Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 13 No 6, 2399 doi: 10.2166/wcc.2022.452

Impacts of hydro-climatic trends and upstream water management on hydropower generation at the Bagré dam

Gnibga Issoufou Yangouliba[a,*], Hagen Koch[b], Stefan Liersch[b], Luc Ollivier Sintondji[c], Moussa Sidibé[d], Isaac Larbi[e], Andrew Manoba Limantol[e], Yacouba Yira[f], Jean-Marie Dipama[g] and Daniel Kwawuvi[a]

[a] Doctoral Research Program in Climate Change and Water Resources, National Water Institute, University of Abomey Calavi, P.O. Box 4521, Cotonou, Benin
[b] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, 14412 Potsdam, Germany
[c] Department of Water for Agriculture and Society, National Water Institute, University of Abomey Calavi, P.O. Box 526, Cotonou, Benin
[d] West Africa Science Service Centre on Climate Change and Adapted Land Use, Competence Center, P.O. Box 9507, Ouagadougou, Burkina Faso
[e] Department of Water Resources and Sustainable Development, University of Environment and Sustainable Development, Private Mail Bag, Somanya, Eastern Region, Ghana
[f] Applied Science and Technology Research Institute – IRSAT/CNRST, P.O. Box 7047, Ouagadougou, Burkina Faso
[g] Department of Geography, University Joseph Ki-Zerbo, P.O. Box 7021, Ouagadougou, Burkina Faso
*Corresponding author. E-mail: yangis2000@yahoo.fr; yangouliba.g@edu.wascal.org

GIY, 0000-0001-8409-0223

ABSTRACT

Global hydro-climatic trends are ambiguous, challenging the management of water resources. This challenge is addressed in the current study by investigating the impacts of hydro-climatic trends and upstream water management on hydropower generation at the Bagré dam. Modified Mann–Kendall trend test, Standard Normal Homogeneity Test and Pettit test were applied to some selected hydro-climatic variables for the trend and the change year detection, whereas the relationship between upstream dam management, hydro-climatic variables and hydropower were assessed through the Spearman correlation. The results revealed an annual positive trend for all hydro-climatic variables except for water level, lake evaporation and outflow. The break years observed in hydropower generation (2002) and inflow (2006) were mainly due to the construction of the Ziga dam in 2000 and its management change in 2005, respectively. The study also showed that hydropower generation declines each May (−30.36 MWh) and June (−16.82 MWh) due to the significant increase in irrigation withdrawals (1.94 hm^3 in May and 0.67 hm^3 in June). The results of this study highlighted the non-linearity in the relationship between hydropower generation and hydro-climatic variables as none of the correlation coefficients (apart from turbine) are very strong (>0.8). As many human activities occurred in the basin, further research should be focused on the use of semi-distributed models to assess the impacts of water-use and land-use change on hydropower generation.

Key words: hydro-climatology, hydropower, modified Mann–Kendall test, Pettit test, Standard Normal Homogeneity Test, upstream water management

HIGHLIGHTS

- All hydro-climatic variables increased significantly except water level, lake evaporation and outflow.
- The construction of the Ziga dam in 2000 led to a significant increase in annual hydropower generation at Bagré dam from 2002.
- The change in management of the Ziga dam in 2005 led to a significant increase in annual inflow at Bagré dam from 2006.
- All the months of the year experienced an increasing trend of hydropower generation except May and June.
- The decline of hydropower generation in May and June is the consequence of the increase of water withdrawals for irrigation.

INTRODUCTION

Climate change is one of the major threats faced by many regions across the world (Khalid *et al.* 2017). The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 2021 highlighted an increase in global temperature of about ±1.2 °C in 2020 compared to the period of 1850–1900, and this is expected to increase by 1.4–4.4 °C in 2100 under the lowest and highest Green House Gases emissions scenarios (SSP1-1.9 and SSP5-8.5), respectively (IPCC 2021). The rate of the increase depends on the location. In the Eastern Himalayas, for instance, the mean temperature increased by 0.02 °C per year while in Nepal the rate of increase was 0.04 °C per year from 1977 to 2000 (Khalid *et al.* 2017). The monsoon precipitation also experienced a decrease from the 1950s to the 1980s and more extreme events since the 1950s (DSB 2011; IPCC 2021). For instance, some droughts in East and West Africa are attributed to the increase of sea surface temperatures (SSTs) in the Indian and the Atlantic Oceans (DSB 2011). Whereas, Western Europe experienced in 2021 a huge flooding which caused 179 deaths in Germany and 36 in Belgium (WMO 2021). These changes in the climate patterns, mostly attributed to human-induced activities (IPCC 2021), have an impact on river discharge and water levels of reservoirs. The seasonality of the global river discharge (increase of high flows and decrease of low flows) is expected to increase by one-third during the period 2070–2100 compared to 1971–2000 (Michelle *et al.* 2013). In the Midwestern United States, the streamflow is predicted to decrease by 41–61% for the period 2051–2095 relative to 1978–2009 (Chien *et al.* 2013). In China, a change of −3.6 to +14.8% in annual rainfall will induce a change in annual discharge of −29.8 to +16.0% (Birkinshaw *et al.* 2017). In Africa, an increase in rainfall of 5–25% by 2080 within the Lake Victoria River basin will lead to an increase in river discharge of 5–267% while a variation of −2 to 5% in the annual rainfall will lead to a change of −20 to 10% in river discharge in the Niger River basin (Stanzel *et al.* 2018; Olaka *et al.* 2019). These changes in river discharges impact water levels of reservoirs used for many activities, including hydropower generation (Boadi & Owusu 2017; Dias *et al.* 2018; Mousavi *et al.* 2018; Sridharan *et al.* 2019; Liu *et al.* 2020).

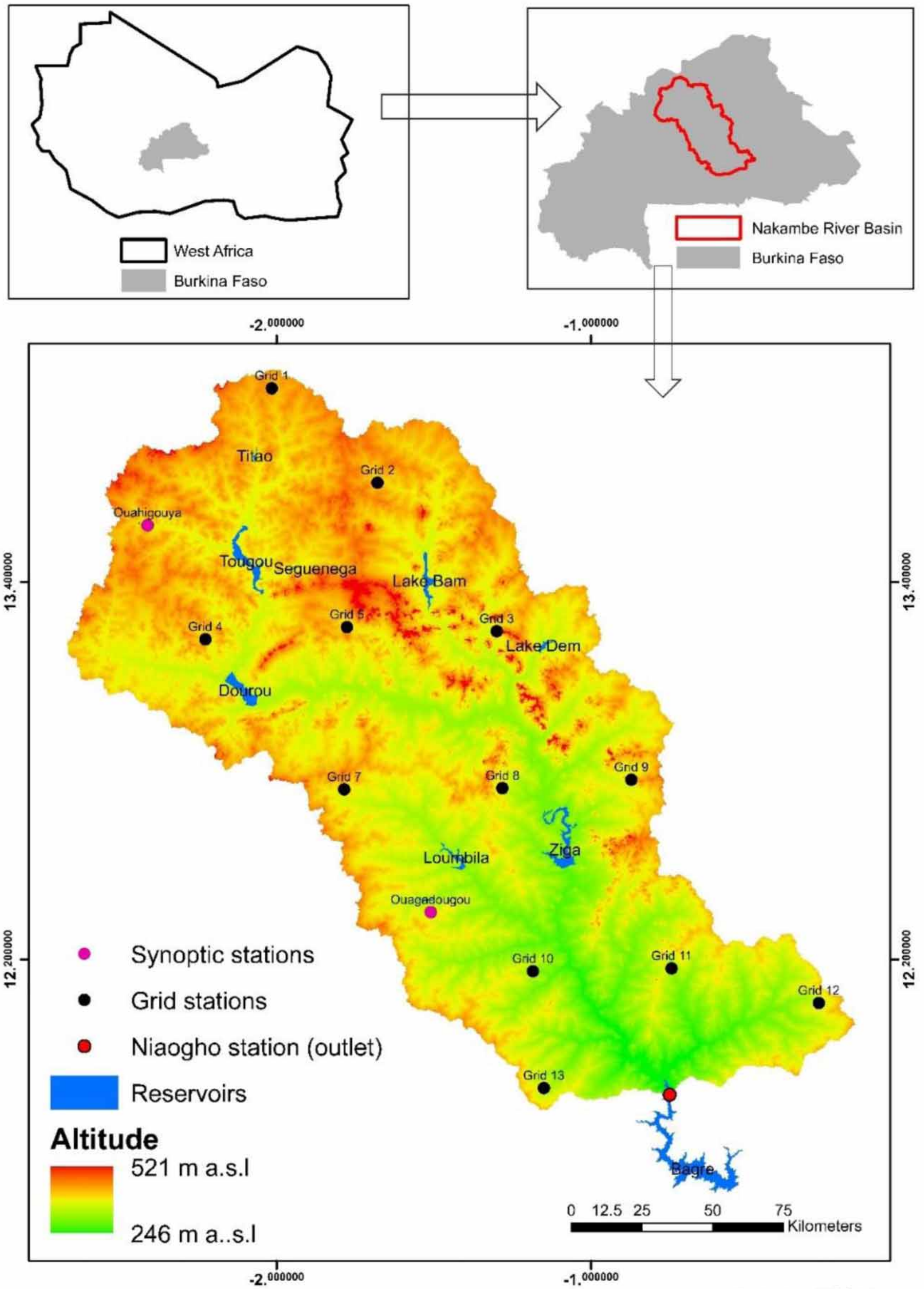
Many African countries rely on hydropower dams to generate electricity for their populations. According to Okudzeto *et al.* (2014), the reliance of societies on climate sensitive sectors such as hydropower has become a challenge to sustainable development as a result of climate variability and change impacts on hydrological processes. In semi-arid areas of West Africa, changes in rainfall are a concern because of their important role in irrigated agriculture, domestic and industrial water supply, reservoir operation and hydropower generation (Ibrahim *et al.* 2016). According to Obahoundje *et al.* (2018), the operation of West Africa's hydropower dams relies strongly on the hydro-climatic condition of their upstream catchments. In addition, hydropower generation could also be affected by other factors such as population growth, land-use land cover, water abstraction and socio-economic development (Boretti & Rosa 2019; Alsaleh *et al.* 2021; Obahoundje & Diedhiou 2022). Therefore, reliable information regarding hydro-climatic trends as well as upstream catchment water management is important to adapt to projected future climate conditions (Sankarasubramanian & Vogel 2003; Oguntunde & Abiodun 2012). Besides, Frumhoff *et al.* (2015) showed that there is a relationship between El Niño-Southern Oscillation (ENSO) and hydropower generation. As ENSO is a major driver of climate variability, there is a need to investigate the prospect of ENSO-driven variability in hydropower generation at dams located in affected river basins (Jia *et al.* 2017).

Burkina Faso is not exempted from impacts of climate variability and change (MEFR 2015). The country is characterized by high rainfall variability resulting in strong fluctuations of river discharge, negatively impacting water resources availability (Karambiri 2017). A study by Ibrahim (2012) analysed rainy season characteristics (1961–2009) in Burkina Faso and found an increased frequency of low rainfall (between 0.1 and 5 mm/day) and heavy maximum daily rainfall, and also projected an increase of the length of the mean dry spell as well as a late cessation of the rainy season (2021–2050). Tazen *et al.* (2012) observed that the Nakambé River Basin (NRB) is under anthropogenic pressure as several small dams were built to supply water for domestic, irrigation, breeding and fishery needs. Changes in climate and land management can result in higher frequencies of droughts and floods, leading to food insecurity, diseases, population migration and loss of natural resources (Tazen *et al.* 2012; Annys *et al.* 2020). Thiombiano (2011) assessed the variability of rainfall and temperature in the NRB from 1940 to 2008. However, there is a lack of scientific evidence on how hydropower generation is related to past hydro-climatic trends and upstream water management in the basin. This study tries to answer the following question: are the trends and changes observed in the natural climate system also detectable in the hydrological system and the reservoir system of Bagré? The objective is to assess the impact of the climate system trend and upstream reservoirs management on the hydrological and reservoir systems in the NRB.

MATERIALS AND METHODS

Study area

The NRB is located in the headwaters of the White Volta Basin in Burkina Faso (Karambiri *et al.* 2011). The basin is located between longitudes 2 °1′ and 0 °3′ West and latitudes 11 °11′ and 14 °1′ North (Figure 1). Its area is about 32,623 km^2 at the Niaogho station and is partly located in the Sahelian and the north Sudanian climate zones. The basin experiences a unimodal rainfall regime with the rainy season from June–July to September–October. The mean annual rainfall varies between 500 and 800 mm from north to



Source: SRTM 30m; BNDT 2012 (IGB)

Projection: WGS 84

Figure 1 | Location of the NRB and the Bagré dam in Burkina Faso.

south. The Water Resources General Directorate highlighted the presence of more than 400 reservoirs in the NRB (DGRE 2010). The most important reservoirs are Bagré, Ziga, Tougou, Dourou, Loumbila, Bam and Dem (Figure 1).

The Bagré dam was built in 1992 in the downstream part of the NRB. It has a water storage capacity of 1.7 billion m^3, a water surface of 255 km^2, a length of 80 km and a width of 3–4 km (Zoungrana 2007). It is a multipurpose dam whose main purpose is to generate 44 million kWh of hydroelectricity per year, corresponding to 20% of the national electricity demand (Kabore & Bazin 2014). The installed hydropower plant (HPP) has a capacity of 16 MW (two units that operate simultaneously producing 8 MW each during peak periods). The dam is also used for fishery and irrigation water supply of around 6,000 ha of rice cultivation (Zoungrana 2007).

Data collection, quality control and pre-processing

The datasets used in this study are both climate (rainfall, minimum and maximum temperature, the Oceanic Niño Index (ONI)) and hydrological data (inflow, outflow, irrigation, turbined flow, evaporation, water level, Ziga volume and hydropower generation). Table 1 presents the spatial and temporal resolution of the data.

Two sources of rainfall data were used. These include observed and satellite-based data. Observed rainfall and temperature from two synoptic stations (Ouagadougou and Ouahigouya) were provided by the National Meteorological Agency (ANAM), whereas the satellite climate products were from the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) and W5E5. CHIRPS is a quasi-global rainfall dataset comprising in situ station data and satellite imagery to form a gridded precipitation time series at 0.05° horizontal resolution (Funk *et al.* 2015; Ogega *et al.* 2021). W5E5 is a merged dataset. Version 2.0 of the W5E5 dataset combines WFDE5 data over land with ERA5 data over the ocean and covers the entire globe at 0.5° horizontal and daily temporal resolution from 1979 to 2019 (Hersbach *et al.* 2020; Lange *et al.* 2021). The satellite rainfall data were used to supplement the limited stations' data in terms of spatial coverage in the basin. All grid cells are located upstream of the Bagré dam (Figure 1), as inflows and water levels are strongly influenced by rainfall volumes upstream of the dam (Khan & Short 2001).

The ONI was taken from Golden Gate Weather Services (GGWS) at https://ggweather.com/enso/oni.htm. It presents the running 3-month mean SST anomaly for the Niño 3.4 region (5 °N–5 °S, 120°–170 °W). All the other data were collected from the General Directorate of Water Resources (DGRE) and the National Electricity Company (SONABEL) which is in charge of the Bagré dam operation.

Data quality control comprised the identification of missing data in satellite and climate station time series and their comparison in the period 1985–2015. No missing data were found in the time series of the two stations. As suggested by Okafor *et al.* (2017), visual inspection has been used to detect outliers and to ensure internal consistency.

All data have been aggregated at monthly and annual scales. Observational rainfall data were used to validate the satellite rainfall. For this purpose, the CHIRPS and the W5E5 rainfall data were compared to the station's rainfall at the monthly scale

Table 1 | Spatial and temporal resolution of datasets used in the study

Data type		Resolution	Temporal	Spatial	Sources
Rainfall (mm)	Observed	Daily	1985–2015	Ouahigouya	ANAM
	Observed	Daily	1985–2015	Ouagadougou	ANAM
	W5E5	Daily	1985–2015	Bagré Dam Basin	ECMWF
	CHIRPS	Daily	1985–2015	Bagré Dam Basin	USGS
Min and max temperature (°C)	Observed	Daily	1985–2015	Ouahigouya and Ouagadougou	ANAM
ONI		3 Months	1993–2012	5 °N–5 °S, 120°–170°W	GGWS
Evaporation (hm^3)		Monthly	1993–2016	Bagré dam	SONABEL
Inflow (hm^3)		Monthly	1993–2018	Bagré dam	SONABEL
Outflow (hm^3)		Monthly	1993–2018	Bagré dam	SONABEL
Water level (m)		Monthly	1993–2018	Bagré dam	SONABEL
Irrigation (hm^3)		Monthly	1996–2018	Bagré dam	SONABEL
Ziga volume (hm^3)		Daily	2001–2019	Ziga dam	DGRE
Hydropower generation (MWh)		Monthly	1993–2012	Bagré dam	SONABEL

using statistical indicators such as Pearson correlation coefficient (R), Root Mean Square Error (RMSE), Nash–Sutcliffe Efficiency (NSE) and Percentage bias (PBias). The satellite product that showed the best performance (CHIRPS) was used to investigate the mean basin rainfall temporal trend, whereas the stations (Ouagadougou and Ouahigouya) were used to investigate the trend at different locations in the NRB.

Change year detection

Breakpoint detection in hydro-climatic time series helps to identify regime shifts (Badou *et al.* 2017). It aims at detecting abrupt changes, called breakpoints, in the distribution of a signal (Bock *et al.* 2020). Many methods exist for breakpoint detection in climate variability and change studies (Caussinus & Mestre 2004; Mestre *et al.* 2013). The Pettitt's test (Pettitt 1979) considers a sequence of random variables $X1$, $X2$, …, XT, which is said to have a change point at τ if Xt for $t = 1,\ldots, \tau$ have a common distribution function F1(x) and Xt for $t = \tau + 1 ,\ldots, T$ has a common distribution function F2(x), with F1(x) and F2(x) different, but continuous (Rybski & Neumann 2011). In this study, the Pettitt's test and the Standard Normal Homogeneity Test (SNHT) were applied to the hydro-climatic variables (Khaliqa & Ouarda 2007; Gulakhmadov *et al.* 2020).

Trend analysis

Several statistical methods exist for detecting trends in climate variables. These are mainly composed of innovative trend analysis approach (Sen 2012), Cumulative Sum (CUSUM), Mann–Kendall (MK), Bayesian analysis, etc. (Sonali & Kumar 2013). Commonly used is MK (Sonali & Kumar 2013). In this study, the trends of hydro-climatic variables and the hydropower generation were analysed using the Modified MK trend test, a non-parametric trend test used to identify monotonic trends present in time series data (Mann 1945; Sen 1968; Kendall 1975). This statistical method requires no specific distribution of the data (Kendall 1975). The method is robust against outliers (Sanogo *et al.* 2015; Abungba *et al.* 2020) and can cope with missing values and values below the detection limit (Gavrilov *et al.* 2016). It measures the correlation of a variable with time and gives information on the direction, magnitude and significance of observed trends (Koudahe *et al.* 2017; Gulakhmadov *et al.* 2020). More information on the Modified MK test is available in the literature (Hamed & Rao 1998; Hamed 2008; Tabari *et al.* 2011; Gavrilov *et al.* 2016; Pingale *et al.* 2016; Abungba *et al.* 2020; Gulakhmadov *et al.* 2020).

First, all time series were checked for autocorrelation. For cases of auto-correlated data, time series were pre-whitened before the trend computation. All statistical analyses were performed with the R software packages *modifiedmk, hydroGOF, correlation* and *trend*. The trend analysis was performed for annual and monthly time series of rainfall, mean temperature (minimum and maximum), inflow, outflow, irrigation, turbined flow, evaporation, water level, Ziga volume and hydropower generation. Results with a p-value $\leq$0.05 indicate a significant trend while a p-value $>$0.05 indicates an insignificant trend.

Correlation between hydro-climatic variables, ENSO and hydropower generation

Variability in hydro-climatic variables and upstream dam management influences downstream hydrology and hydropower generation (Beilfuss 2012; Annys *et al.* 2020). To assess the relationship between hydro-climatic variables, upstream dam management and hydropower generation, Spearman correlation tests were performed. The Spearman correlation test is a non-parametric test based on the rank and it measures the strength of the monotonic relationship between paired variables (Badou *et al.* 2017). The annual hydropower generation was correlated to annual rainfall sums, annual inflow, annual outflow, annual irrigation, annual mean water level, annual lake evaporation and annual Ziga volume over the period 1993–2012 and 2001–2012 (corresponding to the availability of hydropower generation and Ziga volume data). A 3-month mean basin rainfall, inflow, mean water level, lake evaporation and hydropower standardized anomaly indices were computed and correlated to the 3 months' ENSO index. Spearman *rho* results are interpreted as follows: 0–0.20 is negligible, 0.21–0.40 is weak, 0.41–0.60 is moderate, 0.61–0.80 is strong and 0.81–1.00 is considered a very strong correlation (Prion & Haerling 2014).

RESULTS

Satellite rainfall data validation

At the mean monthly scale over the period 1985–2015, the statistics showed a good correlation between the satellite products and the observed rainfall at the two stations (Table 2). The bias is not very significant, considering ranges from −20 to +20% as an acceptable performance for a satellite product (Cohen *et al.* 2012; Diem *et al.* 2014). As the CHIRPS has a lower bias (1 and −1.9) compared to the W5E5 (3.8 and −8.4), it was chosen to analyse the mean basin rainfall trend.

Table 2 | Comparison statistics of monthly observed rainfall and monthly W5E5 and CHIRPS products at Ouagadougou and Ouahigouya stations

	Ouagadougou		**Ouahigouya**	
Statistics	**W5E5**	**CHIRPS**	**W5E5**	**CHIRPS**
Pearson correlation coefficient (*R*)	0.97	0.98	0.98	0.96
Root Mean Square Error (RMSE)	19.6	15.9	13.9	21.1
Nash–Sutcliffe Efficiency (NSE)	0.94	0.96	0.97	0.93
Percentage bias (PBias)	3.8	1.0	−8.4	−1.9

Trend analysis and change of annual hydro-climatic variables and hydropower generation

The results of the Modified MK trend test are presented in Table 3. All variables showed an increasing trend over their respective considered periods. Rainfall, temperature, inflow, turbined flow, irrigation, Ziga volume and hydropower generation show significant increasing trends at the 95% confidence level, whereas the increasing trends of lake evaporation, outflow and water level were not significant. The annual slopes of rainfall were 5.27 mm over the basin, 6.17 mm at the Ouagadougou station, 8.77 mm at the Ouahigouya station, 68.08 hm^3 for inflow, 17.99 hm^3 for turbined flow, 12.54 hm^3 for irrigation, 2.15 hm^3 for Ziga volume and 2,168 MWh for hydropower generation. The results also show that minimum and maximum temperatures increased significantly by 0.04 °C/year at the Ouagadougou station, whereas the Ouahigouya station recorded a significant annual increasing slope of 0.02 °C. Besides, the results of SNHT showed that all variables experienced break years except mean basin rainfall, inflow and water level, whereas the Pettitt's test showed no break for only water level and maximum temperature at the Ouahigouya station.

Trend analysis of monthly hydro-climatic variables and hydropower generation

The Modified MK trend test was performed for the monthly times series of all variables. Tables 4 and 5 summarize the trend direction, the significance and the slope of each month over the variables and considered periods. Mean basin rainfall

Table 3 | Modified Mann–Kendall, Pettitt's test and SNHT statistics of annual hydro-climatic variables and hydropower in the NRB

	Modified Mann–Kendall trend test			**Pettitt's test**		**SNHT**	
Variables	**trend**	***p*-value**	**Sen's slope**	**change**	**year**	**change**	**year**
Climatic variables							
Mean basin rainfall (mm)	+	0.02^c	5.27	Yes	2007	No	–
Ouagadougou rainfall (mm)	+	0.01^c	6.17	Yes	2007	Yes	2008
Ouagadougou T_{min} (°C)	+	0.000^a	0.04	Yes	1997	Yes	1996
Ouagadougou T_{max} (°C)	+	0.000^a	0.03	Yes	2001	Yes	1995
Ouahigouya rainfall (mm)	+	0.006^b	8.77	Yes	2006	Yes	2006
Ouahigouya T_{min} (°C)	+	0.008^b	0.02	Yes	2003	Yes	2003
Ouahigouya T_{max} (°C)	+	0.03^c	0.02	No	–	Yes	1995
Hydrological variables							
Lake evaporation (hm^3)	+	0.9	0.2	No	–	No	–
Inflow (hm^3)	+	0.01^c	68.08	Yes	2006	No	–
Outflow (hm^3)	+	0.11	0.00	No	–	No	–
Water level (m)	+	0.53	0.01	No	–	No	–
Turbine (hm^3)	+	0.03^c	17.99	Yes	2002	Yes	2002
Irrigation (hm^3)	+	0.000^a	12.54	Yes	2006	Yes	2007
Ziga volume (hm^3)	+	0.007^b	2.15	Yes	2009	Yes	2005
Hydropower generation							
Hydropower generation (MWh)	+	0.002^b	2,168.26	Yes	2002	Yes	2002

Significant codes of confidence level are given as superscript letters: 100% 'a', 99% 'b', 95% 'c'.

Table 4 | Modified Mann–Kendall statistics of monthly climatic variables in the NRB

Climatic variables	Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean basin rainfall (mm)	Trend	+	+	–	–	+	+	+	+	+	+	–	+
	p-value	0.06	0.6	0.59	0.56	0.94	0.69	0.01^{c}	0.10	0.09	0.35	0.27	0.88
	Sen's slope	0.001	0.001	–0.02	–0.08	0.02	0.17	1.90	1.23	0.97	0.21	–0.003	0.0009
Ouagadougou rainfall (mm)	Trend	+	+	+	–	+	+	+	+	+	–	–	–
	p-value	0.24	0.07	0.37	0.34	0.27	0.38	0.05^{c}	0.34	0.04^{c}	0.25	0.39	0.68
	Sen's slope	00	00	00	–0.37	0.56	0.53	1.76	1.07	2.23	–0.48	00	–0.4
Ouagadougou $T_{\min}$ (°C)	Trend	+	+	+	+	+	+	+	+	+	+	+	+
	p-value	0.5	0.06	0.1	0.07	0.02^{c}	0.000^{a}	0.004^{b}	0.001^{b}	0.007^{b}	0.000^{a}	0.11	0.3
	Sen's slope	0.02	0.06	0.03	0.03	0.03	0.06	0.03	0.04	0.02	0.06	0.04	0.03
Ouagadougou $T_{\max}$ (°C)	Trend	+	+	+	+	+	+	+	+	+	+	+	+
	p-value	0.29	0.04^{c}	0.008^{b}	0.11	0.9	0.005^{b}	0.02^{c}	0.05^{c}	0.11	0.08	0.01	0.07
	Sen's slope	0.03	0.05	0.05	0.02	0.001	0.04	0.04	0.02	0.02	0.02	0.04	0.05
Ouahigouya Rainfall (mm)	Trend	+	+	+	+	–	+	+	+	+	+	–	+
	p-value	0.9	0.05^{c}	0.9	0.7	0.5	0.1	0.4	0.29	0.09	0.28	0.29	0
	Sen's slope	00	00	00	00	–0.3	2.03	1.05	2.4	1.97	0.76	00	0
Ouahigouya $T_{\min}$ (°C)	Trend	+	+	+	+	+	+	+	+	+	+	+	+
	p-value	0.7	0.3	0.3	0.04^{c}	0.01^{c}	0.08	0.007^{b}	0.01^{c}	0.3	0.01^{c}	0.09	0.24
	Sen's slope	0.01	0.03	0.02	0.03	0.04	0.02	0.03	0.02	0.009	0.03	0.03	0.03
Ouahigouya $T_{\max}$ (°C)	Trend	+	+	+	+	+	+	+	–	–	–	+	+
	p-value	0.26	0.17	0.004^{b}	0.03^{c}	0.29	0.13	0.8	0.62	0.49	0.78	0.03^{c}	0.2
	Sen's slope	0.03	0.04	0.06	0.03	0.01	0.03	0.001	–0.01	–0.02	–0.007	0.03	0.04

Significant codes of confidence level are given as superscript letters: 100% 'a', 99% 'b', 95% 'c'.

increased from May to October over the period 1985–2015. Only the month of July increases significantly at 99% (Table 4). At the station level, rainfall in Ouagadougou increased significantly in July and September (rainy season), whereas in Ouahigouya a significant increase in February (dry season) is observed. This significant increase of rainfall in the dry season has a negligible annual slope (Table 4) and is therefore not relevant in terms of water balance. The minimum temperature increased in all months at the two stations, whereas the maximum temperature increased differently. In Ouagadougou, the maximum temperature increased for all months, whereas in Ouahigouya, it decreased from August to October, but not significantly.

For lake evaporation, significantly increasing trends were found for September and December, whereas for March, August and October non-significant increasing trends were found. Decreasing lake evaporation trends were found for January, February, April to July and November, but these were not significant. Meanwhile, for inflow, the months of February to November show increasing trends between 1993 and 2018. However, significant trends are only noticed in May, July, August and September. During the same period, decreasing trends of mean lake water levels were found from March to July and increasing trends from August to February. Significant negative trends are observed in May and June while significant positive trends were perceived in September and October. Outflow increased from August to October, with a significant increasing trend of water spill in September. The volume of irrigation water supply increased significantly for all months. The turbined flow and the hydropower generation increased for all months except May and June, which decreased. Turbined flow increased significantly in January, March and July to December while for hydropower generation, the months that showed significant increasing trends are February, March and August–December.

Correlation between hydro-climatic variables, ENSO and hydropower generation

The results of the Spearman correlation test showed that all correlation coefficients between annual hydropower generation and hydro-climatic variables vary from 0.49 to 0.98 (Table 6). The hydropower generated at the Bagré dam over the period 1993–2012 is very strongly correlated to turbined volume, strongly correlated to irrigation, water level outflow and inflow,

Table 5 | Modified Mann–Kendall statistics of monthly hydrological variables in the NRB

Climatic variables	Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Inflow (hm^3)	Trend	***	+	+	+	+	+	+	+	+	+	+	***
	p-value	0	0.1	0.7	0.19	0.003^{b}	0.27	0.03^{c}	0.02^{c}	0.01^{c}	0.2	0.09	0
	Sen's slope	0	0	0	0.09	2.15	1.2	11.99	29.4	26.58	2.36	0	0
Outflow (hm^3)	Trend	***	***	***	***	***	***	***	+	+	+	***	***
	p-value	0	0	0	0	0	0	0	0.13	0.04^{c}	0.84	0	0
	Sen's slope	0	0	0	0	0	0	0	0	0	0	0	0
Water level (m)	Trend	+	+	−	−	−	−	−	+	+	+	+	+
	p-value	0.49	0.6	0.6	0.07	0.03^{c}	0.006^{b}	0.29	0.13	0.017^{c}	0.008^{b}	0.07	0.2
	Sen's slope	0.02	0.01	−0.01	−0.06	−0.086	−0.071	−0.02	0.07	0.09	0.05	0.05	0.05
Lake evaporation (hm^3)	Trend	−	−	+	−	−	−	−	+	+	+	−	+
	p-value	0.82	0.28	0.70	0.53	0.22	0.08	0.63	0.07	0.007^{b}	0.53	0.47	0.02^{c}
	Sen's slope	−0.06	−0.31	0.11	−0.24	−0.30	−0.30	−0.04	0.37	0.30	0.17	−0.21	0.80
Irrigation (hm^3)	Trend	+	+	+	+	+	+	+	+	+	+	+	+
	p-value	0.000^{a}	0.000^{a}	0.000^{a}	0.000^{a}	0.000^{a}	0.000^{a}	0.002^{b}	0.000^{a}	0.000^{a}	0.000^{a}	0.009^{b}	0.005^{b}
	Sen's slope	0.53	1.05	1.57	1.57	1.94	0.67	0.21	0.52	0.74	0.58	0.32	0.32
Turbine (hm^3)	Trend	+	+	+	+	−	−	+	+	+	+	+	+
	p-value	0.02^{c}	0.07	0.02^{c}	0.27	0.41	0.27	0.02^{c}	0.000^{a}	0.000^{a}	0.005^{b}	0.001^{b}	0.001^{b}
	Sen's slope	1.88	1.82	2.40	1.27	−1.15	−0.97	2.31	4.75	4.91	3.78	3.65	3.23
Hydropower generation (MWh)	Trend	+	+	+	+	−	−	+	+	+	+	+	+
	p-value	0.07	0.05^{c}	0.04^{c}	0.58	0.77	0.82	0.20	0.02^{c}	0.001^{b}	0.001^{b}	0.001^{b}	0.01^{c}
	Sen's slope	158.54	166.66	201.34	52.89	−30.36	−16.82	81.75	272.09	427.21	421.42	341.31	270.74

Significant codes of confidence level are given as superscript letters: 100% 'a', 99% 'b', 95% 'c', '***' No trend.

Table 6 | Spearman correlation coefficient between annual hydropower generation and hydro-climatic variables

Hydro-climatic variables	MBR	Infl	Evap	WL	Outf	Irr	Turb
HP	0.49	0.68	0.55	0.73	0.5	0.71	0.98

MBR, mean basin rainfall (mm); Infl, inflow (hm^3); Evap, lake evaporation (hm^3); WL, water level (m); Outf, outflow (hm^3); Irr, irrigation (hm^3); Turb, turbined volume (hm^3); HP, hydropower generation (MWh).

whereas the correlation with mean basin rainfall and lake evaporation is moderate. The results show that with annual increasing inflow and water level, annual hydropower generation also increases. This can be observed in the monthly trends where the simultaneous increase of inflow and water level leads to a significant increase in hydropower generation from August to December (Table 5).

The monthly hydropower generation anomaly is less correlated to the ENSO index (–0.23) (Figure 2) but moderately correlated to water level (0.5) and lake evaporation (0.61). The correlation coefficient between the ENSO index and mean basin rainfall and inflow anomalies is negligible (0.02; −0.05). This indicates the need for further studies on the relationship between ENSO and rainfall variability in West Africa. It shows the necessity to investigate the ENSO indices and classification methods in the prediction of rainfall, inflow and hydropower generation in the study area.

For a detailed investigation of the relationship between monthly hydropower anomaly and the ENSO index, in Figure 3 it can be seen that during El Niño phases in 1997 and 2002, there was a decrease of hydropower generation. In comparison, during La Niña phases in 1999, 2000, 2008–2009 and 2011, there was an increase of hydropower generation. During El Niño events of 1995, 2007 and 2010, the hydropower generation was abundant while it fell short during La Niña years of 1996 and 2006. This necessitates a thorough examination of the reservoir management.

Correlation between Ziga dam volume and hydropower generation

The correlation coefficients between annual and monthly hydropower generation and Ziga dam volume are 0.45–0.5, respectively (Table 7). Both annual and monthly hydropower generation at the Bagré dam over the period 2001–2012 are moderately correlated to Ziga volume. The results show that with monthly or annual increasing volume at the Ziga dam, more water could be released and annual hydropower generation would increase at the Bagré dam.

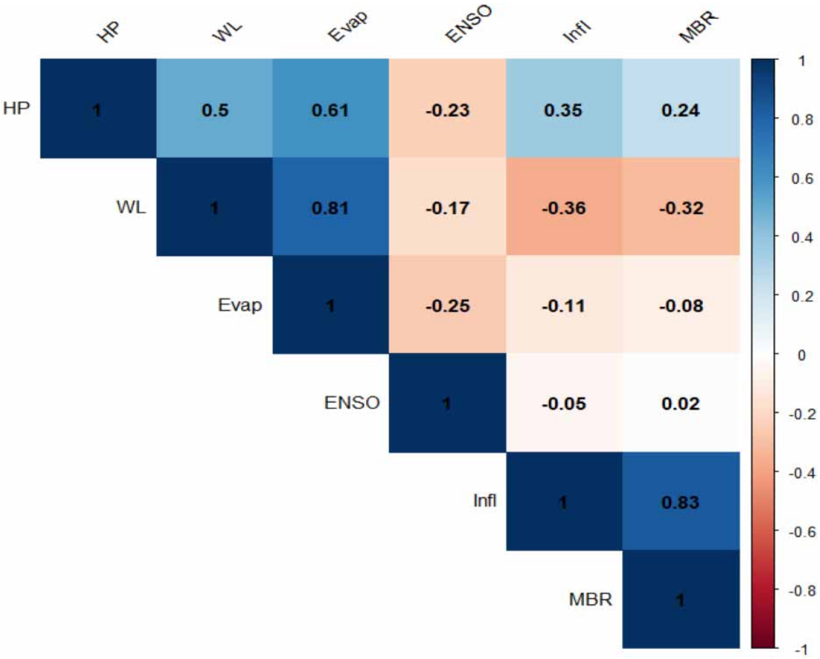


Figure 2 | Correlation coefficients between the hydro-climatic variables, ENSO and hydropower generation anomalies. MBR, mean basin rainfall (mm); Infl, inflow (hm^3); Outf, outflow (hm^3); Evap, lake evaporation (hm^3); WL, water level (m); HP, hydropower generation (MWh).

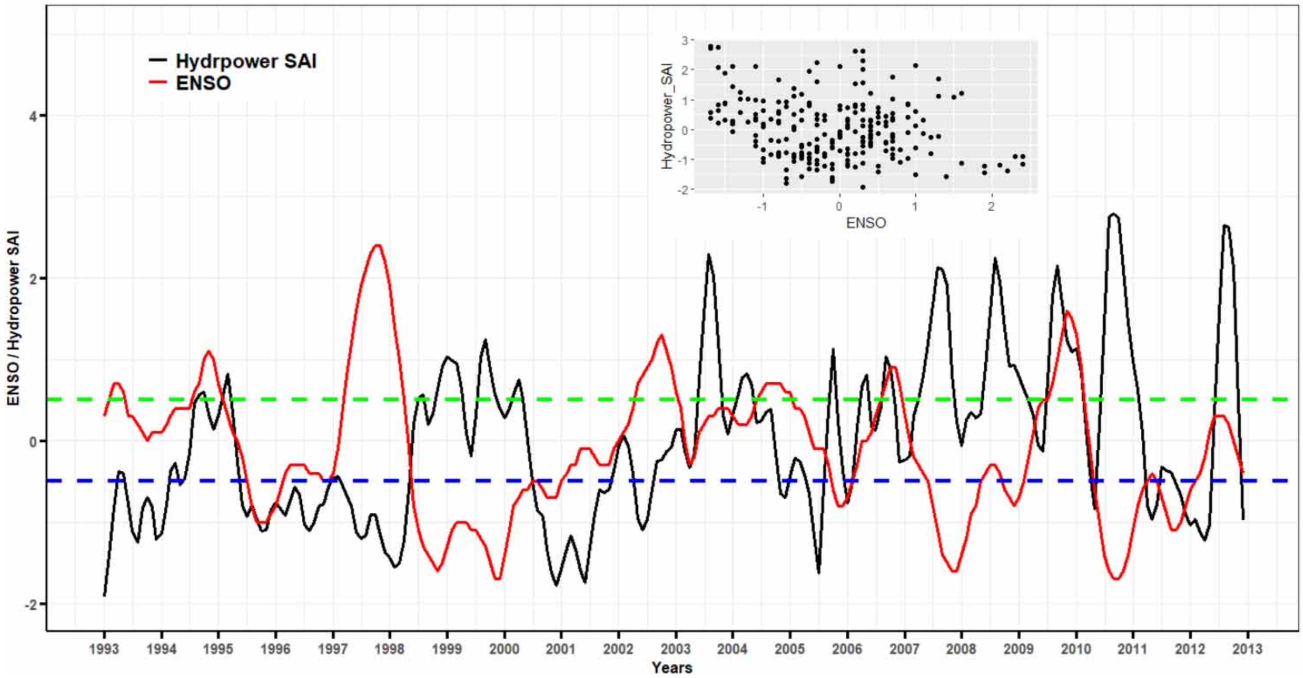


Figure 3 | Comparison of the ENSO index and hydropower generation anomaly. El Niño phases are greater than 0.5 (above the green dash-line); La Niña phases are less than −0.5 (below the blue dash-line). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2022.452.

Table 7 | Spearman correlation coefficient between monthly/annual hydropower generation and Ziga volume

	Ziga volume (hm^3)	
	Monthly	Annual
Hydropower generation (MWh)	0.5	0.45

DISCUSSION

The results in this study show that CHIRPS is the best satellite product compared to W5E5 for rainfall estimation in the NRB. This is confirmed by Dembélé & Zwart (2016) who found that CHIRPS is among the best satellite products for flood monitoring in Burkina Faso. Besides, there was an annual increasing trend for all climatic variables analyzed from 1985 to 2015. The mean basin rainfall increased by 158 mm in 30 years (1985–2015). This increase is higher in the northern (263 mm in Ouahigouya) than in the southern (185 mm in Ouagadougou). As found by Lebel & Ali (2009) and Sanogo *et al.* (2015), after the dry 1970s some parts of West Africa have experienced a return to wetter conditions in the 1990s and 2000s. Several studies are in agreement with the findings from the Modified MK trend test. Sylla *et al.* (2016) found an increasing rainfall trend in Burkina Faso over 1983–2010. A similar study by Ibrahim (2012) also showed that annual rainfall in Burkina Faso increased by about 15% over 1991–2009 compared to 1971–1990. In the Black Volta, the results of the MK trend test showed that annual rainfall increased significantly over 1980–2010 (Aziz & Obuobie 2017).

Although annual rainfall and inflow show a significant positive trend, an increase in annual mean lake water level was found to be not significant. This is a consequence of operator decision-making and dam design specifications (Jia *et al.* 2017). Indeed, outflow and turbined volume increased over 1993–2018. The increase in outflow resulted in flooding recurrence of some villages downstream in Burkina Faso and Ghana (UNEP-GEF Volta Project 2013; Amuquandoh 2016; Manu 2019). Likewise, from 1996 the withdrawals for irrigated areas developed in the downstream are directly taken from the Bagré reservoir, and not utilizable for hydropower generation. This is supported by Yanogo (2012), who indicated that irrigated areas have been developed in the upstream and downstream areas of the Bagré dam since 1997.

The break year detected in hydropower generation in 2002 could be explained by the building of the Ziga dam in 2000. The Ziga dam stores around 200 Mm^3 of rainwater per year. This water is used for irrigation/drinking water supply. To meet the environmental flow needs, a certain amount of water might be released gradually. These releases contribute to a slight increase of inflow at the Bagré dam. This could explain the significant increase in hydropower generation experienced earlier in 2002. In addition, the change in inflow experienced from 2006 is the result of Ziga dam management. Indeed, before 2004, the Ziga dam was used for supplying irrigation water. Since 2005 it is used to supply drinking water to Ouagadougou. Drinking water volumes supplied (up to now) are much lower than irrigation water volumes before 2004 (DGRE 2010). Therefore, Ziga is releasing more water since 2004, i.e. increasing inflow to the Bagré dam. This is in agreement with the result of the break year experienced by Ziga dam volume in 2005.

The overall positive annual trends found for hydro-climatic variables seem to be profitable to hydropower generation at the Bagré dam. The electricity output doubled from 1993 to 2012. The mean electricity output generated by the dam is about 53 GWh per year compared to the predicted 44 GWh per year (Kabore & Bazin 2014). The feasibility study of the dam construction was done in the 1970s when rainfall in the basin was low (Mahe *et al.* 2005). The results of the study are in disagreement with those of Machina & Sharma (2017), who found a decrease in hydropower generation at the Kainji dam (Nigeria) although inflow increased between 2009 and 2011.

On the monthly scale, the study highlighted a decreasing trend of hydropower generation and turbined volume in May and June. This is mainly due to prioritization of agricultural activities. Indeed, irrigation withdrawals increased significantly in May and June, with May being the month recording the highest slope (1.94 hm^3/year). In fact, during these months the evapotranspiration is high due to a combined increase of the minimum and maximum temperatures (Table 4), as also observed in the neighboring Black Volta Basin (Neumann *et al.* 2007; Abungba *et al.* 2020) and over West Africa (Oguntunde & Abiodun 2012; Kabo-Bah *et al.* 2016; Touré *et al.* 2017; Koubodana *et al.* 2020). This led to more water stress of crops and the need for additional irrigation withdrawals, driving down water levels, although an increase of inflow is observed in May and June. These months also correspond, respectively, to the cessation of the dry season and the onset of the rainy season in the Sahel region (Sanogo *et al.* 2015), where many water bodies are almost dried out. The strong correlation coefficients between irrigation (0.73), water level (0.72) and inflow (0.68) with hydropower generation confirm the above-mentioned explanation. Several studies also confirmed that the variability of rainfall, inflow and water level influenced hydropower generation (Kaunda *et al.* 2012; Kabo-Bah *et al.* 2016; Boadi and Owusu 2017; Perera & Rathnayake 2019). Interestingly, hydropower generation is less correlated with mean basin rainfall (0.49) which should be the main driver for inflows. This situation is due to the presence of several small dams in the upstream basin (Mahe *et al.* 2005; Karambiri *et al.* 2011). As Ziga dam management is moderately correlated to hydropower, these multiple reservoirs may have also impacted the inflow at the Bagré dam. This indicates the need for further studies on the role of land cover and land use changes in runoff generation in the NRB, as Mahe *et al.* (2002) also found an increase of runoff in the upper NRB at the Wayen station in the 1990s, but a decrease of rainfall.

Furthermore, hydropower generation anomaly is significantly correlated to the ENSO index (p-value <0.05). This finding is also supported by Jia *et al.* (2017), who stated that hydropower generation correlates significantly with the multivariate ENSO Index for 27% of reservoirs in the world. Moreover, Boadi & Owusu (2017), using 5-month running mean of spatially averaged SST anomalies over the tropical Pacific (4 °S–4 °N, 150 °W–90 °W), found that ENSO is significantly correlated to hydropower generation at the Akosombo plant in the lowermost part of the Volta basin from 1991 to 2010. They further emphasized that the ENSO index is a good predictor for hydropower generation at the Akosombo plant, although the strength of the correlation between hydropower generation anomaly and the ENSO index found in the NRB is weak (−0.2). This is explained by the low correlation between hydropower generation and rainfall. This low correlation could be due to the datasets used and the method of hydro-climatic variables' anomalies calculation. In fact, the magnitude of hydro-climatic anomalies could change significantly depending on the dataset used, the method of anomalies estimation and the phase of ENSO (Salas Parra 2020). It could also be due to the short records of hydropower generation (1993–2012) as it limits the prospects for finding robust ENSO-driven anomalies in hydropower generation (Jia *et al.* 2017).

CONCLUSIONS

This study investigated how hydro-climatic trends and upstream dam management in the NRB in West Africa during the period 1993–2018 influenced hydropower generation at the Bagré dam. On the annual scale, all hydro-climatic variables increased significantly except for water level, lake evaporation and outflow. This increase, combined with the construction of the Ziga dam and its management change, impacted positively the yearly inflow and hydropower generation at the Bagré dam. However, the monthly trend analysis showed that hydropower generation decreases each May and June due to the significant increase in water withdrawals for irrigation. The results ultimately show that annual hydro-climatic variables can moderately be used to predict hydropower generation. But at the monthly scale, only water level and lake evaporation can be moderately relied on to predict hydropower generation at the Bagré dam. Upstream water management plays an important role in the hydropower generation at the Bagré dam. SONABEL and ONEA (National Water and Sanitation Company) who are in charge of the operation of Bagré and Ziga dams, respectively, should work closely in order to maximize dams' management for hydropower generation, irrigation and water supply. However, as the climate and land-use change simultaneously occur in the basin, further studies, combining impacts of climate and land use/cover changes on the hydropower generated at the Bagré dam, should be undertaken.

ACKNOWLEDGEMENTS

This study forms part of a PhD research under the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) program of Climate Change and Water Resources at the University of Abomey-Calavi, Republic of Benin and funded by the German Ministry of Education and Research (BMBF).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

REFERENCES

Abungba, J. A., Khare, D., Pingale, S. M., Adjei, K. A., Gyamfi, C. & Odai, S. N. 2020 Assessment of hydro-climatic trends and variability over the Black Volta Basin in Ghana. *Earth Systems and Environment* **4** (4), 739–755. https://doi.org/10.1007/s41748-020-00171-9.

Alsaleh, M., Abdulwakil, M. M. & Abdul-Rahim, A. S. 2021 Land-use change impacts from sustainable hydropower production in EU28 region: an empirical analysis. *Sustainability (Switzerland)* **13** (9). https://doi.org/10.3390/su13094599.

Amuquandoh, M. K. 2016 *An Assessment of the Effects of the Bagré Hydro Dam Spillage on Ghana-Burkina Faso Relations*. *Master Thesis*, International Affairs; University of Legon, Ghana. Available from: http://ugspace.ug.edu.gh/handle/123456789/27435.

Annys, S., Ghebreyohannes, T. & Nyssen, J. 2020 Impact of hydropower dam operation and management on downstream hydrogeomorphology in semi-arid environments (Tekeze, Northern Ethiopia). *Water (Switzerland)* **12** (8), 2237. https://doi.org/10.3390/w12082237.

Aziz, F. & Obuobie, E. 2017 Trend analysis in observed and projected precipitation and mean temperature over the Black Volta Basin, West Africa. *International Journal of Current Engineering and Technology* **7** (4), 2. Available from: http://inpressco.com/category/ijcet.

Badou, D. F., Kapangaziwiri, E., Diekkrüger, B., Hounkpè, J. & Afouda, A. 2017 Evaluation of recent hydro-climatic changes in four tributaries of the Niger River Basin (West Africa). *Hydrological Sciences Journal* **62** (5), 715–728. https://doi.org/10.1080/02626667.2016.1250898.

Beilfuss, R. 2012 *A Risky Climate for Southern African Hydro: Addressing Hydrological Risks and Consequences for Zambezi River Basin Dams*. International Rivers, Berkeley, CA. Available from: https://www.oieau.fr/eaudoc/system/files/32987.pdf.

Birkinshaw, S. J., Guerreiro, S. B., Nicholson, A., Liang, Q., Quinn, P., Zhang, L., He, B., Yin, J. & Fowler, H. J. 2017 Climate change impacts on Yangtze River discharge at the Three Gorges Dam. *Hydrology and Earth System Sciences* **21** (4), 1911–1927. https://doi.org/10.5194/hess-21-1911-2017.

Boadi, S. A. & Owusu, K. 2017 Impact of climate change and variability on hydropower in Ghana. *African Geographical Review* **38** (1), 19–31. https://doi.org/10.1080/19376812.2017.1284598.

Bock, O., Collilieux, X., Guillamon, F., Lebarbier, E. & Pascal, C. 2020 A breakpoint detection in the mean model with heterogeneous variance on fixed time intervals. *Statistics and Computing* **30** (1), 195–207. https://doi.org/10.1007/s11222-019-09853-5.

Boretti, A. & Rosa, L. 2019 Reassessing the projections of the world water development report. *npj Clean Water* **2** (1). https://doi.org/10.1038/s41545-019-0039-9.

Caussinus, H. & Mestre, O. 2004 Detection and correction of artificial shifts in climate series. *Journal of the Royal Statistical Society: Series C (Applied Statistics)* **53** (3), 405–425. https://doi.org/10.1111/j.1467-9876.2004.05155.x.

Chien, H., Yeh, P. J. F. & Knouft, J. H. 2013 Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the Midwestern United States. *Journal of Hydrology* **491** (1), 73–88. https://doi.org/10.1016/j.jhydrol.2013.03.026.

Cohen, L. T., Matos, J. P., Boillat, J. L. & Schleiss, A. J. 2012 Comparison and evaluation of satellite derived precipitation products for hydrological modeling of the Zambezi River Basin. *Hydrology and Earth System Sciences* **16**, 489–500. https://doi.org/10.5194/hess-16-489-2012.

Dembélé, M. & Zwart, S. J. 2016 Evaluation and comparison of satellite-based rainfall products in Burkina Faso, West Africa. *International Journal of Remote Sensing* **37** (17), 3995–4014. https://doi.org/10.1080/01431161.2016.1207258.

DGRE 2010 *Etat des Lieux de la Gestion des Ressources en eau du Bassin du Nakanbé: Rapport Final*. Available from: https://eaunakanbe.bf/wp-content/uploads/2019/06/Rapport-etat-des-lieux-des-RE-du-Nakanbé-de-2010-Final.pdf.

Dias, V. D. S., Pereira, M., Medero, G. M., Tarley, D. & Nascimento, F. 2018 An overview of hydropower reservoirs in Brazil: current situation, future perspectives and impacts of climate change. *Water* **10**, 592. https://doi.org/10.3390/w10050592.

Diem, J. E., Hartter, J., Ryan, S. J. & Palace, M. W. 2014 Validation of satellite rainfall products for western Uganda. *Journal of Hydrometeorology* **15** (5), 2030–2038. https://doi.org/10.1175/JHM-D-13-0193.1.

DSB 2011 *Trends and Implications of Climate Change for National and National and International Security*. DOD Office of Security, Washington, D.C. 20301-3140.

Frumhoff, P. C., Burkett, V., Jackson, R. B., Newmark, R., Overpeck, J. & Webber, M. 2015 Vulnerabilities and opportunities at the nexus of electricity, water and climate. *Environmental Research Letters* https://doi.org/10.1088/1748-9326/10/8/080201.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. & Michaelsen, J. 2015 The climate hazards infrared precipitation with stations – a new environmental record for monitoring extremes. *Scientific Data* **2** (1), 150066. https://doi.org/10.1038/sdata.2015.66.

Gavrilov, M. B., Tošić, I., Marković, S. B., Unkašević, M. & Petrović, P. 2016 Analysis of annual and seasonal temperature trends using the Mann-Kendall test in Vojvodina, Serbia. *Idojaras* **120** (2), 183–198. https://doi.org/10.2298/TSCI150207062G.

Gulakhmadov, A., Chen, X., Gulahmadov, N., Liu, T., Davlyatov, R., Sharofiddinov, S. & Gulakhmadov, M. 2020 Long-term hydro–climatic trends in the Mountainous Kofarnihon River Basin in Central Asia. *Water* **12** (8), 2140. https://doi.org/10.3390/w12082140.

Hamed, K. H. 2008 Trend detection in hydrologic data: the Mann-Kendall trend test under the scaling hypothesis. *Journal of Hydrology* **349** (3–4), 350–363. https://doi.org/10.1016/j.jhydrol.2007.11.009.

Hamed, K. H. & Rao, A. R. 1998 A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology* **204** (182), 196. https://doi.org/10.1200/JCO.2018.36.15_suppl.522.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M. & Thépaut, J. N. 2020 The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* **146** (730), 1999–2049. https://doi.org/10.1002/qj.3803.

Ibrahim, B. 2012 *Caractérisation des saisons de pluies au Burkina Faso dans un contexte de changement climatique et évaluation des impacts hydrologiques sur le bassin du Nakambé. Thèse de doctorat en Hydrologie*, Université Pierre et Marie Curie – Paris VI, France. Available from: https://tel.archives-ouvertes.fr/tel-00827764.

Ibrahim, M., Djibo, A. G. & Afouda, A. 2016 Recent trend analysis of hydro-climatic data in the upper and Niger Inland Delta of the Niger River basin (West Africa). *International Journal of Current Engineering and Technology* **6** (6), 2167–2177. Available from: http://inpressco.com/category/ijcet.

IPCC 2021 Climate Change 2021. In: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. & Zhou, B., eds.). Cambridge University Press, Cambridge, UK.

Jia, Y. N., Turner, S. W. D. & Galelli, S. 2017 Influence of El Niño Southern Oscillation on global hydropower production. *Environmental Research Letters* **12** (3). https://doi.org/10.1088/1748-9326/aa5ef8.

Kabo-Bah, A., Diji, C., Nokoe, K., Mulugetta, Y., Obeng-Ofori, D. & Akpoti, K. 2016 Multiyear rainfall and temperature trends in the Volta River Basin and their potential impact on hydropower generation in Ghana. *Climate* **4** (49), 1–17. https://doi.org/10.3390/cli4040049.

Kabore, E. & Bazin, F. 2014 *Evaluation économique ex-post du barrage de Bagré au Burkina Faso*. Available from: https://pubs.iied.org/sites/default/files/pdfs/migrate/G04006.pdf.

Karambiri, B. L. C. N. 2017 *Variabilité Climatique et Gestion Intégrée des Ressources en Eau Dans le Bassin-Versant du Sourou au Burkina Faso*. *Thèse de doctorat unique en Géographie*, Université Ouaga I Pr Joseph Ki Zerbo, Burkina Faso.

Karambiri, H., García Galiano, S. G., Giraldo, J. D., Yacouba, H., Ibrahim, B., Barbier, B. & Polcher, J. 2011 Assessing the impact of climate variability and climate change on runoff in West Africa: the case of Senegal and Nakambé River basins. *Atmospheric Science Letters* **12** (1), 109–115. https://doi.org/10.1002/asl.317.

Kaunda, C. S., Kimambo, C. Z. & Nielsen, T. K. 2012 Potential of small-scale hydropower for electricity generation in Sub-Saharan Africa. *ISRN Renewable Energy* **15**. https://doi:10.5402/2012/132606.

Kendall, M. G. 1975 *Rank Correlation Methods*, 4th edn. Charles Griffin, London, England.

Khalid, S., Azad, S., Naz, A., Ur Rahman, Z. & Iqbal, A. 2017 Climate change: a review of the current trends and major environmental. *Science, Technology and Development* **36** (3), 160. 176. https://doi.org/10.3923/std.2017.160.176.

Khaliqa, M. N. & Ouarda, T. B. M. J. 2007 The impact of the positive Indian Ocean dipole on Zimbabwe droughts Tropical climate is understood to be dominated by. *International Journal of Climatology* **27**, 2011–2029. https://doi.org/10.1002/joc.

Khan, S. & Short, L. 2001 *Assessing the Impact of Rainfall Variability on Water Tables in Irrigation Areas*. Technical report; Griffith Laboratory, Research Station Road, Griffith, NSW, 2680. https://citeseerx.ist.psu.edu/viewdoc/download?doi = 10.1.1.936.2294&rep=rep1&type=pdf.

Koubodana, H. D., Adounkpe, J., Tall, M., Amoussou, E., Atchonouglo, K. & Mumtaz, M. 2020 Trend analysis of hydro-climatic historical data and future scenarios of climate extreme indices over Mono River Basin in West Africa. *American Journal of Rural Development* **8** (1), 37–52. https://doi.org/10.12691/ajrd-8-1-5.

Koudahe, K., Kayode, A. J., Samson, A. O., Adebola, A. A. & Djaman, K. 2017 Trend analysis in standardized precipitation index and standardized anomaly index in the context of climate change in Southern Togo. *Atmospheric and Climate Sciences* **07** (04), 401–423. https://doi.org/10.4236/acs.2017.74030.

Lange, S., Menz, C., Gleixner, S., Cucchi, M., Weedon, G. P., Amici, A., Bellouin, N., Müller Schmied, H., Hersbach, H., Buontempo, C. & Cagnazzo, C. 2021 WFDE5 over land merged with ERA5 over the ocean (W5E5 v2.0). ISIMIP Repository. https://doi.org/10.48364/ISIMIP.342217.

Lebel, T. & Ali, A. 2009 Recent trends in the central and western sahel rainfall regime (1990–2007). *Journal of Hydrology* **375** (1–2), 52–64. https://doi:10.1016/j.jhydrol.2008.11.030.

Liu, B., Lund, J. R., Liu, L., Liao, S., Li, G. & Cheng, C. 2020 Climate change impacts on hydropower in Yunnan, China. *Water* **12** (197), 1–20. https://doi:10.3390/w12010197.

Machina, B. M. & Sharma, S. 2017 Assessment of climate change impact on hydropower generation: a case study of Nigeria. *International Journal of Engineering Technology Science and Research* **4** (8), 753–762. Available from: http://www.ijetsr.com/images/short_pdf/1503180983_753-762-baba_ijetsr.pdf.

Mahe, G., Dray, A., Paturel, J. E., Cres, A., Koné, F., Manga, M., Crès, F. N., Djoukam, J., Maiga, A. A. H., Ouedraogo, M., Conway, D. & Servat, E. 2002 Climatic and anthropogenic impacts on the flow regime of the Nakambé River in Burkina. In: *FRIEND 2002 Regional Hydrology: Bridging the gap Between Research and Practice*, Vol. 274. IAHS Pub., pp. 69–76. Available from: http://hydrologie.org/redbooks/a274/iahs_274_069.pdf.

Mahe, G., Paturel, J. E., Servat, E., Conway, D. & Dezetter, A. 2005 The impact of land use change on soil water holding capacity and river flow modelling in the Nakambé River, Burkina-Faso. *Journal of Hydrology* **300** (1–4), 33–43. https://doi.org/10.1016/j.jhydrol.2004.04.028.

Mann, H. 1945 Nonparametric tests against trend. *Econometrica* **13** (3), 245–259.

Manu, D. K. 2019 *Assessing the Impact of Bagré dam Spillage in the Pru East District of Brong Ahafo Region. Master Thesis of Technology*, University of Education, Winneba, Ghana. Available from: http://ir.uew.edu.gh/xmlui/handle/123456789/2218.

MEFR 2015 *Burkina Faso National Adaptation Plan (NAP)*. Final Report. Available from: https://www4.unfccc.int/sites/NAPC/Documents/Parties/BurkinaFasoNAP_English.pdf.

Mestre, O., Domonkos, P., Picard, F., Auer, I., Robin, S., Lebarbier, E., Böhm, R., Aguilar, E., Guijarro, J., Vertachnik, G., Klancar, M., Dubuisson, B. & Stepanek, P. 2013 HOMER: A homogenization software – methods and applications. *Idojaras* **117** (1), 47–67.

Michelle, T. H., Wietse, H. P., John, R. Y., Fulco, L., Ingjerd, H., Dennis, P. L. & Pavel, K. 2013 Global river discharge and water temperature under climate change. *Global Environmental Change* **23** (2), 450–464. https://doi.org/10.1016/j.gloenvcha.2012.11.002.

Mousavi, R., Ahmadizadeh, M. & Marofi, S. 2018 A multi-GCM assessment of the climate change impact on the hydrology and hydropower potential of a semi-arid basin (a case study of the Dez Dam Basin, Iran). *Water* **10** (10), 1458. http://dx.doi.org/10.3390/w10101458.

Neumann, R., Jung, G., Laux, P. & Kunstmann, H. 2007 Climate trends of temperature, precipitation and river discharge in the Volta basin of West Africa. *International Journal of River Basin Management* **5** (1), 17–30. https://doi.org/10.1080/15715124.2007.9635302.

Obahoundje, S. & Diedhiou, A. 2022 Potential impacts of climate, land use and land cover changes on hydropower generation in West Africa: a review. *Environmental Research Letters* **17** (4), 043005. https://doi.org/10.1088/1748-9326/ac5b3b.

Obahoundje, S., Diedhiou, A., Ofosu, E. A., Anquetin, S., François, B., Adounkpe, J., Amoussou, E. & Kouame, Y. M. 2018 Assessment of spatio-temporal changes of land use and land cover over south-western African basins and their relations with variations of discharges. *Hydrology* **5** (56). https://doi.org/10.3390/hydrology5040056.

Ogega, O. M., Mbugua, J., Misiani, H. O., Nyadawa, M., Scoccimarro, E. & Endris, H. S. 2021 Detection and attribution of lake Victoria's water-level fluctuations in a changing climate. *Preprints* **2021070575**. https://doi.org/10.20944/preprints202107.0575.v1.

Oguntunde, P. G. & Abiodun, B. J. 2012 The impact of climate change on the Niger River Basin hydroclimatology, West Africa. *Climate Dynamics* **40** (1–2), 81–94. https://doi.org/10.1007/s00382-012-1498-6.

Okafor, G. C., Jimoh, O. D. & Larbi, K. I. 2017 Detecting changes in hydro-climatic variables during the last four decades (1975–2014) on downstream Kaduna River Catchment, Nigeria. *Atmospheric and Climate Sciences* **07** (02), 161–175. https://doi.org/10.4236/acs.2017.72012.

Okudzeto, E., Mariki, W. A., Paepe, G. D. & Sedegah, K. 2014 *Ghana 2014*. Available from: http://www.africaneconomicoutlook.org/fileadmin/uploads/aeo/2014/PDF/CN_Long_EN/Ghana_ENG.pdf.

Olaka, L. A., Ogutu, J. O., Said, M. Y. & Oludhe, C. 2019 Projected climatic and hydrologic changes to Lake Victoria Basin Rivers under three RCP emission scenarios for 2015–2100 and impacts on the water sector. *Water (Switzerland)* **11** (7). https://doi.org/10.3390/w11071449.

Perera, A. & Rathnayake, U. 2019 Impact of climate variability on hydropower generation in an un-gauged catchment: erathna run-of-the-river hydropower plant, Sri Lanka. *Applied Water Science* **9** (3). https://doi.org/10.1007/s13201-019-0925-9.

Pettitt, A. N. 1979 A non-parametric approach to the change-point problem. *Journal of the Royal Statistical Society. Series C (Applied Statistics)* **28** (2), 126–135. http://doi.org/10.2307/2346729.

Pingale, S. M., Khare, D., Jat, M. K. & Adamowski, J. 2016 Trend analysis of climatic variables in an arid and semi-arid region of the Ajmer District, Rajasthan, India. *Journal of Water and Land Development* **28** (1), 3–18. https://doi.org/10.1515/jwld-2016-0001.

Prion, S. & Haerling, K. A. 2014 Making sense of methods and measurement: spearman-rho ranked-order correlation coefficient. *Clinical Simulation in Nursing* **10** (10), 535–536. https://doi.org/10.1016/j.ecns.2014.07.005.

Rybski, D. & Neumann, J. 2011 A Review on the Pettitt Test. In: *Extremis* (Kropp, J. & Schellnhuber, H. J., eds.). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-14863-7_10.

Salas Parra, H. D. 2020 *Synchronization and Interdependence Between the Cycles of Colombia's Hydroclimatology and El Nino-Southern Oscillation*. *PhD Thesis*, Universidad Nacional de Colombia, Colombia. Available from: https://repositorio.unal.edu.co/handle/unal/78420.

Sankarasubramanian, A. & Vogel, R. M. 2003 Hydroclimatology of the continental United States. *Geophysical Research Letters* **30** (7), 1363. https://doi:10.1029/2002GL015937.

Sanogo, S., Fink, A. H., Omotosho, J. A., Ba, A., Redl, R. & Ermert, V. 2015 Spatio-temporal characteristics of the recent rainfall recovery in West Africa. *International Journal of Climatology* **35** (15), 4589–4605. https://doi.org/10.1002/joc.4309.

Sen, P. 1968 Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* **63** (324), 1379–1389. https://doi:10.1080/01621459.1968.10480934.

Sen, Z. 2012 An innovative trend analysis methodology. *Journal of Hydrologic Engineering* 1943–5584. http://dx.doi.org/10.1061.

Sonali, P. & Kumar, N. D. 2013 Review of trend detection methods and their application to detect temperature changes in India. *Journal of Hydrology* **476**, 212–227. https://doi.org/10.1016/j.jhydrol.2012.10.034.

Sridharan, V., Broad, O., Shivakumar, A., Howells, M., Boehlert, B., Groves, D. G., Rogner, H., Taliotis, C., Neumann, J. E. & Strzepek, K. M. 2019 Resilience of the Eastern African electricity sector to climate driven changes in hydropower generation. *Nature Communications* **10**, 302. https://doi.org/10.1038/s41467-018-08275-7.

Stanzel, P., Kling, H. & Bauer, H. 2018 Climate change impact on West African rivers under an ensemble of CORDEX climate projections. *Climate Services* **11** (April), 36–48. https://doi.org/10.1016/j.cliser.2018.05.003.

Sylla, M. B., Nikiema, P. M., Gibba, P., Kebe, I. & Klutse, N. A. B. 2016 Climate Change over West Africa: Recent Trends and Future Projections. In: *Adaptation to Climate Change and Variability in Rural West Africa* (Yaro, J. & Hesselberg, J., eds.). Springer, Cham. https://doi.org/10.1007/978-3-319-31499-0_3.

Tabari, H., Marofi, S., Aeini, A., Talaee, P. H. & Mohammadi, K. 2011 Trend analysis of reference evapotranspiration in the western half of Iran. *Agricultural and Forest Meteorology* **151** (2), 128–136. https://doi.org/10.1016/j.agrformet.2010.09.009.

Tazen, F., Yacouba, H., Karambiri, H., Barbier, B., Paturel, J. E. & Boubacar, I. 2012 Impacts des Scenarii Climatique et de l'occupation des Sols sur les Ressources En Eau du Bassin Versant Du Nakanbe (Burkina Faso). *Climat et Développement* **14**, 123–137.

Thiombiano, A. N. 2011 *Variabilité Climatique et Impacts sur les Ressources en eau au Burkina Faso: étude de cas du Bassin Hydrographique du Fleuve Nakambé*. *Master Thesis in environment*, Université de Moncton, Canada. Available from: https://www.collectionscanada.gc.ca/obj/thesescanada/vol2/002/MR81178.PDF?is_thesis=1&oclc_number=812063916.

Touré, H. A., Kalifa, T. & Kyei-Baffour, N. 2017 Assessment of changing trends of daily precipitation and temperature extremes in Bamako and Ségou in Mali from 1961–2014. *Weather and Climate Extremes* **18** (5), 8–16. https://doi.org/10.1016/j.wace.2017.09.002.

UNEP-GEF Volta Project. 2013 *Volta Basin Transboundary Diagnostic Analysis*. Available from: http://gefvolta.iwlearn.org/project-resources/studies-reports/tda-final/regional-tda/volta-basin-tda-english.

WMO 2021 *State of the Global Climate 2021*. Available from: https://library.wmo.int/doc_num.php?explnum_id=10859

Yanogo, P. I. 2012 *Les Stratégies D'Adaptation Des Populations Aux Aléas Climatiques Autour Du Lac Bagré (Burkina Faso)*. PhD Thesis in Geography, Université Abomey Calavi, Benin.

Zoungrana, T. P. 2007 Problématique de l'accès à l'eau potable sur les rives du lac de Bagré, Burkina Faso. *Rev. Sc. Env. Univ.* (Togo), no 003 ISSN 1812-1413. Available from: https://www.academia.edu/30747796/Probl%C3 %A9matique_de_lacc%C3 %A8s_%C3 %A0_leau_potable_sur_les_rives_du_lac_Bagr%C3 %A9_Burkina_FAso.

First received 4 December 2021; accepted in revised form 5 May 2022. Available online 19 May 2022