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Evaluation of the potential for small-scale hydroelectricity in the Wassadou catchment using the SWAT hydrological model

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Abstract: The increase in the amount of CO_2 and global warming due to fossil fuels has made it necessary to explore other inexhaustible, available and non-polluting energy sources such as renewable energies. Hydroelectric power accounts for 19% of the global production. Small hydroelectric power stations are small, inexpensive production units. The hydroelectric power potential depends on the flow and the head. In this study, we select sites for the evaluation of small hydroelectric power potential in the Wassadou watershed on the Gambia River. Using ArcGis, and the digital elevation model (DEM), 35 small hydroelectric power (SHP) sites have been found on 11 streams flows. The soil water assessment tool (SWAT) hydrological model was calibrated for a 1990-1995 observation period and validated for the 1996-1998 period. The accuracy of the model was confirmed by the coefficient of determination (R^2 = 0.70) and the Nash-Sutcliffe efficiency criterion (NSE = 0.80). This model was used to generate daily flows at each site over the period 1990-1998 which allowed us to plot the flow duration curve. A total hydroelectric potential of 147,421kW, 14,229kW, and 1,859 kW available at 40%, 50%, and 60% respectively at all 35 sites was evaluated. The results of this study provide a decision tool for policy makers and investors for the selection of suitable sites and implementation of small hydroelectric power plants to meet energy needs in remote areas.

Key words: renewable energy; small hydropower; hydropower potential

1 Introduction

Electricity is a form of energy that makes a major contribution to people's quality of life and to the economic development of nations, thanks to its ease of use and the large number of people who use it. It can be produced from exhaustible fossil fuels (oil, gas and coal) or nuclear energy. However, where favourable sites exist, electricity can also be generated using the hydraulic energy of a river or reservoir, which is known as hydroelectricity. This particular form of energy production is renewable and produces no greenhouse gases. It is safe in terms of supply and protection of our environment.

There are two types of hydroelectric project: large hydroelectric power stations and small hydroelectric power stations. The classification is based on power output, and varies from country to country or from NGO to NGO (World Bank). Large hydroelectric power plants are often defined as facilities with an output of more than 30 megawatts (MW). They rely on dams to create artificial lakes that can provide huge amounts of reliable, renewable energy (Energy BC, 2016). They are always connected to the grid and can be run-of-river (ROR) or reservoir-fed (IFC). Dams are expensive, but once built, the fuel is free and the cost of the electricity they produce is very cheap.

In isolated locations, the construction of small hydroelectric plants is sometimes more advantageous and less costly. Small hydropower plants (SHP) are defined as small production units with a capacity of less than 30 MW (Lea Kosnik 2010, Breezy 2018). They can be classified by different sizes (mini, micro, pico), depending on the country. According to the World Bank, small hydropower generates 7% of the world's renewable electricity (Breezy, 2018), with production estimated at 78,000 MW at the end of 2016, according to the International Center of Small Hydro Power (ICSHP). In remote areas that are not connected to the grid, especially in developing countries such as Senegal, small-scale hydropower can provide reliable, long-term electrification for schools, health centers, small businesses, public lighting, agricultural machinery and so on. It makes a major contribution to the economic and social development of these regions. The construction of a hydroelectric project requires knowledge of the topography and availability of flows in the catchment area. Gathering and analyzing accurate information on topography, land use patterns, river morphology and geology in a geographic information system (GIS) environment is easier than conventional field surveys. The combination of GIS and hydrological modelling provides a powerful tool for studying hydrology in catchments and also for assessing hydropower potential (Kurse et al, 2012). Distributed hydrological models are preferred to global conceptual models for runoff prediction. In these models, the catchment area is divided into small basins with characteristics that are as uniform as possible (Ntoandis et al, 2013). Among them, the soil water assessment tool (SWAT) is a semi-distributed hydrological model that makes it possible to determine all the morphometric parameters of a basin and to simulate the flows at any point in the watercourses (Ravi shanker et al 2016).

For hydropower potential assessment and hydrological study, many researchers such as Kurse et al (2010), Ashish Pandey et al (2014), and Ravi Shanker Mathi et al (2016) have used GIS and SWAT to assess hydropower potential in India; Christian Bauer et al (2015) in Nepal used spatial tools based on GIS and SWAT hydrological model. Nagendra Kayastha et al (2018) proposed to assess key potential hydropower sites and explicitly identify potential hydropower locations spatially, over a large area and in a short time frame. Kontantinos X. Soulis et al (2016) presented a geo-information system for the evaluation of individual hydropower sites, which estimates flow values at each point of the drainage network. Rovick P. Tarife et al (2016) focused on the application of GIS tools to identify and rank theoretical potential hydropower sites in Misamis Occidental, Northern Mindanao, Philippines. Thomas M. Mosier et al (2016) presented a novel modelling package, called the hydropower potential assessment tool, to assess the potential and projection of small-scale hydropower resources in a single location or spread over a study region. Dante G. Larentis et al (2010) used GIS-based procedures to identify hydropower potential.

In this work, we combine GIS and the hydrological model (SWAT) to determine the location of sites, generate flows and thus assess hydroelectric potential.

2 Methodology

2.1 Geographical position

The Wassadou catchment area lies between two (2) countries, part of which is in Senegal and part in Guinea (Figure 1). Senegal accounts for 70.88% of the Gambia River, which covers an area of 77,069 km^2. The Wassadou basin lies at longitude 12°21 W and latitude 12°23 N, with a total surface area of 26,540 km^2. With such potential, the basin has so far remained unexploited for hydroelectricity, but provides an important natural resource for the economic development of the region's populations.

Figure 1. Location map of research area (Ndiaye, 2020)

There are two seasons in this region, the rainy season from July to September and the dry season from October to January. The rainfall in this region varies between 1,500 and 2,000 millimeters per year, with approximately 78% of the annual rainfall occurring during the monsoon season (June to September). The monthly temperature range is from 25 ° C (lowest) to 42 ° C (highest), and the relative humidity reaches its highest in September and lowest in January.

2.2 Morphometric parameters

These parameters (Table 1) are used to characterize the physical environment and its influence on surface flow. In this study, we used automatic techniques that facilitate the extraction of these indices. The Gravelius compactness indices are greater than 1 and therefore have an elongated shape. The overall slope indices obtained from the hypsometric curves and their concave shapes indicate that the basin is mature. The specific gradient used to classify the catchment and according to the ORSTOM method we have a very low relief for the Wassadou catchment (Ds between 10 and 25). Drainage density depends on the geology (structure and lithology), the topographical characteristics of the catchment and, to a certain extent, climatological and anthropogenic conditions.

Table 1. Morphometric parameters

Characteristic	Morphometric parameters	Formule	Wassadou
Basin morphology	Surface (km^2)	ArcGis	26,540
	Perimeter (km)	ArcGis	596.38
	Gravelius coefficient	$C_c = 0.28\, P.A^{-1/2}$	1.03
	Length of watercourse (km)	$L = A^{1/2}\frac{C_c}{1.12}\left[1+\sqrt{1-\left(\frac{1.12}{C_c}\right)^2}\right]$	369.93
Relief	Minimum height (m)	ArcGis	9
	Maximum height (m)	ArcGis	1,533
	Average height (m)	$H_{moy} = \sum \frac{A_i h_i}{A}$	140.60
	Mean altitude	Hypmetric curve	296.60
	Unlevel (D)	$D = H_{5\%} - H_{95\%}$	798
	Slope index (I_g)	$I_g = \frac{D}{L}$	2.16
	Specific height difference(D_s)	$D_s = I_g . \sqrt{S}$	351.42

	Drainage density (km^{-1})	$D_d = \frac{\sum l_i}{A}$	0.10

2.3 Website identification standards

In order to select potential locations for implementing hydropower projects, the following criteria were adopted:

Traffic availability: Adequate traffic availability must be ensured by using third-order or higher-order rates. (Figure 2)

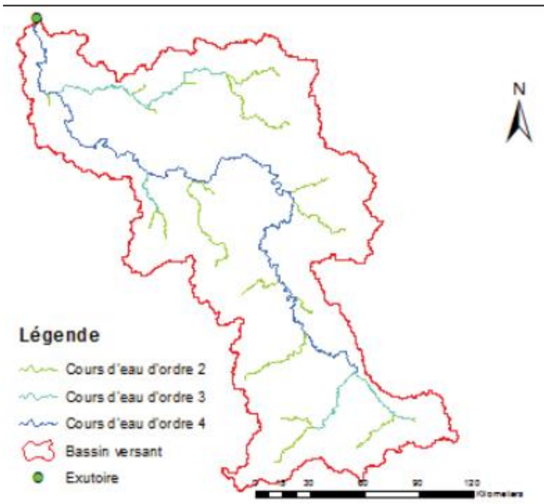

Figure 2. Level 2 and above rivers (Ndiaye, 2020)

Distance between sites: (a) The minimum distance between two consecutive sites should not be less than 500 m (Kusre et al. 2010). This will ensure that there is sufficient space between the tailrace of one site and the diversion arrangement of the next, so that the river ecosystem will have sufficient opportunity to rejuvenate. (b) The maximum distance from the river considered to find the head should not be more than 3,000 m.

The availability of drop height: Drop height is defined as the pressure generated by the height difference between the intake and turbine (Rovick P et al., 2017). There are different methods to estimate pressure drop along rivers. In our research case, hydropower projects require a drop height of at least 20 meters. The data in Figure 3 determines the drop height of each river.

MinEl	MaxEl	Shape_Length
12	24	67842.062384
24	88	164887.519253
24	54	152830.495393
54	103	109578.232068
54	65	24787.151081
103	107	12878.008353
103	205	138920.682851
205	283	19978.415192
205	255	54714.682174
255	411	38101.372672
255	489	58583.002718

Figure 3. Minimum and maximum heights of rivers in the Vasadou Basin (Ndiaye, 2020)

2.4 Input data for SWAT model

The data required for the operation of the SWAT model includes terrain, climate, soil and land use/land cover data, as well as emission data. The terrain data of the Gambia Basin upstream of Wassadou come from the 30 * 30 digital elevation model of the space shuttle radar terrain mission (SRTM), which can be obtained on the website https://vertex.daac.asf.alaska.edu/?#. Climate data such as precipitation, maximum and minimum temperatures, solar radiation, relative humidity, and wind speed are sourced from the SWAT website. https://globalweather.tamu.edu/.

Land use and soil type activities are closely related, and their combined effects have a singular impact on surface runoff. Land use is one of the most important factors affecting watershed infiltration, evapotranspiration, and therefore, in turn, runoff from a catchment.

A soil map is a geographical representation that displays the spatial distribution of different soil types and their properties within a watershed (Ravi Shanker Matthi et al., 2016). The soil type affects the rate and volume of flood rise. The soil map is shown in Figure 4 and is provided by the Global Land Cover 2000 Project (https://www.gvm.jrc.it/glc2000). Leptosols predominate in the Wassadou basin (51.98%), followed by Regosols (31.93%) and Acrisols (9.03%).

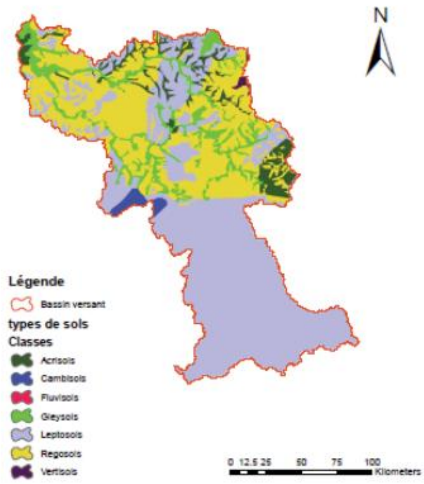

Figure 4. Soil map of Wassadou Basin

The land use map of the Kedougou catchment is shown in Figure 5. Approximately 100% of the land is covered by deciduous woodland (FRSDO) 28.82% and scrub (RNGB) 70.87%. The rest of the land is occupied by western wheatgrass (WWGR) 0.29% and crested wheatgrass (CWGR) 0.20% (http://www.fao.org/geonetwork/srv/en/main.home#soils). The average daily flows are taken in part from the database of the Office de Gestion et de Planification des Ressources en Eau (DGPRE Dakar, Senegal) and the IRD (Institution de Recherche pour le Développement). Observed daily rainfall is taken from the database of the Organisation pour la mise en valeur du bassin du fleuve Sénégal (OMVS) and the IRD (Institut de recherche pour le développement).

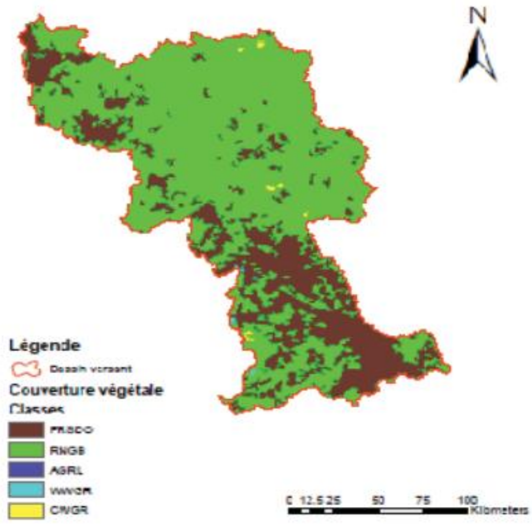

Figure 5. Plant coverage map

2.5 Calibration and verification

Model calibration consists of adjusting model parameters within a recommended range so that simulated data (obtained after model simulation) match observed data as closely as possible. The Arc-SWAT calibration tool allows various parameters to be adjusted by user intervention. These parameters can be adjusted manually or automatically. The calibrated SWAT parameters are shown in Table 1. In this study, flow data from 1999, 2000, 2001, 2002 and 2003 were used for manual model calibration. Twenty-one (21) SWAT model parameters were manually adjusted and, after each change, the simulated flow was compared with the observed flow.

Validation is the process of determining the degree to which a model or simulation is a correct representation of observed behaviour from the point of view of intended uses. Simulated flow values at a specific location are compared with observed flows for model validation. The calibration of the SWAT model was validated using flow data for 2004, 2005 and 2006.

The statistical index, also known as the Nash coefficient, was used to evaluate the model's performance. It is given by the Nash-Sutcliffe equation (3) (Nash and sutcliffe 1970).

$$E_{ns} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Q_i^{obs} - Q_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Q_i^{obs} - Q_{moy}^{obs} \right)^2} \right] \quad (3)$$

Among them, Q^{obs} is the observed traffic, and Q^{sim} is the traffic simulated by the SWAT model, and N is the amount of data considered.

2.6 Estimation of hydroelectric potential

The energy generated when the discharge Q is allowed to decrease through the top difference of H is given by the following equation:

$$P = \rho g Q H \quad (4)$$

Where p is power, ρ is water density (1,000 kg/m3), g is gravitational acceleration (9.81 m/s2), and η is the total efficiency of the turbine or generator. The energy generated will increase with the increase of Q and H. This study only estimates the theoretical power.

3 Results

3.1 Calibration and verification

The SWAT model was calibrated between 1999 and 2003 and validated between 2004 and 2006. The effectiveness criteria for adjustment during the calibration period are R^2=0.76 and NSE=0.75, and during the validation period, R^2=0.67 and NSE=0.65. The calibrated and validated R^2 and ENS values demonstrate good consistency between the simulated and observed daily flow rates. The parameters and their values calibrated after sensitivity analysis are shown in Table 3. Figure 6 shows the observed and calculated flow rates for the calibration and validation of the SWAT model. According to the figure, the rising and falling parts of the simulated hydrological map are well reproduced.

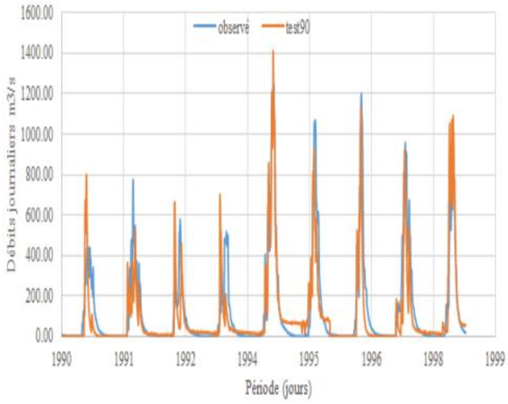

Figure 6. Simulation and observation flow curves for SWAT model calibration and validation

3.2 Website recognition

The methodology used to identify potential sites depends on two main criteria: a head of 20 m or more is available; a distance between two sites ranging from a minimum of 500 m to a maximum of 3,000 m is measured. In addition to hydrological criteria, many other criteria (e.g. geological suitability, proximity to important locations) must also be met to finalize the siting of hydropower projects (A. Pandey et al 2015).

The first point is the outlet. From this point, we take the first main watercourse (watercourse 1). For this section, SWAT gives the maximum altitude, minimum altitude and length. The difference between the maximum and minimum elevation of this watercourse, which corresponds to the head (gross head), is deducted. However, the head for a PCH must not exceed 20 m. The head is divided by 20. The number of sites is determined from this result and the length. For example: for a fall height of 100 m, there could be 5 sites counted from the first (site 0), site 1 at 20 m, site 2 at 40 m, site 3 at 60 m, site 4 at 80 m and site 5 at 100 m. We measure the distance between sites 0 and 1. If the distance between the two sites is greater than 500 m and less than 3,000 m, we place the site, otherwise we move on to the next site (Figure 7).

Thirty-five (35) potential sites and their locations were identified on these watercourses (Figure 7). Table 2 shows all these rivers with their length, altitude, number of sites, bed slope and average spacing between two potential sites. Figure 7 shows the locations of all the sites in the river basin studied. As can be seen, it is not the longest river (164.88 km) that has the most potential sites (3) with 64 m of gradient and the shortest (12.87 km) has only (0) sites due to its gradient value (1 m).

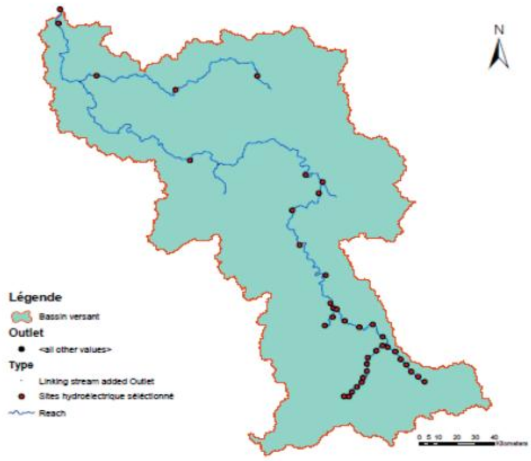

Figure 7. Map of 35 selected locations

Table 2. Information on different rivers in the watershed

Waterway	Waterway length (km)	Maximum height (m)	Minimum height (m)	Height difference (m)	Number of sites	Steep hill	Average distance between sites (km)
1	7.84	24	12	12	1	0.01	0
2	164.88	88	24	64	3	0.03	54.9
3	152.83	54	24	30	1	0.01	76.41
4	109.57	103	54	49	2	0.04	54.78
5	24.78	65	54	11	0	0.04	0
6	12.87	107	103	4	0	0.03	0
7	138.92	205	103	102	5	0.07	27.78
8	19.97	283	205	78	3	0.39	6.65
9	54.71	255	205	50	2	0.09	27.35
10	38.2	411	255	156	7	0.4	5.45
11	58.58	489	255	234	11	0.39	5.32

3.3 Classification traffic curve for each selected site

Due to the lack of river flow measurements in the selected 35 locations, the SWAT model was used to generate daily flow for these locations from 1990 to 1998. The Weibull position method in Figure 8 was used to represent the flow velocity duration curves for all these sites.

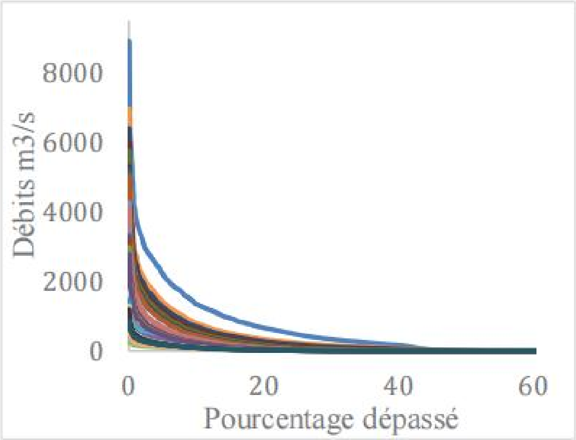

Figure 8. Classification flow curve of each station within the watershed

Calculate the flow rate that reaches or exceeds each determined site within 40%, 50%, and 60% of the time, and evaluate the corresponding hydropower potential. The results for all 35 locations are shown in Table 3.

Table 3. Potential estimation

Select site	Flow rate (m3/s)			Puissance (W)		
	Q40	**Q50**	**Q60**	**P40**	**P40**	**P60**
1	176.80	11.93	0.02	34,652,800	2,338,280	3,382.96
2	179.00	14.93	0.75	35,084,000	2,926,280	146,960.8
3	14.24	2.32	0.74	2,791,040	455,504	144,687.2
4	19.46	3.46	0.80	3,814,160	677,180	156,114
5	36.32	5.38	0.83	7,118,720	1,055,068	163,150.4
6	128.60	13.49	1.74	25,205,600	2,644,040	341,432
7	92.10	7.80	0.92	18,051,600	1,528,016	179,751.6
8	71.25	8.21	1.77	13,965,000	1,608,572	347,508
9	13.47	2.14	0.74	2,640,120	419,832	145,745.6
10	12.92	1.12	0.28	2,532,320	219,324	55,605.2
11	5.70	0.73	0.18	1,116,808	142,766.4	35,299.6
12	0.31	0.16	0.12	60,799.2	30,458.4	22,696.8
13	0.06	0.02	0.02	11,697.28	3,959.2	2,953.72
14	0.08	0.00	0.00	16,585.52	814.576	582.512
15	0.14	0.05	0.01	27,714.4	8,870.96	1,190.896
16	0.01	0.01	0.01	2,263.8	1,759.884	1,276.744
17	0.21	0.13	0.10	41,473.6	25,813.2	19,835.2
18	0.22	0.13	0.10	42,159.6	25,421.2	18,892.44
19	0.02	0.01	0.01	4,898.04	2,597	1,477.448
20	0.04	0.03	0.02	7,908.6	6,136.76	4,500.16
21	0.04	0.02	0.01	7,773.36	4,068.96	2,342.2
22	0.01	0.00	0.00	1,883.364	977.844	564.48

23	0.04	0.02	0.01	8,661.24	4,517.8	2,573.48
24	0.01	0.00	0.00	1,502.536	634.256	351.82
25	0.01	0.00	0.00	1.166.396	617.008	351.036
26	0.05	0.01	0.01	10,188.08	2,120.72	1,552.908
27	0.01	0.01	0.00	1,349.46	1,012.144	742.644
28	0.09	0.00	0.00	17,122.56	584.08	397.292
29	0.02	0.00	0.00	4,800.04	481.376	349.272
30	0.13	0.04	0.00	25,421.2	8,163.4	652.876
31	0.17	0.10	0.05	32,732	19,121.76	9,504.04
32	0.08	0.02	0.01	15,172.36	3,745.56	2,742.04
33	0.22	0.15	0.11	42,238	29,654.8	20,991.6
34	0.10	0.01	0.00	19,029.64	1,597.008	1,953.728
35	0.23	0.16	0.12	44,531.2	31,810.8	23,480.8
Puissance total (W)				147,421,239.5	14,229,801.1	1,859,835.141

4 Conclusion

The aim of this work was to estimate the hydroelectric potential of the Kedougou catchment. First, we calibrated and validated (1990-1998) the SWAT model with a Nash of 0.75 and 0.79, and an R^2 of 0.75 and 0.64 respectively for calibration and validation. We then used the simulated flows at each site to calculate their hydroelectric potential from equation 1. The location of the sites is based on two major criteria: a head of 20 m and a spacing between 2 sites between a minimum of 500 m and a maximum of 3,000 m. Finally, we plotted the flow duration curve for each site, then determined the potential P40, P50 and P60 equal to 147,421 Kw, 14,229 Kw and 1,859 Kw respectively.

Hydroelectricity is a major issue, which is essential to be preserved and developed by forging the necessary compromise between the different uses of water to enable future generations to benefit from a genuine choice of renewable energy sources. In this respect, development prospects must be strongly encouraged by the public authorities and accompanied by the creation of a stable environment from both a regulatory and financial point of view. In Africa, the development of hydropower has not changed at all, and yet there is no shortage of resources and accessible technologies, apart from the determination and lack of awareness of most African authorities. In this respect, this study has proposed a line of thought and action to ensure optimal exploitation of our hydropower potential.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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