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Analysis of hydroclimatic trends and variability and their impacts on hydropower generation in two river basins in Côte d'Ivoire (West Africa) during 1981–2017

Salomon Obahoundje[1,9,*], Arona Diedhiou[1,2], Kouakou Lazare Kouassi[3], Marc Youan Ta[4], Eric Mensah Mortey[5,6], Philippe Roudier[7] and Didier Guy Marcel Kouame[8]

[1] LASMES-African Centre of Excellence on Climate Change, Biodiversity and Sustainable Development,Université Félix Houphouët Boigny, 22 B.P. 582 Abidjan 22, Abidjan, Ivory Coast
[3] University Grenoble Alpes, IRD, CNRS, Grenoble INP, IGE, Grenoble F-38000, France
[3] UFR-Environnement, Université Jean Lorougnon GUEDE, 12 BP V 25 DALOA 12, Daloa, Ivory Coast
[4] CURAT (Centre Universitaire de Recherche et d'Application en Télédétection), Université Félix Houphouët Boigny, 22 BP 801 Abidjan 22, Abidjan, Ivory Coast
[5] Doctoral Research Program in Climate Change and Energy (DRP-CCE) of the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL), Faculty of Science and Techniques (FAST), Universite Abdou Moumouni (UAM), PO Box 10662, Niamey 8000, Niger
[6] Earth Observation Research and Innovation Center (EORIC), University of Energy and Natural Resources (UENR), P.O. Box 214, Sunyani, Ghana
[7] Innovation, Research and Knowledge Department, Agence Française de Développement, Paris, France
[8] Ivory Coast National Company of Electricity (CIE), 01 BP 6923 Abidjan 01, Côte D'Ivoire
[9] World Energy and Meteorology Council, The Enterprise Centre, University of East Anglia, Norwich NR4 7TJ, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: arona.diedhiou@ird.fr, k_lazare@yahoo.fr, youanta@yahoo.fr, morteyeric@gmail.com, roudierp@afd.fr, mgdkouame@cie.ci and obahoundjes@yahoo.com

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Abstract

Climate change (CC) and variability impacts on hydroelectric generation have become critical for hydropower management. The trends of inflow, outflow, reservoir water level, and storage as well as hydraulicity indices of three main dams in Côte d'Ivoire, namely Kossou and Taabo in the Bandama basin and Buyo in the Sassandra basin were examined during 1981–2017 and their impacts on hydropower generation were analyzed. Moreover, the hydropower generation sensitivity to CC of these dams was assessed using statistical analysis. The results reveal that the inflow is highly dependent on rainfall while the water level is highly influenced by the outflow, which is a function of the inflow to the reservoirs and water management policy. Furthermore, the Mann Kendall test revealed that temperature and potential evapotranspiration have increased significantly in all three sub-basins while precipitation shows a significant upward trend only within the Taabo dam catchment area. Meanwhile, inflow to reservoir increased significantly and greatly than precipitation probably due to land use/cover change. Precipitation and inflow show a strong correlation as energy generation is significantly and strongly correlated to outflow (inflow) in all stations (except Kossou). Furthermore, the energy generation at Buyo and Taabo dams is more sensitive to reservoir inflow, while that of Kossou dam is more affected by water level. In addition, the power of a given year is also dependent on the total rainfall of that year and/or the previous year depending on the plant.

1. Introduction

The fast demographic and socio-economic growth in Africa has resulted in increased energy demand and consumption [1]. To meet the growth in energy demand, energy production sources have increased. However, energy generation has been proven by scientists to be a contributor to global warming and global change [2], hence the recommendations to use renewable energy to combat climate change [3]. Hydropower is the main renewable energy source globally [4], in West Africa (WA) and is identified as a major source to mitigate and adapt to climate change. Hydropower is a flexible, reliable, cost-effective, and clean source of energy that could help to reduce greenhouse gas emissions from electricity generation [5]. This source has recorded rapid growth over the world, especially in West African countries [4]. However, in WA, there is a 19% gap between actual and technically feasible hydropower potential, [6]. Côte d'Ivoire and other West African countries have unexploited hydropower capacity [4] which could increase access to electricity if they are all put into contribution.

For instance, in Côte d'Ivoire, hydropower energy represents about 94% and 21% of the total electricity consumption of the country in 1981 and 2017 respectively. The hydropower energy occupies more than 95% share of renewable energy generation of the country. In Côte d'Ivoire's Third National Communication to the United Nations Framework Convention on Climate Change, a 'low emission scenario by 2030' where the projected share of hydropower production is 26% [7] is envisaged. However, the main challenge is, hydropower depends on water availability which is a function of the climate. Hydropower systems may be highly vulnerable to the changing climatic conditions, effects, and impacts [8] such as changes in precipitation, extremes events, and rising temperatures. Thus, any change or variability in climate factors could be challenging to hydropower plants [9, 10].

The impacts of climate change on hydropower development are complex [11]. Indeed, hydropower plants rely heavily on water available in a reservoir or in the river which depends both on climate and other water-consuming sectors upstream of the hydropower dam. Thus changes in river flow [12] could be a threat to the hydropower facility [13]. Climate change could create conflict among water users within a basin, a country, and a region [14, 15]. Besides, river flow dynamics caused by changes in the hydrologic cycle as a result of changing climate conditions, and change in upstream anthropic water usage (domestic, agriculture, livestock, industry), as well as land use/cover change could burden water availability [16].

Water availability depends mainly on precipitation and potential evapotranspiration (PET) which is a function of temperature, wind, radiation, etc. Changes in precipitation and temperature have a hydrological implication which could affect the water availability for power generation [17, 18]. Extreme events such as drought and flooding can also impact hydropower generation. It has been reported that hydropower has been impacted in the past and is projected to be affected in the future in many regions all over the world, e.g. in California [19], Brazil [20, 21], China [22], India [23, 24], Zambia [25], South Africa, Cameroon [26] and Ghana [27, 28] due to climate variability or frequent occurrence of extremes events. Climate change impacts on hydropower facilities are responsible for draw-down in reservoirs leading sometimes to the non-operation of some power plants [13]. For instance, the drought events of 2015–2016 have led to a decline of 50 percent of the country's hydroelectric generation due to the reduction of the water level in the Zambian hydropower facilities which though alleviated by the wet year event of 2018. This has been worsened again by the drought of 2019 [29]. In 2016, the Zambian hydropower generation deficit was estimated at around 600 MW compared to demand, requiring costly imports from the Southern African Power Pool (SAPP) region [29]. The link between most West African countries' past electricity crises and power disruption and climate extremes events is reported in [30]. For instance, the 1998 drought caused low water levels in the Akosombo reservoir, resulting in energy crises in Ghana, Benin, and Togo [31], and the 2014 energy crises in Ghana were reported as a result of the inadequacy of the Akosombo and Bui hydroelectric plants to meet Ghana's needs [30]. The cases of Nigeria, Mali, and Senegal were raised but it is not clear at which level the change in precipitation affected the hydropower generation in Côte d'Ivoire.

Aside from power generation, these impacts have also been perceived to affect food production as well as the education sector of these countries. Less rainfall has caused less food production and low water levels in reservoirs for electricity generation [32]. The low water levels in reservoirs have often resulted in frequent power cuts at various times of the day affecting socio-economic activities and productivity.

Moreover, recent studies have shown that WA temperature has significantly increased over the past ranging from 0.3 to 1 °C and from 0.2 °C to 0.5 °C over the gulf of guinea [33] and this trend will continue in the future (from +3 °C to +7 °C at the end of the century [34]). The rising temperature could increase the evaporative water demand of the atmosphere and thus lead to an upward trend of PET. The rising in temperature could also increase the water temperature and reduce the performance of thermoelectric facilities [35] while it increases the electricity demand for cooling [36–38]. However, uncertainties associated with future changes in precipitation [39] make the prediction of water resource availability for future hydropower challenging which may also vary depending on the geographical location of the dam [27, 40]. An assessment of the impacts of changes in temperature, precipitation, and inflow (past, present, and future) on hydropower facilities is therefore important in WA and Cote d'Ivoire for that matter, whose energy share has a significant amount of hydropower. Indeed, the recent energy crises, notably the last one in 2021, faced by most WA countries, in particular Côte d'Ivoire, due to the delay in the onset rainy season. For the fact that the hydroclimatic variables that modulate inflow are highly variable geographically and temporally at different local and regional scales, it is critical to

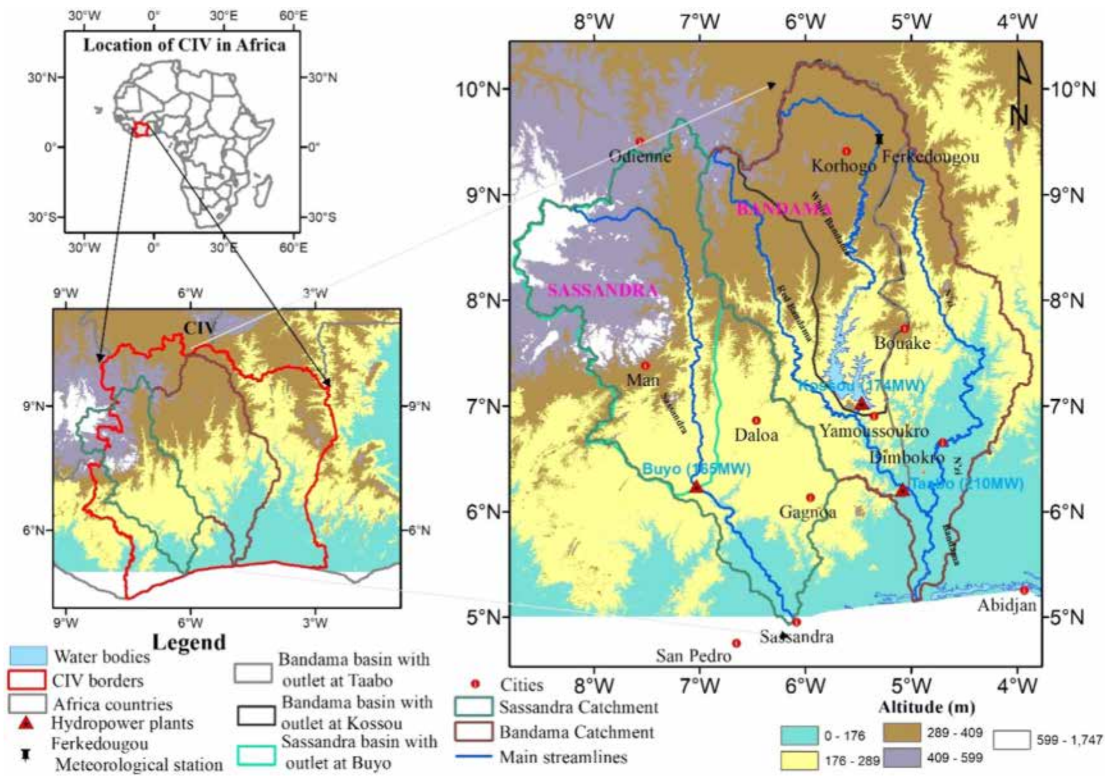

Figure 1. Presentation of Bandama and Sassandra basins in Côte d'Ivoire.

understand how sensitive hydropower generation is to hydroclimatic variables and what impact climatic variability has on hydroelectricity generation.

This study thus aims to assess the impacts of past temperature and precipitation variability and changes on hydropower generation in Côte d'Ivoire. This work focuses on the three largest and older dams of Côte d'Ivoire namely Buyo in the Sassandra basin and Taabo and Kossou dams in the Bandama basin. These dams were selected based on data availability and contribution to installed capacity. The chosen dams have at least 30 years of hydrological and energy data and with installed capacities greater than 100 MW, contributing significantly to Cote d'Ivoire's generation capacity. Changes in energy generation, inflow to reservoir, outflow from turbines, the energy equivalent of water storage and water level as well as the hydraulicity index from 1981 to 2017 will be examined.

2. Materials and methods

2.1. Study area

The study area is presented in figure 1 and consists of Bandama and Sassandra basins located in the Central and Western parts of Côte d'Ivoire, respectively. The Bandama basin with the outlet at Taabo dam's catchment area is 60.51% of the study area and covers an area of 97,000 km^2 while the Sassandra basin coverage is estimated at 24,282.26 km^2. Bandama basin elevation varies from 0 to 800 m above sea level (m.a.s.l) [41] while that of Sassandra varies from 0 to 985 m.a.s.l [42]. The Kossou dam's catchment area [43] and the Taabo dam's catchment area [41] cover 32,400 km^2 and 58,700 km^2 respectively while that of Buyo [44] accounts for 37,080 km^2. Within the Sassandra basin, the Buyo dam (operated since 1980) and Soubre dam (operated since 2017) are constructed with a capacity of 165 Mega Watt (MW) and 275 MW [42] respectively. The Kossou dam (operated since 1972) and the Taabo hydropower plant (operated since 1979) were also installed in the Bandama basin with 174 MW and 210 MW capacities, respectively [41] (see figure 1). In this study, we focused on the three oldest dams (Kossou, Taabo, and Buyo) with a reservoir capacity of multi-yearly regularization for which there are at least 30 years of data available.

The study area has equatorial and tropical climates which are controlled by the movement of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ is delimited by the crossing of warm and dry air from the Sahel (Harmattan) and the humid air from the ocean (Monsoon). Its location delimits the area and the period of the rainy season. The precipitation of the Bandama and Sassandra basins can be subdivided into three regimes/

climates [41]. The first regime is the northern part of the study area located in the Sahelian zone with a dry season from November to April and a rainy season from May to October. The second and third regimes located in the center (sudano-sahelian zone) and southern (Guinean zone) parts of the study area respectively are characterized by four seasons: a long dry season from December to February, a great rainy season from March to June, a short dry season from July to August and the second rainy season from September to November). The rainfall seasons are differentiated by the rainfall amount, their onset, and the duration which are associated with the migration of ITCZ [41].

In Côte d'Ivoire, the mean annual precipitation varies between 1050 and 2500 mm; decreases progressively from South-Western to North-East and increases while moving in the South-Eastern-North-Western direction [45]. However, over the Bandama basin, the mean annual precipitation varies between 1250–1750mm, 1100–1600mm, and 1500–2500 mm in the tropical (above 8°N latitude), transitional (between 6–8°N latitudes) and the Guinean (below 6°N latitude) climatic zones, respectively. Nevertheless, the total annual precipitation of the Sassandra basin varies from 1250 to 1700 mm (Southward). The mountainous areas (Man region) record the highest annual precipitation which varies from 1600–2500 mm [45]. The mean annual discharge at Buyo station (in the Sassandra basin) is estimated at 350 $m^3 s^{-1}$ [46], while at Kossou and Taabo (Bandama basin) is 93.72 $m^3 s^{-1}$ [41] and 93.8 $m^3 s^{-1}$ [44], respectively. The mean, highest and lowest temperatures in the study are respectively, 26 °C, 44 °C, and 15 °C. The relative humidity varies between 20%–30% during the Harmattan period in the dry season and 70%–80% during the rainy season. Generally, the potential evapotranspiration varies from 1400 to 1500 mm/year [47].

The vegetation cover in the Sassandra and Bandama basins is composed of three main types namely clear forest and easily penetrable (called forest), inaccessible gallery forest (called evergreen forest), and woody savanna associated with cocoa and coffee plantation (called savanna) [48]. The Sahelian zone (north) and sudano-Sahelian are mainly dominated by savanna and forest respectively while the Guinean zone is made of the more evergreen forest [49]. The Bandama is made of hydromorphic soil, eutrophic ferruginous brown tropical soil, and granite [48] while the Sassandra basin's soils are ferralitic type and not very permeable with a significant retention capacity [50].

2.2. Data

2.2.1. Data used

Observed hydrological and energy data on the Kossou, Taabo and Buyo hydrorlectric dams were obtained from the national electricity company of Cote d'Ivoire (Compagnie Ivoirienne d'Electricité, CIE). The data consist of a monthly time series of inflow into the reservoir, outflow from the reservoir, reservoir water level, reservoir water storage, hydraulicity index, and energy generation from 1981 to 2017. It is worth noting that the hydraulicity index of a dam or river refers to the ratio of its monthly (or annual) flow compared to its interannual average. Quality control was performed on the data to check its consistency before usage.

Rainfall data of the Climate Hazard group Infrared Precipitation with Stations (CHIRPS) accessible via https://www.chc.ucsb.edu/data is used due to the lack of observed *in situ* precipitation data over the two basins. The CHIRPS is a 30 + year quasi-global rainfall dataset spanning 50°S–50°N (and all longitudes) and starting in 1981 to the near-present. CHIRPS incorporates 0.05° resolution satellite imagery with *in situ* station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring [51, 52]. The CHIRPS product was validated in a previous study over Bandama and Mono river basins where it shows a strong correlation and lowest mean absolute error compared to GPCP and CRU precipitation products [53]. CHIRPS data has also been validated with *in situ* observed data over the Sahel and Guinea Coast and has been used in previous studies to investigate climate change in WA [54–56]. To address the lack of observed *in situ* temperature data, the air temperature from the Climate Research Unit (CRU) of the University of East Anglia is used [57]. CRU data are monthly climate data over the last century calculated at 0.5 × 0.5-degree resolution grids from 1901 to the present [57].

The global aridity index (AI) and potential evapotranspiration (PET) from climate database version 2 accessible via https://cgiarcsi.community described by Trabucco & Zomer [58] were used to develop AI and PET profile maps. The AI and PET data used for map development are available at 1 km resolution and mean of the 1970–2000 period. Due to the lack of observed PET from 1981 to 2017 at the reservoir site, PET was estimated using the Thornthwaite method [59]. Thornthwaite computes the monthly potential evapotranspiration (PET) according to the Thornthwaite [59] equation (see equation (1)). It can be used when only temperature data are available and knowing the latitude of the site. The PET is the combined loss of water from a given area, and during a specified period, by evaporation from the soil surface and by transpiration from plants [60] while the Reference evapotranspiration (ET0) is the amount of evaporation and transpiration from reference vegetation of grass. The PET and ET0 are usually considered equivalent. CRU temperature data was validated before usage.

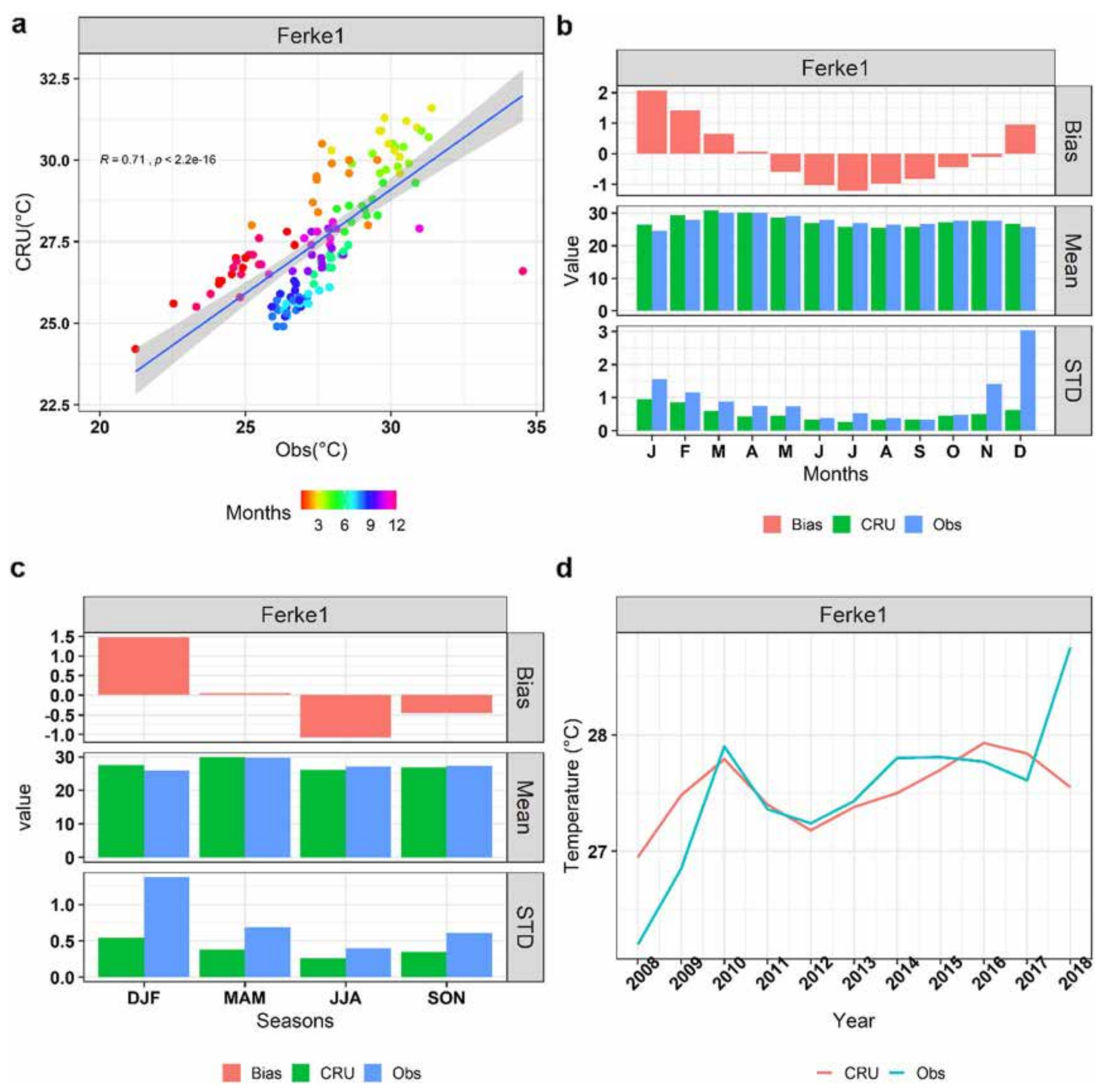

Figure 2. Validation of CRU air temperature dataset.

$$PET = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T_d}{I}\right)^{\alpha} \tag{1}$$

Where: L refers to the average day length (hours) of the month being calculated

N, the number of days in the month being calculated;

T_d, the average daily temperature (degrees Celsius) of the month being calculated;

I refers to the heat index which depends on the 12 monthly mean temperatures (T_{mi})

$$I = \sum_{i=1}^{12}\left(\frac{T_{mi}}{5}\right)^{1.514} \tag{2}$$

$$\alpha = (6.75 * 10^{-7})I^3 - (7.71 * 10^{-5})I^2 - (1.792 * 10^{-2})I + 0.49239 \tag{3}$$

2.2.2. Validation of CRU data

The air temperature from CRU was validated using observed air temperature data (Obs) from Ferkessedougou (Ferke1) station (see figure 1). This station is chosen because it has continuous daily data of at least ten (10) years (2008–2017). The mean, bias (CRU-Obs data), and the standard deviation (STD) were computed at monthly, seasonally, and annual time scales. Figure 2 shows the correlation between observed and CRU data (figure 2(a)), the evaluation metrics for monthly (figure 2(b)), seasonal (figure 2(c)), and mean annual (figure 2(d)). The analysis reveals that the observed and the CRU dataset were strongly correlated at monthly timescales ($R = 0.71$) which is statistically significant at 99% confident level (p-value<2.2e-16) (figure 2(a)). The CRU data overestimate the mean air temperature during the dry months (December to March) and underestimate air temperature during the rainy months (April to November). However, the bias varies from −1 °C to 2 °C with the highest overestimation and underestimation in January and July respectively. The same biases are observed at the seasonal time scale (figure 2(c)). The observed and CRU data present almost the same monthly dispersion except for the driest months (November to March). This is also evident at the seasonal scale where similar STDs were recorded for both datasets except the DJF (December-January-February) season (figure 2(c)). The mean annual air temperature for both datasets also reveals the same trend (figure 2(d)). It has been established that CRU data and the reanalysis products (ERA-40, NCEP, and ERA-Interim) show a good agreement in locating the highest temperature values in the north (Sahara Desert, Sahel) and lowest around the Gulf of Guinea of WA [61]. For this reason, air temperature (CRU) is used in this study without any bias correction. The PET is thus computed from the validated air temperature as described in the methodology below.

2.2.3. Aridity index and potential evapotranspiration profile

The AI and PET datasets presented above were extracted over Bandama and Sassandra river basins. The extracted data was used to develop the maps of AI and PET. The AI is given by:

$$AI = \frac{MAP_r}{MAE} \tag{4}$$

Where MAPr stands for Mean Annual Precipitation while MAE refers to Mean Annual Potential Evapotranspiration (PET).

Figures 3(a)–(d) show the mean PET and the mean AI profiles respectively for the river basins over the 1970–2000 period. For both river basins, the PET increases according to the South-North gradient. The analysis reveals that from 1970 to 2000, the spatial distribution of the mean potential evapotranspiration ranges from 1475 to 1929 mm/year (figure 3(a)) and 1500 to 2000 mm/year (figure 3(b)) in Sassandra and Bandama basins, respectively and according to the South-North gradient. However, the reservoir of Kossou presents the greatest PET (∼1750mm/year) followed by Taabo reservoir (∼1574 mm/year) both located in the Bandama river basin. The Buyo reservoir shows the lowest PET (∼1650mm/year). The Bandama basin is composed of humid and dry sub-humid climatic zones while the Sassandra is made of humid and very humid zones. The climatic zone of the Sassandra basin is humid in northern and eastern parts and very humid in the south, central and north-western parts (figure 3(c)). However, the AI profile reveals that the Bandama basin has a dry sub-humid climatic zone in the northern, central, and eastern parts with a humid climatic zone in the western part (figure 3(d)). Overall, the Kossou reservoir, located in the dry sub-humid climatic zone, loses the most water due to PET, followed by the Taabo and Buyo reservoirs, located in the humid and very humid climatic zones respectively.

2.3. Methodology

Before performing any statistical analysis, the outliers were detected and removed for all datasets. The Standardized Precipitation Anomalies (SPA) defined by Lamb [62] were computed for each basin following Ali & Lebel, (2008). The formula is given by:

$$SPA_b^i = \frac{P_b^i - \overline{P_b}}{\sigma_b} \tag{5}$$

With P_b^i the rainfall over basin b at year i, $\overline{P_b}$ and σ_b the mean and standard deviation of the precipitation over basin b for the period considered. The precipitation patterns are adapted from the precipitation indices defined by [63]:

i. When the SPA >0.5 a year/period is considered as Excess (wet year/period);

ii. When the SPA <−0.5 a year/period is considered as Deficit (Dry year/period); and

iii. When −0.5 <SPA <0.5 a year/period is considered as Normal.

The trend over the 1981–2017 period was computed using the Mann-Kendall test for all the three sub-basins after an autocorrelation test at annual scale. The non-parametric Mann–Kendall test is a rank-based nonparametric test for assessing the significance of a trend [64]. This method is recommended by the World Meteorological Organization (WMO) for trend detection in hydro-meteorological time series[65]. The test is based on null and alternate hypotheses. The null hypothesis H0 is that a sample of chronologically ordered data is i.i.d. while the alternate hypothesis is that a trend exists and can be positive, negative, or non-null. The description of the different factors guiding this test is presented in our previous work [42]. The change is also detected for temperature, PET, and energy generation.

Air temperature and computed PET dataset were divided into two periods: P1 from 1951–1980 and P2 from 1981–2017. The P1 was considered as the reference period and the difference between the average temperature

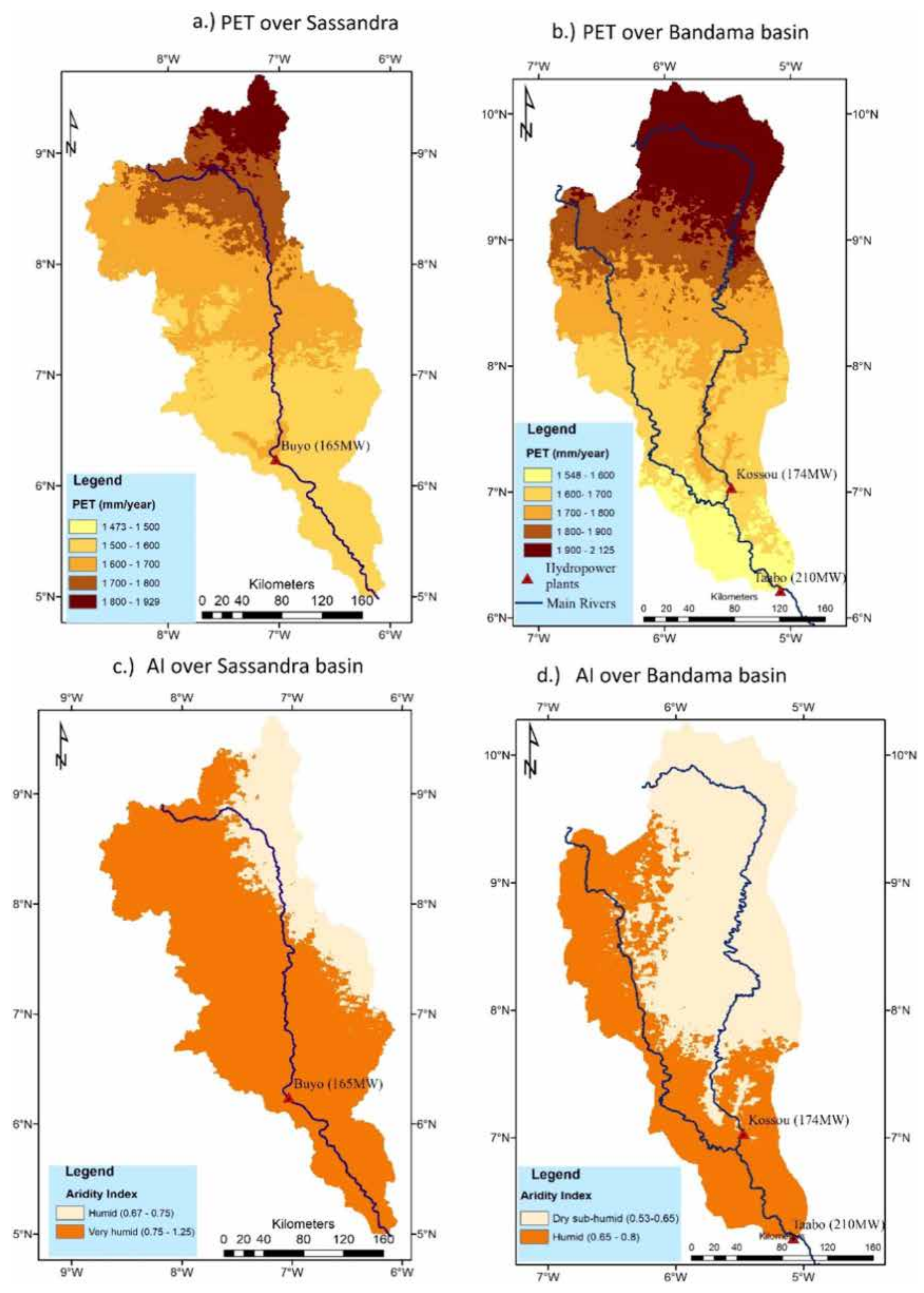

Figure 3. Profile of mean potential evapotranspiration ((a). Bandama; (b). Sassandra) and mean aridity index data ((c). Bandama; (d). Sassandra) [58].

of the P2 period and the reference period was made. The student's test (t.test) was performed for each difference to check the significance of the change. Also, the inter-decadal change over the 1981–2017 period was assessed for air temperature, PET, and energy generation. The decade 1981–1989 was considered as a reference (D1). The inter-decadal changes were computed for 1990–1999 (D2), 2000–2009 (D3), and 2010–2017 (D4) relative to D1. The significance was detected using the Wilcoxon test at a 95% confidence level due to the length of the tested data (10years). The number of moderate wet days (R75P which refers to the number of days with rainy days RR >75percentile calculated for wet days) and lag of precipitation (precip_lag1 with shift=1 or the lagged-1

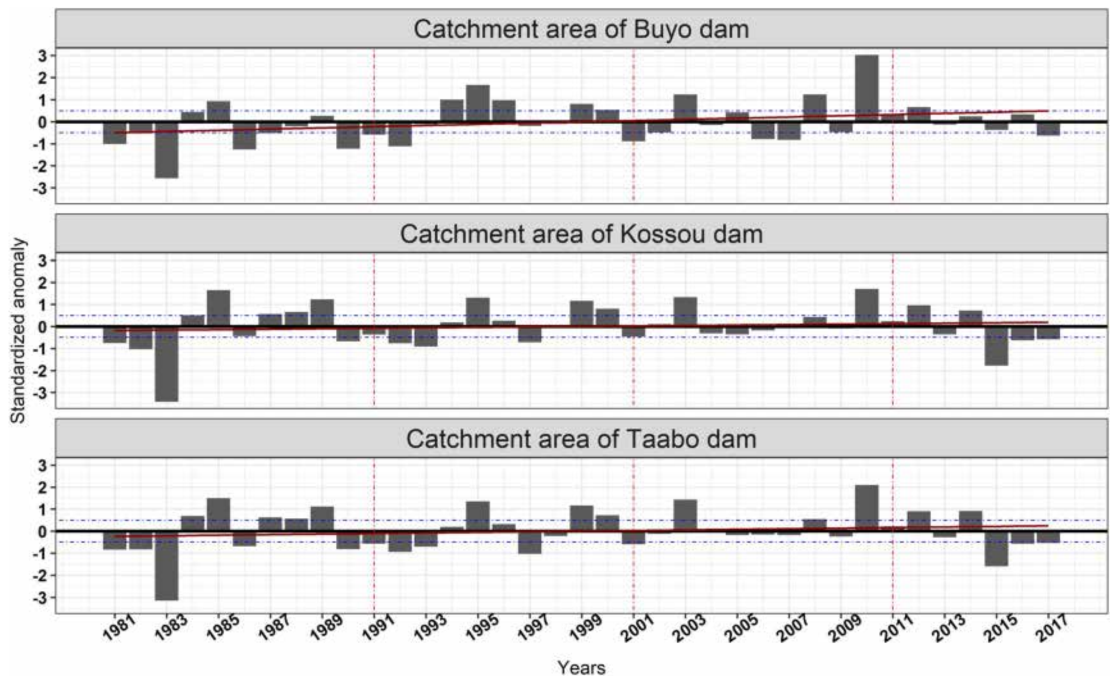

Figure 4. Standardized precipitation anomaly over Bandama and Sassandra river basins. The blue dotted-dashed lines are values beyond which a year is considered deficit or excess rainfall and the red dotted-dashed vertical lines mark the decades while the red line refers to a linear regression of each sub-basin.

precipitation time series) were computed based on precipitation data. The trends of other variables namely energy generation, inflow, outflow, hydraulicity index, R75P, precip_lag1, water level, and water storage as energy equivalent, were assessed using the same approach. Moreover, the correlation matrix between all listed variables is also assessed at the 95% confidence level. Finally, the sensitivity analysis of energy generation at each hydropower plant is computed using a random forest model. This is a method for determining how uncertainties in one or more input variables can lead to uncertainties in the output variables. In other words, it also determines what is the degree of influence that input variables (predictors) can have on the target variable (energy here). Indeed, in matching production histories, the random forest can be a more reliable sensitivity analysis tool [66] since it gives a robust, internally cross-validated estimate of the importance of the variable [67]. The Mean Decrease Accuracy (%IncMSE) is then used to detect the most important variables, i.e., those that influence the energy production the most. The results are presented in the following section.

3. Results

3.1. Rainfall variability and anomaly

The Mann-Kendall test over each grid point and each dam's catchment area shows no significant trend for all three basins over the 1981–2017 period at annual scale. Nevertheless, over the catchment areas of the Buyo, Kossou, and Taabo dams, the rainfall shows an upward trend even though this is significant only in the catchment area of the Taabo dam. This trend also influenced the precipitation anomaly.

Figure 4 presents the precipitation anomaly over Bandama (the catchment area of Kossou and Taabo dams) and Sassandra (the catchment area of Buyo dam) river basins for the 1981–2017 period. The standardized precipitation anomaly analysis reveals that 15 and 11 over 37 years are normal years for catchments areas delimited by Kossou and Taabo dams while 16 (43.24%) over 37 years for Buyo dam catchment area were normal ($-0.5 < \text{SPA} < 05$). However, the dry ($\text{SPA}<-0.5$), and wet ($\text{SPA} > 0.5$) years for the Kossou, Taabo, and Buyo dam catchments areas are 27.02% (35.14%), 32.43% (35.14%), and 29.73% (27.02%) respectively of the 37-years.

In the first decade 1981–1990, 40% of the 10 years within the Kossou and Buyo dam catchment areas were dry, while 50% of dry years were experienced in the Taabo dam catchment area for the same decade. The catchment area of the Kossou dam records 40% wet and dry years each. That of Buyo dam is 50% a normal year with four dry years (1981, 1983, 1986, and 1990) and one wet year (1985). The second decade 1991–2000 is marked by 30% wet years for both Bandama sub-basins. However, 30% (40%) and 40% (30%) of the decade were dry and wet respectively for the catchment area of the Kossou (Taabo) dams. The third decade 2001–2010,

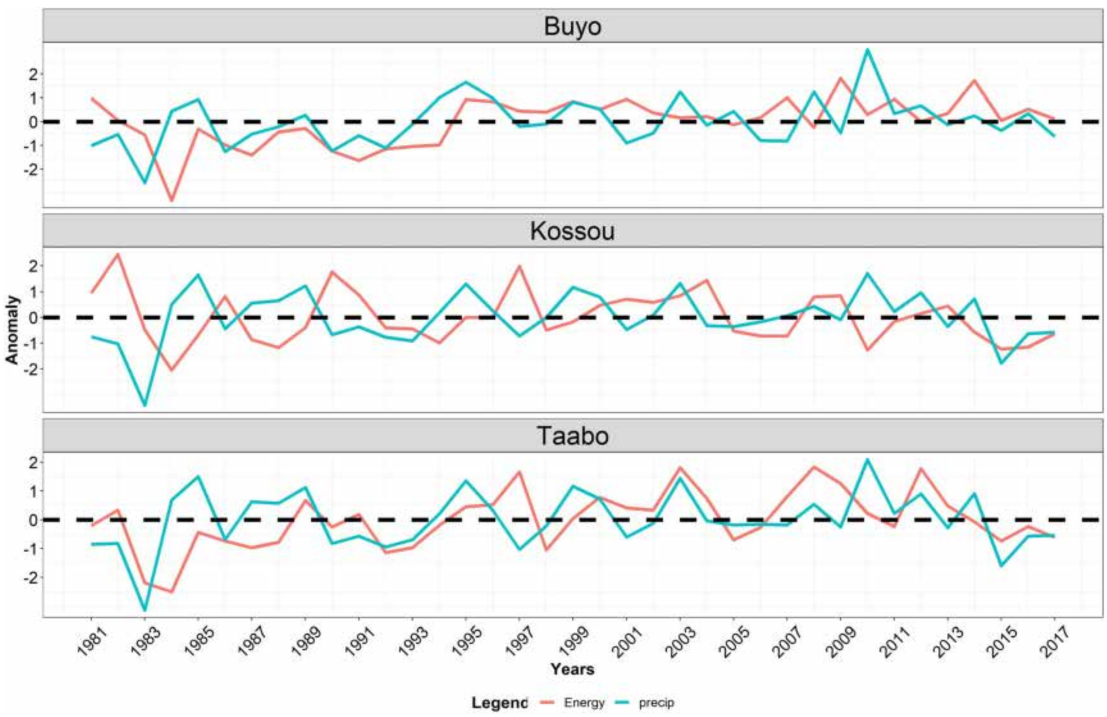

Figure 5. Interannual variability anomaly of energy and hydro-climatological related variables (1981–2017). NB: The black dashed lines represent the reference (y = 0) for each station.

was largely normal over the three sub-basins (60% and 80% for the catchment areas of Taabo and Kossou dams respectively, and 40% for the catchment area of Buyo dam). The last period 2011–2017 is marked by two wet years (2012 and 2014) and three dry years (2015,2016 and 2017) over both Bandama sub-basins while one wet year (2014) and one dry year (2015) were recorded for the Sassandra sub-basin.

3.2. Interannual variability and change of energy generation

3.2.1. Interannual variability of the energy generation and hydroclimatic variables

Figure 5 shows the anomaly of interannual variability of energy and precipitation variables from 1981 to 2017 in the three dams. All the variables (hydraulicity index, precipitation, inflow, outflow, energy, water level, PET, and storage) present a positive Kendall score at the Buyo plant (not shown). The precipitation and inflow present almost the same interannual variability anomaly as well as energy during the considered period for all the sites. It was also noted that the energy generation at a year y depends on the precipitation of the year y and/or y+1. For instance, the deficit of energy generation for all hydropower stations in 1983 is mainly due to the occurrence of the drought in this same year. However, the deficit of generation in 1984 despite the normal precipitation year is due to the previous dry year 1983. Moreover, the energy generation from 2014 to 2017 shows a negative anomaly at Kossou and Taabo associated with a deficit in precipitation during the 2014–2017 period. Additionally, the energy generation depends on the management system set in place at each site. For illustration, despite the consecutive dry years at the sub-catchment delimited by the Buyo dam during 2004–2011, the energy generation at the Buyo plant remains relatively normal. This is due to the fact that within that period, 2003 (preceded year), 2008, 2010, and 2011 were wet years, and 2004, 2005, and 2009 were normal. The energy generation, outflow, water level, and storage have decreased in the Kossou dam (not shown) between 1981 and 2017.

Table 1 summarizes the trend analysis resulting from the Mann-Kendall test of all variables. At the Buyo plant, all the variables present a significant upward trend except the precipitation and the hydraulicity index. At Kossou plant, only water level, stored water (storage), and PET present a significant trend (water level and storage with downward trend and PET with upward trend) while at Taabo dam, the energy, PET, inflow, and outflow have a statistically significant upward trend (table 1).

The energy generation at Buyo increases as well as the inflow, outflow, water level, and storage. In the Taabo dam, the upward trend of inflow and outflow caused by an increase in precipitation (significant) has consequently resulted in a significant increase in energy generation. At Kossou dam, the negative trend in energy generation is directly linked to the decrease of outflow associated with the downward trend of water level and storage. Indeed, despite the high inflow and lower outflow, it is expected upward trend of water level and storage. Paradoxically, the downward trend is obtained for both water level and storage. This downward trend in water

Table 1. Mann-Kendall test result (1981–2017) for the different hydropower plants.

Plant		Energy	Inflow	Outflow	Level	Storage	Hydraulicity	Precip	PET[b]
Buyo	P-value	**0.006**[a]	**0.001**[a]	**0.000 24**[a]	**0.009**[a]	**0.011**[a]	0.39	0.628	**<0.05**[a]
	tau	0.312	0.365	0.429	0.303	0.295	0.102	0.057	0.502
	z-score	208	230	270	191	186	64	38	353
Kossou	P-value	0.353	0.204	0.521	**0.0004**[a]	**0.0003**[a]	0.3397	0.199	**<0.05**[a]
	tau	−0.108	0.147	−0.075	−0.471	−0.407	0.111	0.147	0.482
	z-score	−72	98	−50	−314	−318	74	103	339
Taabo	P-value	**0.035**[a]	**0.015**[a]	**0.045**[a]	0.266	0.339	0.146	**0.012**[a]	**<0.05**[a]
	tau	0.243	0.279	0.231	−0.129	−0.111	0.168	0.283	0.488
	z-score	162	186	154	−86	−74	112	199	343

NB: Highlighted data with

[a] are statistically significant at the 95% confidence level.

[b] the computed data.

storage and level could be associated with many factors such as increase PET, silting, seepage as well as water abstraction for socio-economic activities but need to be elucidated. It has been already shown earlier that the temperature has increased and resulted in an upward trend of PET over all the study basins, and thus a significant increase in PET of all reservoirs. Indeed, it was found that the PET increased considerably by 5.67%, 5.62%, and 5.35% during the 1981–2017 period relative to the 1951–1980 period at Kossou, Taabo, and Buyo stations, respectively. This change in PET could have a significant incidence in water availability at all reservoirs which may differ from one decade to another and from one plant to another. Moreover, an anthropized basin as is the case of the Bandama catchment is exposed to soil erosion leading to silting the reservoir. Furthermore, as response to socio-economic development, the water abstraction from reservoir could increase significantly. Finally, some geological fractures or structural accidents may lead to important water loss through the underground.

Figure 6 displays the interannual hydraulicity index (first row/upper plots), the water level (second-row/middle plots), and the water storage (third row/bottom plots) for the three hydropower stations. The first, second, and third columns stand for Buyo, Kossou, and Taabo stations, respectively. The analysis reveals that all three variables (index, water level, and storage) present the same trend and moving average. Nevertheless, at Kossou and Taabo stations located in the Bandama basin, the hydraulicity index trend is different from those of water level and storage.

Water level and storage have decreased in Kossou and Taabo dams but increased at the Buyo plant during the 1981–2017 period. The hydraulicity indices show an increasing trend for all stations over the study period. Within this period, the water level and storage continue to decrease in Kossou dam while Taabo and Buyo show upward water storage trend in 1981–2000 and a downward trend in 2001–2017. Generally, all three variables, show a consecutive increased and decreased trend over 1981–2000 and 2001–2017 periods respectively for both Buyo and Taabo.

A break test on water storage, inflow, and outflow of the Kossou dam shows only two break dates (1990 and 2004), and for the water storage variable only. No break dates were observed with the inflow and outflow within the 1981–2017 period. Despite the upward trend of inflow and decreased outflow over 1981–1990 and 1991–2004 periods, the water storage has considerably decreased. Within the 2005–2017 period, however, the inflow and storage shows an upward trend due to a lower decrease in the outflow.

3.2.2. Interdecadal change in energy generation and hydroclimatic variable

The interdecadal change in air temperature and PET were also assessed over the 1981–2017 period. The analysis reveals that both variables increased during the three last decades (which is significant for D3 and D4 decades) relative to D1. For instance, the temperature has increased by 0.42 °C for both Bandama sub-basins whereas in the Sassandra sub-basin it has risen by 0.45 °C during the last decade D4 (table 2) relative to D1. During the same decade (D4) the Kossou, Taabo, and Buyo reservoirs recorded an increased PET of 6.46%; 6.42%, and 5.84% respectively (table 2). This high increased in PET during these last decades could negatively affect the hydropower generation at each site.

The precipitation and the inflow to the reservoir have increased during all the three last decades relative to the 1981–1989 decade (table 2). The positive change of precipitation and inflow were significant only over the Taabo dam's catchment area for D3 and D4 decades. Strangely, the inflow has changed significantly at least five times higher than precipitation for all the sub-basins. For instance, an increase of 15.66% of inflow despite a −0.14% reduction of precipitation during D2 relative to D1 (table 2). The difference in magnitude between

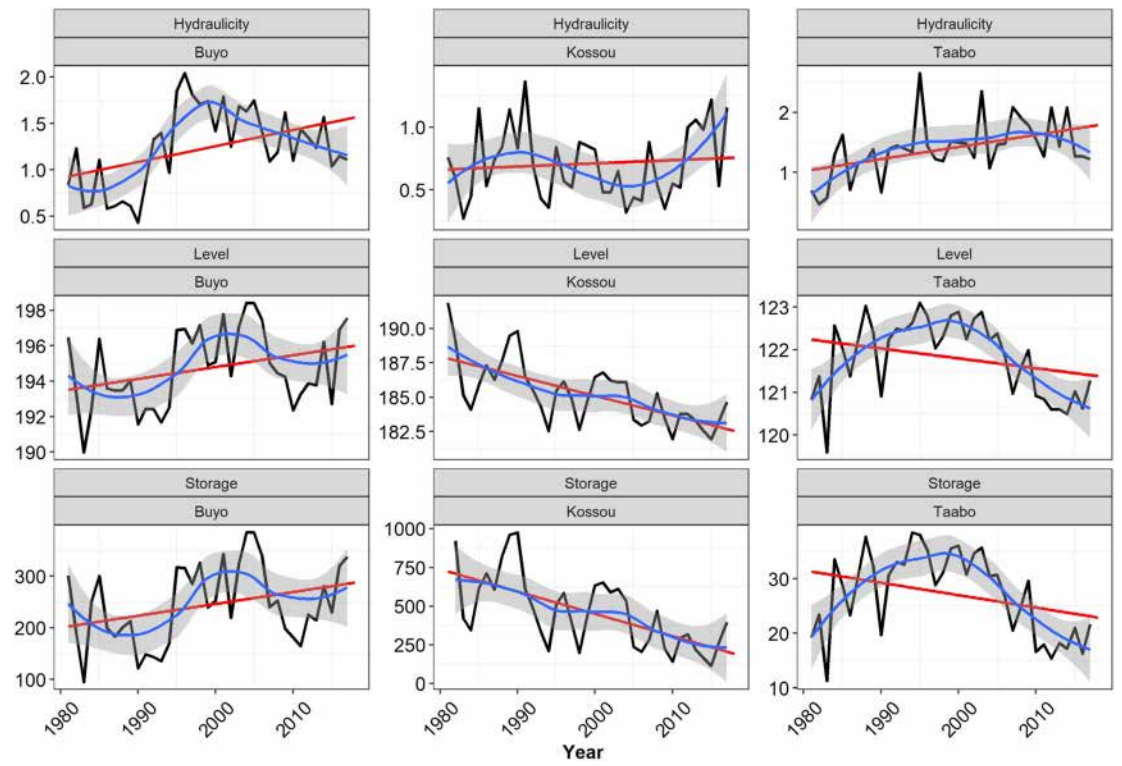

Figure 6. Interannual variability of hydraulicity indices (1st row), water level (2nd row), and water storage (3rd row) at Buyo (1st column), Kossou (2nd column), and Taabo (3rd column) hydropower plants over 1981–2017 period. The red line is the linear regression line, the blue line represents the smoothing curve while the grey area (span) gives the proportion of points in the plot which influence the smooth at each value.

Table 2. Decadal change in energy, climate variables (1980–2017) over each study dam.

		Interdecadal change		
Basin	Variables	D2-D1	D3-D1	D4-D1
Sassandra (Buyo HP)	Temperature	0.10 °C	0.29 °C[a]	0.45 °C[a]
	PET	0.96%	3.79%[a]	5.84%[a]
	Precipitation	4.69%	3.71%	7.28%
	Inflow	24.93%[a]	49.88%[a]	41.59%[a]
	Outflow	18.83%	33.85%[a]	40.17%[a]
	Storage	11.81%	42.14%[a]	18.32%
	Energy	13.26%	32.14%[a]	33.69%[a]
Bandama (Taabo HP)	Temperature	0.08 °C	0.29 °C[a]	0.42 °C[a]
	PET	0.91%	3.93%[a]	6.42%[a]
	Precipitation	−0.14%	2.27%[a]	2.51%[a]
	Inflow	15.66%	48.56%[a]	26.65%[a]
	Outflow	16.67%	61.16%[a]	22.88%
	Storage	23.22%	17.96%[a]	−13.43%
	Energy	18.48%	41.45%[a]	22.43%
Bandama (Kossou HP)	Temperature	0.08 °C	0.28 °C[a]	0.42 °C[a]
	PET	0.56%	3.92%[a]	6.46%[a]
	Precipitation	0.62%	2.49%	1.49%
	Inflow	4.58%	12.21%	12.27%
	Outflow	13.17%	19.53%	−15.59%
	Storage	−60.49%	−68.69%[a]	−111.17%[a]
	Energy	16.46%	24.41%	−15.16%

[a] NB: refers to a Wilcoxon test that is statistically significant at the 95% confidence level. It is worth noting that the decade 1981–1989 refers to D1, 1990–1999 as D2, 2000–2009 as D3, and 2010–2017 as D4.

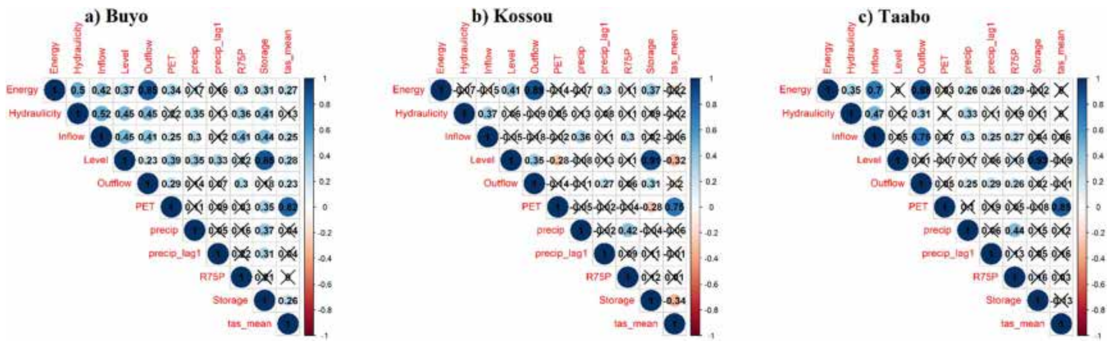

Figure 7. Correlation Matrix between variables at Buyo (in Sassandra), Kossou, and Taabo (in Bandama) hydropower plants for 1981–2017. NB: The circle with x indicates that the correlation is not statistically significant at 95% confident level while the values are the Pearson correlation coefficient R.

precipitation and inflow could be due to land use/cover change. This change of inflow to the reservoir also affects directly the outflow and then the energy generation.

The energy generation in all plants has increased in the considered D2, D3, and D4 decades relative to the 1981–1989 decade except Kossou dam at last decade (table 2). These increases were significant only at the Buyo dam at D3 and D4 decades and Taabo dam only at D3 decade. In the last decade D4, the Kossou dam experienced a decrease (not significant) of −15.16% while the Taabo dam has increase by +22.43% and Buyo by +33.69% (significant). The Taabo (Buyo) annual energy generation has increased by 2.24% (significantly by 3.37%) over the last decade (D4) relative to the first decade (D1). In contrast, the Kossou energy generation has decreased (not significant) by 1.52% annually over the last decade relative to the first one (D1). At the Kossou plant, despite the increase in inflow (not significant) and low outflow over the last decade (D4) relative to the first decade (D1), the storage considerably decreases. This paradox could be due to some factors such as PET, silting, water abstraction, and seepage which will be explained later.

It is worth noting that during June, July, and August of the years 1994 and 1998 and June, July, August, and September of the years 2010 and 2015, the Kossou hydropower plant run below the activate level and caused a frequent power shedding and blackout. Most of these years follow a dry or normal year. For instance, the years 1994 and 1998 follow the dry years 1993 and 1997 respectively while 2010 follow the 2009 normal year. The year 2015 was itself dry.

3.2.3. Correlation matrix between energy and other variables and energy sensitivity analysis

A correlation matrix (Pearson correlation coefficient) was built between energy generation and other hydrological and climate-related variables to assess the relationship between energy generation and each of these variables and the significance of their correlation at a 95% confidence level. Those variables investigated are hydraulicity index, inflow to the reservoir, water level, outflow which stands for flow passed through the turbine, PET, precipitation, water storage, and temperature.

Figure 7 shows the correlation matrix per pairwise variables of the three hydropower stations. The correlation among variables varies according to the hydropower site. Nevertheless, the energy generation is significantly and strongly correlated to the outflow at all stations. Energy generation is also correlated to hydraulic indices and inflow at Buyo and Taabo stations. The correlation between energy and climate variables (precipitation, PET, temperature) varies according to the station. For instance, in all stations, the energy generation is not correlated with the PET (precipitation) except at Buyo (Taabo) station. The energy generation correlates with the air temperature at Buyo and inversely at Kossou. Moreover, the precipitation is strongly correlated to the inflow at all stations. Furthermore, the inflow correlates with all other variables at Buyo, whereas at Taabo, it only correlates with outflow, hydraulicity index, energy generated, and precipitation. At Kossou, the inflow is only correlated to the hydraulicity index and precipitation. Overall, the correlation matrix per pairwise variables shows that energy generation dependency on hydroclimatic variables varies according to the station and this also highlighted the management system set in place at each site.

The storage positively correlates with PET and mean temperature at the Buyo plant while no correlation is found at the Taabo plant. In contrast, the storage at Kossou dam negatively correlates with the PET and mean temperature. This means that at the Kossou plant, the increase in PET due to the rising in temperature contributes to reducing the water level and then the storage. This explained the decrease in storage earlier highlighted despite the increase in inflow and reduction in outflow at Kossou dam.

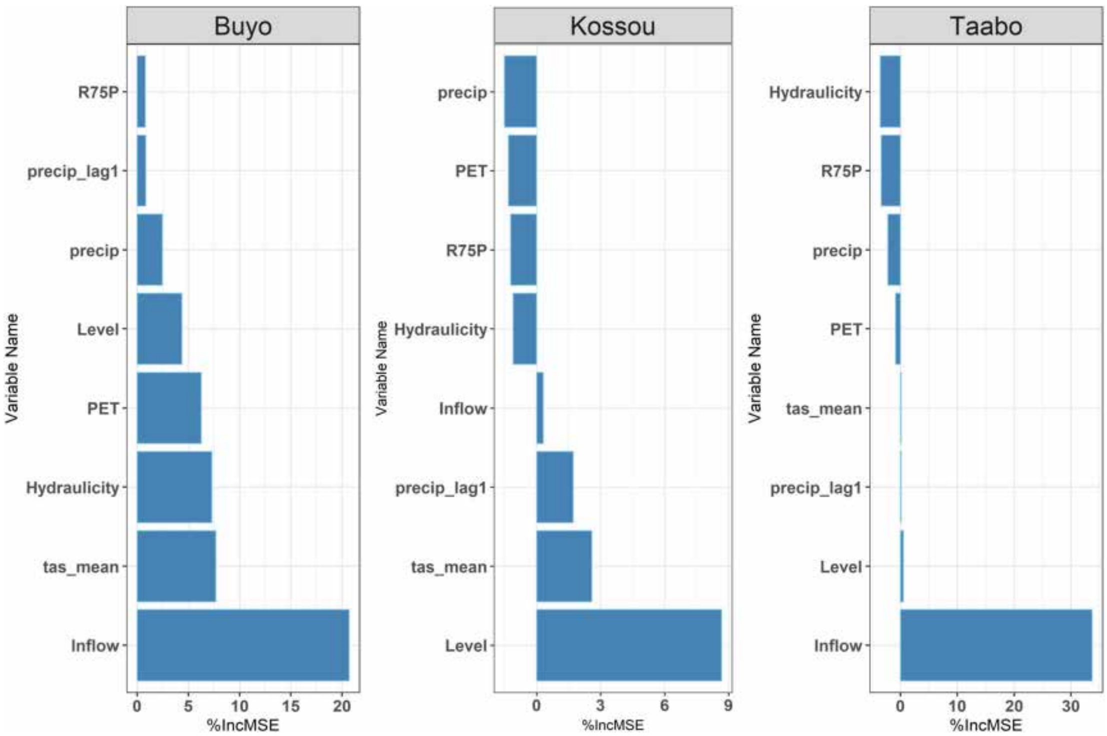

Figure 8. Random Forests-based sensitivity plot of energy generation at Buyo (in Sassandra), Kossou, and Taabo (in Bandama) hydropower plants for 1981–2017.

3.2.4. Sensitivity analysis of energy generation to hydroclimatic variables

Figure 8 shows the sensitivity analysis of energy production to hydroclimatic variables. This analysis is based on the Mean Decrease Accuracy (%IncMSE) of the Random Forest model. The higher the %IncMSE of a variable, the more sensitive the energy is to that variable. The analysis reveals that the sensitivity varies according to the hydroelectric plant. For instance, the energy production of the Buyo and Taabo dams is very sensitive to the inflow into the reservoir, while that of the Kossou dam is more sensitive to the water level. This difference in the sensitivity of hydroelectric plants shows how different the dam management implemented in each plant is.

4. Discussion

The results reveal that the energy generation is more sensitive to the inflow to the reservoir at the Buyo and Taabo dams, while that is very dependent on the water level at the Kossou dam. The inflow has shown to be more sensitive to precipitation while the water level is found more dependent on mean temperature and PET as well as outflow in all three sites. This highlights how energy production from hydropower plants depends on climatic conditions and water management policy. Indeed, the inflow to the reservoir is highly dependent on climatic conditions as well as on the characteristics of the basin, i.e., land use and cover dynamics. The water level, on the other hand, is highly dependent on the inflow to the reservoir and the water management policy at the dam. This could explain why the previous year's climate type (normal/wet/dry) has affected the energy generation of the current year at all stations including the Kossou dam. This finding corroborates with the finding of [41]. Nonetheless, the trend of change in power generation may vary according to the magnitude of changes of sensitive variables.

Regarding the inflow to the reservoirs, all three plants have recorded an upward trend as a consequence of precipitation change even though this is not statistically significant. Consequently, the energy generation has increased for all three plants except the Kossou dam which presents a downward trend. This has been shown in the Akosombo dam that the increased variability and declining total rainfall are the main cause of the decrease in lake levels [68] which negatively affect the energy generation [69]. It has also highlighted how climate change has a considerable influence on runoff [70], reservoir storage [71], and hydropower generation in Kainji dam of Niger river basin, WA [72]. There is a strong correlation between hydropower production and climate variability and reservoir water levels reduction [73] in the Volta river basin and the Kainji dam [70–72, 74] and in the Manantali dam located in the Senegal river basin [75].

During the three decades 1990–1999, 2000–2009, and 2010–2017 relative to 1981–1999, the information is given on the storage, the inflow, and outflow were convergent for all reservoirs except for Kossou dam. The considerable reduction of storage at Kossou reservoir (2010–2017) despite the increase in inflow and reduction of outflow could be mainly due to a significant increase in PET. Indeed, the total annual PET (averaging over 1981–2017 period) at Kossou reservoir (1720 mm) in the dry subhumid zone is greater than at Taabo (1684 mm) and Buyo (1447 mm) reservoirs in humid and very humid zones respectively. Additionally, the water level and storage were shown to be negatively correlated to the PET and air temperature at Kossou Reservoir. This means that the increase in PET tends to reduce the water level and storage at the Kossou dam. But, due to the considerable reduction in water storage and level at the Kossou reservoir, the PET alone may not be enough to explain this paradox.

The paradox of Kossou storage may also be caused by an increase in water abstraction in reservoir or reservoir silting as a consequence of land use/cover dynamic or underground infiltration as suggested by the study [41]. Indeed, there are some non-climate factors such as land-use dynamics, or water withdrawals which could also significantly impact the runoff [76], thus on water availability for hydropower generation, but they generally do not offset the effects of climate change. In the context of the Bandama basin, the land use dynamic may result in reservoir silting and sedimentation. This has been reported by [77] that most of the reservoirs built in Côte d'Ivoire to improve water supply, electricity, agriculture, and cattle no longer work due to silt deposits and eutrophication. It was also stated that the Kossou lakes have lost 40% of their initial surface which is on average 600 km^2 coverage area and 19 m of height according to the FAO [78]) between 1971 and 2002. Thus, the Kossou reservoir could be subjected to siltation due to land use and land cover dynamic. Moreover, the Kossou storage situation may also depend on the hydrogeological characteristic of the soil and then caused the water seepage at the reservoir. Indeed, a significant loss of water estimated at about 1 billion m^3 of water on the Bandama Blanc, from Marabadiassa to Kossou, and an inflow of water estimated at about 500 million m^3 on the Marahoué, from Zuénoula to Bouaflé, was noted. This is due to dominant linear geologic fractures in NW-SE and NE-SW directions suggested causing sustained underground water flow from the White Bandama subbasin towards the Marahoué subbasin [79]. Hence, the paradox observed at the Kossou dam could be attributed to factors such as increasing in PET, silting caused by erosion as a result of land use/cover dynamic, seepage, and water abstraction from the reservoir for domestic usage, or irrigation. Though the inflow is sensitive to basin characteristics, it also highly depends on the total annual precipitation and mean temperature over the basin area delimited by the dam as well as the atmospheric water demand through PET.

The PET has been shown to increase significantly due to rising temperature at all considered reservoirs. The water level and storage depend on the PET and air temperature. Indeed, the analysis of the change in temperature reveals an upward statistically significant trend (95% confidence level) over both basins. The upward trend of the air temperature has led to a significant increase in the PET during these last three decades relative to 1981–1989-decade overall stations which may influence the hydropower generation at each site. There is a significant relationship between air temperature energy demand and hydropower generation [80]. It has been reported that the African continent's temperature has significantly increased [81], especially over WA. For instance, the countries such as Ghana, Côte d'Ivoire, Guinea, and Senegal over the Gulf of Guinea and the west Sahel experienced the most significant and warmest signals ranging from 0.2 °C to more than 0.5°C per decade at 90% confidence level [33]. Some studies found that the temperature may increase in the range of 3 °C to 4.2 °C associated with a reduction of annual precipitations of 4.9% by the 2100 horizon over Côte d'Ivoire [82]. The change may be amplified in the future depending on the greenhouse gas scenario and at the end of the century, possible warming over WA from 1.5 to 6.5 °C [33]. Another study reported that the temperature projections over WA for the end of the 21st century from global climate simulation range between 3 and 6 °C above the late 20th-century baseline depending on the emission scenario. Over the White Bandama basin, the temperature may increase around 5% and the rainfall may decrease by 15 to 25% in the future in the 2040 horizon but the conclusion about changes in streamflow is divergent [83] according to models. This could increase the PET over the basin and reservoir as it has been shown above as a result of risen in temperature. Thus, this might reduce the water availability in the reservoirs for hydropower generation. A significant increasing air temperature trend will be associated with a decrease in discharge and consequently resulted in a reduction in hydropower generation [80]. Furthermore, using a coupled hydrological–electricity modeling framework with data on 24,515 hydropower and 1,427 thermoelectric power plants, it has shown that increase in temperature could lead to the reductions in the usable capacity of 61%–74% of the hydropower plants and 81%–86% of the thermoelectric power plants worldwide for 2040–2069 [84].

5. Conclusion

Hydropower generation depends on water availability in rivers or reservoirs which is a function of change/variability of climatic patterns such as precipitation and temperature through PET. The change and/or variability of precipitation and temperature have a direct or indirect effect on power generation. This study assessed firstly, the trends of hydroclimate variables namely precipitation, temperature, inflow, water level and storage, hydraulicity index, and computed PET using the Mann-Kendall test and their impacts on hydropower generation. Secondly, the sensitivity of hydropower generation to hydroclimatic on the Buyo dam in the Sassandra basin and Kossou and Taabo dams in the Bandama basin in Côte d'Ivoire during 1981–2017 was analysed.

The precipitation analysis displayed an upward trend for all catchments even though it is statistically significant only at the catchment area delimited by the Taabo dam. This led to an upward trend of inflow to reservoirs of the three plants. The 1981–2000 period was marked by more dry years over the sub-basins while 2001–2017 is predominantly by normal and wet years which consequently affected the energy generation. Overall, the trend of energy generation is modulated by the trend of precipitation, temperature, and inflow but this varies according to the dam.

The usage of the Mean Decrease Accuracy (%IncMSE) of the random forest algorithm allows us to determine the variables (most important variables) to which the energy generation is more sensitive. In summary, the energy generation is more sensible to inflow at Buyo and Taabo dams while it is more dependent on the water level. It has been also shown that inflow to the reservoir is strongly and significantly dependent on the precipitation as well as on basin characteristics namely land use/cover change. The water level is highly dependent on outflow which is also a function of the inflow and water management system. It is also important to highlight that both inflow and water levels are modulated by precipitation.

It is shown from this study that hydropower is an important resource for Côte d'Ivoire's future energy, but changing hydrology as a result of climate change has underlined increasing uncertainties associated with hydropower generation. As the analysis also reveals that the air temperature has significantly increased resulting in an increase in PET during the last period 1981–2017 also based on literature, all the models agreed on the probable increase of the global air temperature projection and with high uncertainties for precipitation projections. Therefore, we recommend that subsequent studies should be carried out to evaluate the impacts of hydropower plants (existing and planning) on future change in climate variables namely the precipitation, temperature, and PET by integrating IPCC scenarios while considering land use/cover dynamic as well as socio-economic development conditions in Côte d'Ivoire and over WA hydropower plants. Studies on the impacts of compounds climate extremes on energy generation and consumption from thermal and hydropower sources in Côte d'Ivoire are also needed to evaluate how co-occurence of climate extremes may affect the generation and the demand. Lastly, we recommend that Côte d'Ivoire as well as West Africa Governments to opt for mix energy sources in order to strengthen the country's power sector and supplement energy demand during seasonal climate extremes.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Conflicts of interest

The authors declare no conflict of interest.

Authors' contributions

SO conducted this research. AD, LKK and MYT were the advisors: Conceptualization, SO and AD; Methodology, SO, AD, MYT and LKK; Data Curation, LKK and DGMK; Writing—Original Draft Preparation, SO and AD; Writing—Review and Editing, PR, EMM and MYT; Funding Acquisition, AD.

ORCID iDs

Salomon Obahoundje https://orcid.org/0000-0001-8093-5241
Arona Diedhiou https://orcid.org/0000-0003-3841-1027
Kouakou Lazare Kouassi https://orcid.org/0000-0002-8514-9714

References

[1] BP Energy Outlook 2019 BP Energy Outlook 2019 edition The Energy Outlook explores the forces shaping the global energy transition out to 2040 and the key uncertainties surrounding that (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf)
[2] IPCC 2013 Summary for Policymakers *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed V B and P M M (eds.)]* ed T F Stocker *et al (Cambridge, United Kingdom and New York, NY, USA)* (Cambridge University Press)
[3] IPCC 2011 *Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) ed C von S (eds)]* ed O Edenhofer *et al (Cambridge, United Kingdom and New York, NY, USA)* (Cambridge University Press)
[4] IHA 2019 Hydropower Status Report 2018 (https://www.hydropower.org/publications/status2019)
[5] Tarroja B, AghaKouchak A and Samuelsen S 2016 Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation *Energy* **111** 295–305
[6] IRENA 2014 Africa 2030: Roadmap for a Renewable Energy Future (https://www.irena.org/publications/2015/Oct/Africa-2030-Roadmap-for-a-Renewable-Energy-Future)
[7] MINSEDD 2017 Rapport De La Troisième Communication Nationale (Tcn) De La Côte D ' Ivoire Dans Le Cadre De La Sur Les Changements Climatiques (Abidjan) (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://www.un-gsp.org/sites/default/files/documents/3069145_cite_divoire-nc3-1-cote_divoire_-_third_national_communication.pdf)
[8] Wang B, Liang X J, Zhang H, Wang L and Wei Y M 2014 Vulnerability of hydropower generation to climate change in China: results based on Grey forecasting model *Energy Policy* **65** 701–7
[9] IHA 2019 Hydropower status report 2019: sectors trends and insights *Int. Hydropower Assoc.* **1** 1–83 (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.enerjiportali.com/wp-content/uploads/2019/05/2019_hydropower_status_report.pdf)
[10] Rim B 2019 Energies renouvelables en Afrique : Enjeux, défis et opportunités (https://www.policycenter.ma/publications/energies-renouvelables-en-afrique-enjeux-d%C3%A9fis-et-opportunit%C3%A9s)
[11] Shu J, Qu J J, Motha R, Xu J C and Dong D F 2018 Impacts of climate change on hydropower development and sustainability: a review *IOP Conf. Ser.: Earth Environ. Sci.* **163** 0–11
[12] Sharma R and Shakya N 2006 Hydrological changes and its impact on water resources of Bagmati watershed, Nepal
[13] Robinson P J 1997 Climate change and hydropower generation *Int. J. Climatol.* **17** 983–96
[14] Brown O and Crawford A 2008 Climate change: a new threat to stability in West Africa? Evidence from Ghana and Burkina Faso *African Secur. Rev.* **17** 39–57
[15] Brown O and Crawford A 2008 Assessing the security implications of climate change for West Africa: Country case studies of Ghana and Burkina Fasochrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://olibrown.org/wp-content/uploads/2019/01/2008-Country-case-studies-of-Ghana-and-Burkina-Faso-IISD.pdf
[16] Mehta V K, Rheinheimer D E, Yates D, Purkey D R, Viers J H, Young C A and Mount J F 2011 Potential impacts on hydrology and hydropower production under climate warming of the sierra Nevada *J. Water Clim. Chang.* **2** 29–43
[17] Hamududu B H and Killingtveit Å 2016 Hydropower production in future climate scenarios; the case for the Zambezi River *Energies* **9** 1–18
[18] Hamududu B and Killingtveit A 2012 Assessing climate change impacts on global hydropower *Energies* **5** 305–22
[19] Tarroja B, Forrest K, Chiang F, AghaKouchak A and Samuelsen S 2019 Implications of hydropower variability from climate change for a future, highly-renewable electric grid in California *Appl. Energy* **237** 353–66
[20] de Lucena A F P, Szklo A S, Schaeffer R, de Souza R R, Borba B S M C, da Costa I V L, Júnior A O P and da Cunha S H F 2009 The vulnerability of renewable energy to climate change in Brazil *Energy Policy* **37** 879–89
[21] Dias V, de S, da Luz M P, Medero G M and Nascimento D T F 2018 An overview of hydropower reservoirs in Brazil: current situation, future perspectives and impacts of climate change *Water (Switzerland)* **10** 592
[22] Fan J L, Hu J W, Zhang X, Kong L S, Li F and Mi Z 2020 Impacts of climate change on hydropower generation in China *Math. Comput. Simul* **167** 4–18
[23] Ali S A, Aadhar S, Shah H L and Mishra V 2018 Projected increase in hydropower production in india under climate change *Sci Rep.* **8** 1–12
[24] Iimi A 2007 Estimating global climate change impacts on hydropower projects : application in Idia, Sri Lanka and Vietnam *Policy Res. Work. Pap.* **4344** 1–40

[25] Yamba F D, Walimwipi H, Jain S, Zhou P, Cuamba B and Mzezewa C 2011 Climate change/variability implications on hydroelectricity generation in the Zambezi River Basin *Mitig. Adapt. Strateg. Glob. Chang.* **16** 617–28
[26] Africa Energy Practice 2014 Understanding the Impact of Climate Change on Hydropower: the case of Cameroon Understanding the Impact of Climate Change on Hydropower: the case of Cameroon Climate Risk Assessment for hydropower generation in Cameroon (https://documents.worldbank.org/en/publication/documents-reports/documentdetail/243651468010867538/understanding-the-impact-of-climate-change-on-hydropower-the-case-of-cameroon-climate-risk-assessment-for-hydropower-generation-in-cameroon)
[27] Cole M A, Elliott R J R and Strobl E 2014 Climate change, hydro-dependency, and the african dam boom *World Dev.* **60** 84–98
[28] Falchetta G, Gernaat D E H J, Hunt J and Sterl S 2019 Hydropower dependency and climate change in sub-Saharan Africa: a nexus framework and evidence-based review *J. Clean. Prod.* **231** 1399–417
[29] Simon T 2019 The impact of climate change on hydropower in Africa
[30] Kabo-bah A T, Diji C J and Yeboah K A 2018 *Hydropower Generation in West Africa—The Working Solution Manual* (Academic Press: Elsevier) pp 197–207978-0-12-813016-2
[31] Gnansounou E, Bayem H, Bednyagin D and Dong J 2007 Strategies for regional integration of electricity supply in West Africa *Energy Policy* **35** 4142–53
[32] Nkonde H 2019 Less rain, less electricity, less food
[33] Sylla M B, Nikiema P M, Peter, Gibba I, And bourahima K and Klutse N A B 2016 Climate change over West Africa: recent trends and future projections *Adaptation to Climate Change and Variability in Rural West Africa* ed J A Y And and J Hesselberg 2016 (Switzerland: Springer) pp 25–40
[34] Sultan B and Gaetani M 2016 Agriculture in West Africa in the twenty-first century: climate change and impacts scenarios, and potential for adaptation *Front. Plant Sci.* **7** 1–20
[35] Turner S W D, Ng J Y and Galelli S 2017 Examining global electricity supply vulnerability to climate change using a high-fidelity hydropower dam model *Sci. Total Environ.* **590–591** 663–75
[36] Campbell R J 2012 *Weather-Related Power Outages and Electric System Resiliency Specialist in Energy Policy Weather-Related Power Outages and Electric System Resiliency* (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://sgp.fas.org/crs/misc/R42696.pdf)
[37] Mideksa T K and Kallbekken S 2010 The impact of climate change on the electricity market : a review *Energy Policy* **38** 3579–85
[38] Sridharan V *et al* 2019 Resilience of the Eastern African electricity sector to climate driven changes in hydropower generation *Nat. Commun.* **10** 1–9
[39] Riede J O, Posada R, Fink A H and Kaspar F 2016 What's on the 5th IPCC Report for West Africa? *Adaptation to Climate Change and Variability in Rural West Africa* ed J A Y And and J Hesselberg (Switzerland: Springer) pp 7–23
[40] Kling H, Stanzel P and Fuchs M 2016 Regional assessment of the hydropower potential of rivers in West Africa *Energy Procedia* 97 (New York, NY: Elsevier) pp 286–93
[41] Kouame Y M *et al* 2019 Climate, land use and land cover changes in the Bandama basin (Côte D'Ivoire, West Africa) and incidences on hydropower production of the Kossou Dam *Land* **8** 103
[42] Obahoundje S *et al* 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
[43] Camus H 1972 *Le Bandama Blanc Hydrology du Bandama* 1 (Abidjan: Office de la recherche scientifique et technique ouer-mer) p 287
[44] ORSTOM 1974 Tome1: Caractéristiques hydrologiques *Annuaire hydrologique de Côte d'Ivoire* **1** 252 (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers12-12/15210.pdf)
[45] Servat E, Paturel J E, Lubès H, Kouamé B, Ouedraogo M and Masson J M 1997 Climatic variability in humid Africa along the Gulf of Guinea. Part I: detailed analysis of the phenomenon in Cote d'Ivoire *J. Hydrol.* **191** 1–15
[46] Morrell M 1974 *Estimation Des Modules Mensuels Et Du Module Interannuel Du Sassandra Au Site De Buyo* (Abidjan: Centre O.R.S.T.O. M. d'Adiopodoumé République de Côte d'Ivoire)
[47] Obahoundje S, Ofosu E, Akpoti K and Kabo-bah A 2017 Land use and land cover changes under climate uncertainty: modelling the impacts on hydropower production in Western Africa *Hydrology* **4** 2
[48] Soro T D, Kouakou B D, Kouassi E A, Soro G, Kouassi A M, Kouadio K E, Yéi M-S O and Soro N 2013 Hydroclimatologie et dynamique de l'occupation du sol du bassin versant du Haut Bandama à Tortiya (Nord de la Côte d'Ivoire) *VertigO* **13** 1–22
[49] Coulibaly T J H, Coulibaly S L, Ouattara P J M and Savane I 2017 *Spatial Analysis of the Distribution of Trees According to the Order of Rivers* **5** 142–7
[50] Perraud A 1971 *Les sols Le Milieu Naturel de la Côte D'ivoire; Mémoires ORSTOM* (Paris, France: Paris : ORSTOM, 1971, 391 p. (Mémoires ORSTOM ; 50).) pp 265–391
[51] Funk C C, Peterson P J, Landsfeld M F, Pedreros D H, Verdin J P, Rowland J D, Romero B E, Husak G J, Michaelsen J C and Verdin A P 2014 A quasi-global precipitation time series for drought monitoring *U.S. Geol. Surv. Data Ser.* **832** 4
[52] Funk C *et al* 2015 The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes *Sci. Data* **2** 1–21
[53] Obahoundje S, Bi V H N, Kouassi K L, Ta M Y, Amoussou E and Diedhiou A 2020 Validation of three satellite precipitation products in two South-Western African watersheds: Bandama (Ivory Coast) and Mono (Togo) *Atmos. Clim. Sci.* **10** 597–613
[54] Bichet A and Diedhiou A 2018 Less frequent and more intense rainfall along the coast of the Gulf of Guinea in West and Central Africa (1981–2014) *Clim. Res. (Clim Res)* **76** 191–201
[55] Bichet A and Diedhiou A 2018 West African Sahel has become wetter during the last 30 years, but dry spells are shorter and more frequent *Clim. Res.* **75** 155–62
[56] Didi S R M, Mouhamed L, Kouakou K, Adeline B, Arona D, Houebagnon J C S, Kouadio A K C, Coulibaly H T J, Obahoundje S and Savané I 2020 Using the CHIRPS dataset to investigate historical changes in precipitation extremes in West Africa *climate* **8** 1–26
[57] New M, Lister D, Hulme M and Makin I 2002 A high-resolution data set of surface climate over global land areas *Clim. Res.* **21** 1–25
[58] Trabucco A and Zomer R J 2018 Global aridity index and potential evapotranspiration (ET0) climate database v2 *CGIAR Consort. Spat. Inf.* **10** m9
[59] Thornthwaite C W 1948 On the deformation mechanisms in sap single crystals *Geogr. Rev.* **38** 55–94
[60] Kirkham M B 2014 Potential evapotranspiration *Principles of Soil and Plant Water Relations* (Burlington, MA: Elsevier) pp 501–14
[61] Diallo I, Sylla M B, Giorgi F, Gaye A T and Camara M 2012 Multimodel GCM-RCM ensemble-based projections of temperature and precipitation over West Africa for the Early 21st Century *Int. J. Geophys.* **2012** 1-19
[62] Lamb P J 1982 Persistence of Subsaharan drought *Nature* **299** 46–8

[63] Kouakou A B P, Lawin E A, Kamagaté B, Dao A, Savané I and Srohourou B 2016 Rainfall variability across the agneby watershed at the agboville outlet in Côte d ' Ivoire, West Africa *Hydrology* **3** 1–11
[64] Kendall M and Gibbons J D 1938 *Rank Correlation Methods* (London: Oxford University Press) C1990
[65] WMO 2009 Extreme values analysis in: the guide to hydrological practices. Volume II *Management of Water Resources and Application of Hydrological Practices* **2** 302
[66] Aulia A, Jeong D, Saaid I M, Kania D, Shuker M T and El-Khatib N A 2019 A Random Forests-based sensitivity analysis framework for assisted history matching *J. Pet. Sci. Eng.* **181** 106237
[67] Polewko-Klim A, Lesiński W, Golińska A K, Mnich K, Siwek M and Rudnicki W R 2020 Sensitivity analysis based on the random forest machine learning algorithm identifies candidate genes for regulation of innate and adaptive immune response of chicken *Poult. Sci.* **99** 6341–54
[68] Owusu K, Waylen P and Qiu Y 2008 Changing rainfall inputs in the Volta basin: implications for water sharing in Ghana *GeoJournal* **71** 201–10
[69] Kabo-bah A, Diji C, Nokoe K, Mulugetta Y, Obeng-Ofori D and 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
[70] Salami A W, Mohammed A A, Adeyemo J A and Olanlokun O K 2015 Assessment of impact of climate change on runoff in the Kainji lake basin using statistical methods *Int. J. Water Resour. Environ. Eng.* **7** 7–16
[71] Olofintoye O and Adeyemo J 2011 The role of global warming in the reservoir storage drop at Kainji dam in Nigeria *Int. J. Phys. Sci.* **6** 4614–20
[72] Baba M and Sharma S 2017 Assessment of climate change impact on hydropower generation : a case study of Nigeria *Int. J. Eng. Technol. Sci. Res.* **4** 753–62
[73] Boadi S A and Owusu K 2017 Impact of climate change and variability on hydropower in Ghana *African Geogr. Rev.* **38** 19–31
[74] Adegbehin A B, Iguisi E O, Yusuf Y O, Zubairu I and Anumonye E N 2016 Effect of Weather Parameters on Hydroelectric Power Generation in Kainji Dam *Paper Presented at the 57th Annual Conf. of the Association of Nigerian Geographers (UNILAG ANG-2016)*
[75] Faye C 2015 Impact du changement climatique et du barrage de manantali sur la dynamique du régime hydrologique du fleuve sénégal à bakel (1950–2014) *BSGLg.* **64** 69–82
[76] Roudier P, Ducharne A and Feyen L 2014 Climate change impacts on runoff in West Africa: a review *Hydrol. Earth Syst. Sci.* **18** 2789–801
[77] Kouassi K L, Innocent K K, Sanchez M and Meledje N H 2013 Two-dimensional numerical simulation of the hydro-sedimentary phenomena in lake Taabo, Cte d ' Ivoire two-dimensional numerical simulation of the hydro-sedimentary phenomena in Lake Taabo, Côte d ' Ivoire *Water Resour Manag.* **27** 4379–94
[78] FAO 2002 *Profil de pauvreté des communautés riveraines du lac de Kossou en Côte d'Ivoire ed P pour des moyens d'existence durables dans la pêche GCP/INT/735/UK* (Cotonou: République du Bénin)
[79] Kouamé A K, Koudou A, Sorokoby V M, Kouamé K F and Kouassi A M 2017 Relationship between surface and underground water flow in the upper bandama watershed in Ivory Coast *Larhyss J.* **29** 137–52
[80] Kachaje O, Kasulo V and Chavula G 2016 The potential impacts of climate change on hydropower: an assessment of Lujeri micro hydropower scheme, Malawi *African J. Environ. Sci. Technol.* **10** 476–84
[81] Collins J M 2011 Temperature variability over *Africa Am. Meteorol. Soc* **24** 3649–66
[82] Eugène K K, Bi G, Albert T and Michel K A 2012 Analyze of climate variability and change impacts on hydro-climate parameters : case study of Côte d ' Ivoire *Int. J. Sci. Eng. Res.* **3** 1–8
[83] Soro G E, Amichiatchi N J M C, Kouassi W F and Goula Bi T A 2019 Assessment of climate change impacts on Kossou power dam inflows (White Bandama River, Côte d'Ivoire) *Clim. Chang.* **5** 82–9
[84] Vliet M T H V, Wiberg D, Leduc S and Riahi K 2016 Power-generation system vulnerability and adaptation to changes in climate and water resources *Nat. Clim. Chang.* **6** 375