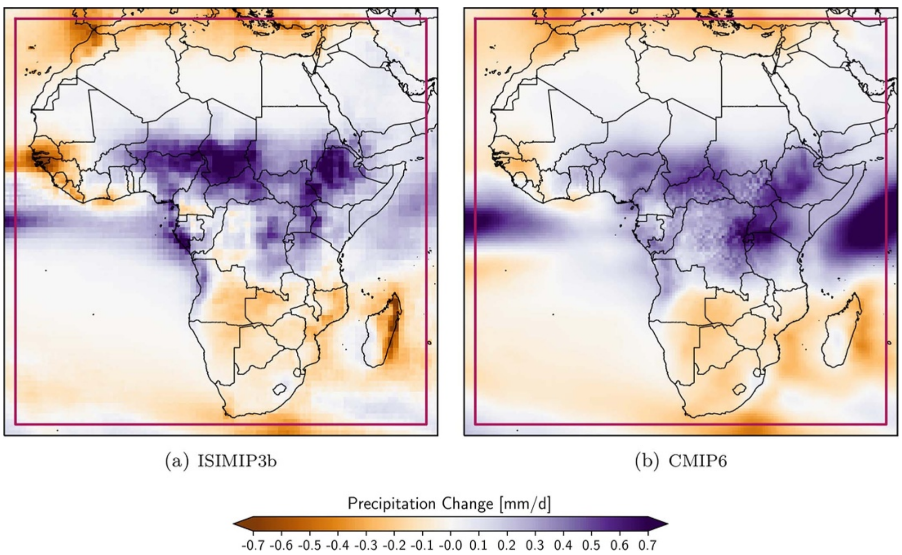


Figure C6. Comparison of average precipitation anomalies in P2 compared to P0. ISIMIP3b ensemble (left) and CMIP6 ensemble (right).

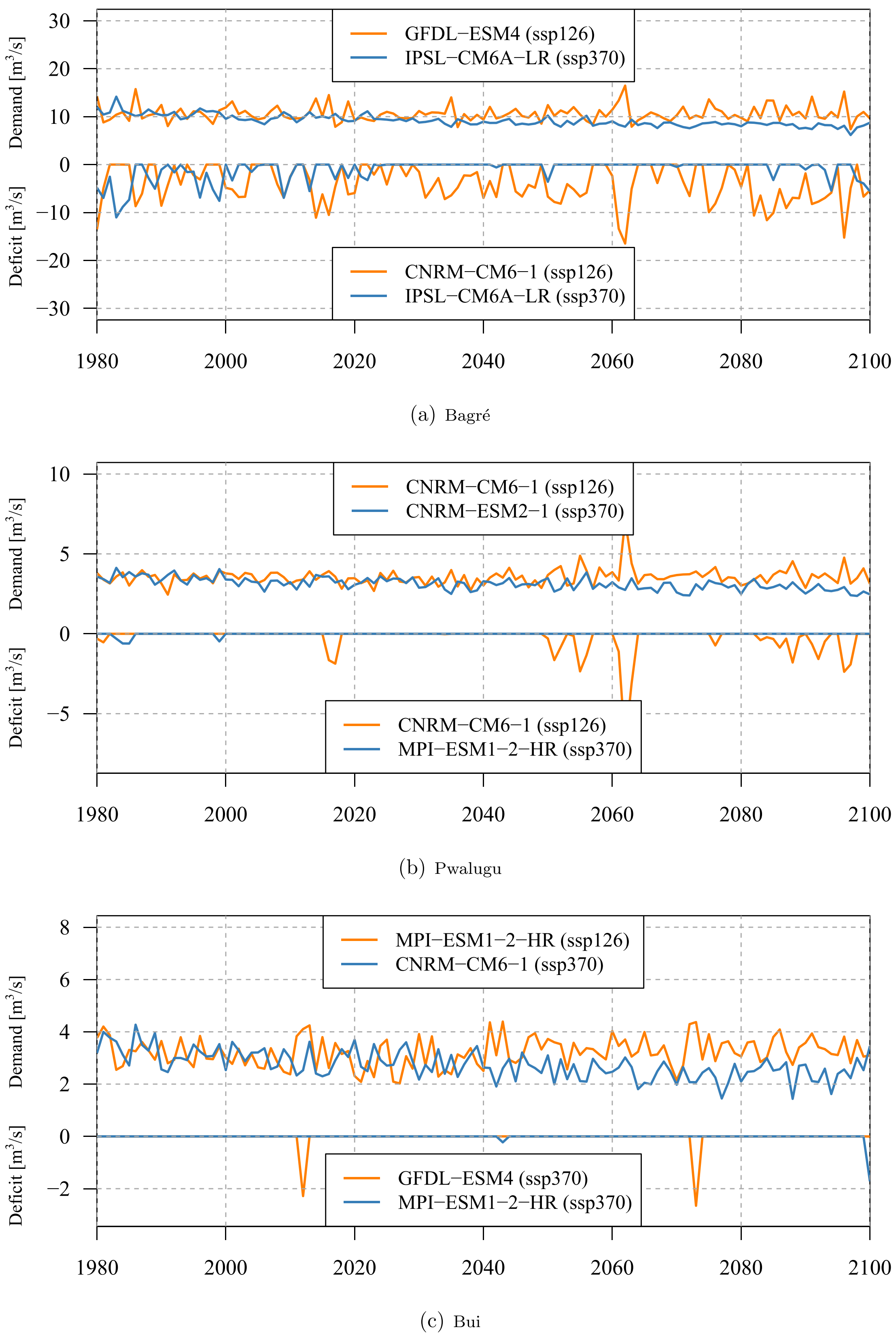


Figure C7. Highest and lowest irrigation water demand and deficit at the three sites, ISIMIP3b.

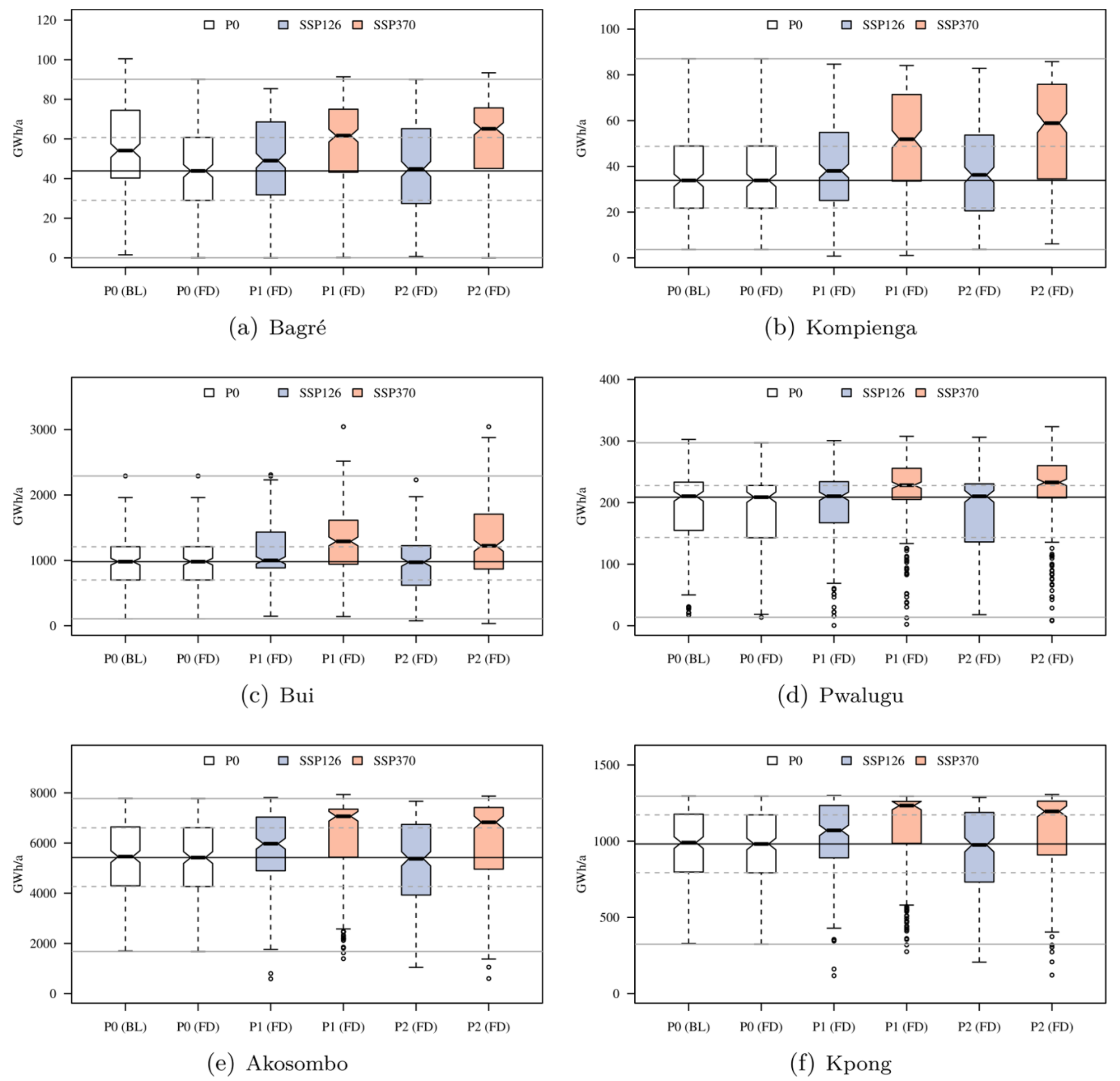


Figure C8. Hydropower potentials under climate change for SSP126 and SSP370, *FD* scenario, ensemble of 8 ISIMIP3b GCMs.

ORCID iDs

S Liersch https://orcid.org/0000-0003-2778-3861
F F Hattermann https://orcid.org/0000-0002-6046-4670

References

[1] Engelbrecht F *et al* 2015 *Environ. Res. Lett.* **10** 085004
[2] Salack S, Klein C, Giannini A, Sarr B, Worou O N, Belko N, Bliefernicht J and Kunstman H 2016 *Environ. Res. Lett.* **11** 104008
[3] Salack S, Saley I A, Lawson N Z, Zabré I and Daku E K 2018 *Weather Clim. Extremes* **21** 36–42
[4] Sarr Bît, Atta S, Ly M, Salack S, Ourback T, Subsol S and George A D 2015 *J. Agric. Ext. Rural Dev.* **7** 16–271
[5] Robinson A, Lehmann J, Barriopedro D, Rahmstorf S and Coumou D 2021 *npj Clim. Atmos. Sci.* **4** 45
[6] Gonzalez J M *et al* 2021 *Front. Environ. Sci.* **9** 107
[7] Baah-Kumi B and Ward F A 2020 *J. Hydrol.* **582** 124548
[8] Oyebande L and Odunuga S 2010 *The Open Hydrology Journal* **4** 163–72
[9] Nacro S 2015 *Int. J. Agric. Innov. Res.* **4** 502–6 (available at: https://ijair.org/administrator/components/com_jresearch/files/publications/IJAIR_1692_Final.pdf)
[10] Bhaduri A, Manna U, Barbier E and Liebe J 2011 *Nat. Resour. Model.* **24** 409–44
[11] Amisigo B A, McCluskey A and Swanson R 2015 *Sustainability* **7** 6957–75
[12] PARI 2020 From potentials to reality: transforming Africa's food production investment and policy priorities for sufficient, nutritious and sustainable food supplies *Technical Report* (Center for Development Research (ZEF), University of Bonn (Program of Accompanying Research for Agricultural Innovation)) (available at: www.zef.de/fileadmin/downloads/ZEF_Akademiya2063.pdf) (Accessed 13 October 2021)
[13] You L, Ringler C, Wood-Sichra U, Robertson R, Wood S, Zhu T, Nelson G, Guo Z and Sun Y 2011 *Food Policy* **36** 770–82
[14] Xie H, Perez N, Anderson W, Ringler C and You L 2018 *Water Int.* **43** 796–814
[15] Kottek M, Grieser J, Beck C, Rudolf B and Rubel F 2006 *Meteorol. Z.* **15** 259–63
[16] Pole B 2011 Project appraisal document on a proposed grant to Burkina Faso for a Bagré Growth Pole Project *Technical Report* No: 60099-BF (World Bank)
[17] VRA 2021 Pwalugu multi-purpose dam project *Technical Report* (The Volta River Authority) (available at: www.vra.com/pwalugu/projectbackground.html) (Accessed 9 October 2021)

[18] VBA 2018 Water Charter for the Volta River Basin *Technical Report* (Volta Basin Authority) (available at: https://abv.int/wp-content/uploads/2022/02/Water-Charter_VBA_Eng.pdf) (Accessed 9 September 2021)
[19] 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 *Working Paper* 166 (International Water Management Institute) (available at: www.iwmi.cgiar.org/Publications/Working_Papers/working/wor166.pdf)
[20] Leemhuis C, Jung G, Kasei R and Liebe J 2009 *Adv. Geosci.* **21** 57–62
[21] Huber V *et al* 2014 *Earth Syst. Dyn.* **5** 399–408
[22] Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O and Schewe J 2014 *Proc. Natl. Acad. Sci.* **111** 3228–32
[23] Lange S 2019 *Geosci. Model Dev.* **12** 3055–70
[24] Lange S 2021 ISIMIP3b bias adjustment fact sheet *Technical Report* (PIK) (available at: www.isimip.org/documents/413/ISIMIP3b_bias_adjustment_fact_sheet_VGtWmOp.pdf)
[25] Krysanova V, Hattermann F and Wechsung F 2005 *Hydrol. Process.* **19** 763–83
[26] Krysanova V, Hattermann F, Huang S, Hesse C, Vetter T, Liersch S, Koch H and Kundzewicz Z W 2015 *Hydrol. Sci. J.* **60** 606–35
[27] Mul M, Pettinotti L, Amonoo N A, Bekoe-Obeng E and Obuobie E 2017 Dependence of riparian communities on ecosystem services in northern Ghana *IWMI Working Paper* 179 (International Water Management Institute (IWMI)) (available at: www.iwmi.cgiar.org/publications/iwmi-working-papers/iwmi-working-paper-179/)
[28] Dossou-Yovo E R, Vandamme E, Dieng I, Johnson J M and Saito K 2020 *Field Crops Res.* **258** 107963
[29] Haefele S, Nelson A and Hijmans R 2014 *Geoderma* **235–236** 250–9
[30] Carr T W, Mkuhlani S, Segnon A C, Ali Z, Zougmoré R, Dangour A D, Green R and Scheelbeek P 2022 *Environ. Res. Lett.* **17** 053001
[31] Saito K *et al* 2019 *Geoderma* **338** 546–54
[32] Dzanku F M, Jirström M and Marstorp H 2015 *World Dev.* **67** 336–62
[33] FAO 2011 The state of the world's land and water resources for food and agriculture (SOLAW)—managing systems at risk *Technical Report* (London: Food and Agriculture Organization of the United Nations Rome and Earthscan) (available at: www.fao.org/docrep/017/i1688e/i1688e.pdf)
[34] Gadédjisso-Tossou A, Avellán T and Schütze N 2018 *Water* **10** 1803
[35] Rolls R J and Bond N R 2017 Environmental and ecological effects of flow alteration in surface water ecosystems *Water for the Environment* ed A C Horne, J A Webb, M J Stewardson, B Richter and M Acreman (New York: Academic) ch 4, pp 65–82
[36] Leigh C, Boulton A J, Courtwright J L, Fritz K, May C L, Walker R H and Datry T 2016 *Freshw. Biol.* **61** 1181–99
[37] IHA 2021 Hydropower status report 2021, sector trends and insights *Technical Report* (International Hydropower Association Limited)
[38] Vetter T *et al* 2017 *Clim. Change* **141** 419–33
[39] Hattermann F F *et al* 2018 *Environ. Res. Lett.* **13** 015006
[40] Liersch S *et al* 2020 *Environ. Res. Lett.* **15** 104014
[41] Liersch S, Tecklenburg J, Rust H, Dobler A, Fischer M, Kruschke T, Koch H and Hattermann F F 2018 *Hydrol. Earth Syst. Sci.* **22** 2163–85
[42] Dembélé M, Vrac M, Ceperley N, Zwart S J, Larsen J, Dadson S J, Mariéthoz G and Schaefli B 2021 *Hydrol. Earth Syst. Sci. Discuss.* **2021** 1–35
[43] Dosio A, Turner A G, Tamoffo A T, Sylla M B, Lennard C, Jones R G, Terray L, Nikulin G and Hewitson B 2020 *Environ. Res. Lett.* **15** 064007
[44] Jin L, Whitehead P G, Addo K A, Amisigo B, Macadam I, Janes T, Crossman J, Nicholls R J, McCartney M and Rodda H J 2018 *Sci. Total Environ.* **637–638** 1069–80
[45] Sterl S 2021 *Curr. Sustain. Renew. Energy Rep.* **8** 274–81
[46] Sterl S, Vanderkelen I, Chawanda C J, Russo D, Brecha R J, van Griensven A, van Lipzig N P M and Thiery W 2020 *Nat. Sustain.* **3** 710–9
[47] Taylor J C, van de Giesen N and Steenhuis T S 2006 *JAWRA J. Am. Water Resour Assoc.* **42** 1113–26
[48] Jarvis A, Reuter H, Nelson A and Guevara E 2008 Hole-filled seamless SRTM data V4 and International Centre for Tropical Agriculture (CIAT) (available at: http://srtm.csi.cgiar.org.)
[49] FAO, IIASA, ISRIC, ISSCAS and JRC 2009 Harmonized World Soil Database (version 1.1) (FAO and Rome and Italy and IIASA and Laxenburg and Austria) (available at: www.fao.org/nr/land/soils/harmonized-world-soil-database/en/)
[50] Bartholomé E and Belward A 2005 *Int. J. Remote Sens.* **26** 1959–77
[51] Cucchi M, Weedon G P, Amici A, Bellouin N, Lange S, Schmied H M, Hersbach H and Buontempo C 2020 *Earth Syst. Sci. Data Discuss.* **2020** 1–32
[52] Koch H, Liersch S and Hattermann F 2013 *Water Sci. Technol.* **67** 1525–33
[53] Williams J R, Jones C A, Kiniry J R and Spanel D A 1989 *Trans. ASABE* **32** 497–511
[54] Owusu A, Zatarain Salazar J, Mul M, van der Zaag P and Slinger J 2022 *Hydrol. Earth Syst. Sci. Discuss.* **2022** 1–27