Journal of Hydrology: Regional Studies 32 (2020) 100757

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Potential for small hydropower development in the Lower Pra River Basin, Ghana

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ARTICLE INFO

Keywords:
Hydropower
SWAT
Flow duration curve
Power duration curve
Firm power
Pra basin

ABSTRACT

Study region: : Lower Pra River (LPR) Basin, Ghana
Study focus: : This study examines the potential for Small Hydropower Development in a semi-arid environment albeit the lack of data. Geographic and site specific information acquired through geographic and remote sensing techniques are applied in a physically based semi-distributed hydrologic model to simulate discharges for ungauge areas for consideration of hydropower. Flow Duration Curves (FDC) and Power Duration Curves (PDC) have been constructed for suitable sites from which design flow and firm energy is established.
New hydrological insights for the region: : The final assessment resulted in the identification of ten sites (HP1 – HP10) along the LPR with potential for hydropower generation. The maximum and minimum mean annual flows were 172.9 m^3/s and 5.3 m^3/s at hydropower sites HP1 and HP2 respectively. HP1 demonstrated the highest hydropower potential with firm power and annual firm energy at 90 % dependability estimated as 12.22 MW and 77.10 GW h with a total annual energy production (AEP) of 183.77 GW h. Hydropower sites HP3 and HP7 also had relatively high hydropower potential with firm power and annual firm energy of 10.0 MW, 47.01 GW h and 9.0 MW, 40.77 GW h respectively with AEP expected to be in the order of 157.67 GW h and 141.91 GW h respectively. A cascade system is proposed for hydropower sites HP1, HP3 and HP7 with estimated combined AEP of 483.4 GW h.

1. Introduction

Hydropower development has over the years shown a competitive edge over other energy sources (wind, solar, thermal, nuclear, etc) as a reliable, efficient, sustainable and environmental friendly energy generation option. Globally, untapped hydropower potential stands at 10,000 TW h/year with the potential for future development reaching 2000–2050 GW of installed hydropower capacity by 2050 (International Hydropower Association (IHA, 2016). From the viewpoint of environmental sustainability, hydropower technologies produce less greenhouse gas emissions (GHGs) relative to fossil-fuel electricity generation options (Kuanda et al., 2012) and

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https://doi.org/10.1016/j.ejrh.2020.100757
Received 7 August 2020; Received in revised form 2 November 2020; Accepted 4 November 2020
Available online 13 November 2020

hence preferable to fossil fuels or nuclear power (Renofalt et al., 2010). It is estimated that the life-cycle GHG emission factors for hydropower is about 40–48 times less than that of fossil-fuel generation options, an indication of the environmental friendliness of hydropower systems (Kabo-bah and Mensah, 2018).

The multi-faceted dimension of hydropower infrastructure in the provision of water supply systems, water navigation and transport systems, irrigation schemes, fishing, flood control among others cannot be over emphasized. As large scale hydropower developments are capital intensive, the concepts of small hydropower (SHP) development has shot to limelight due to its ease of development, cost effectiveness and environmental friendliness. There is no internationally acceptable definition of SHP; however variant definitions exist based on a country's level of hydropower development (Ohunakin et al., 2011). For example, in Canada, installed capacity of less than 50 MW is classified as SHP (Cyr et al., 2011) whereas a capacity in the ranges of 5–100 MW is considered SHP in the United States (Johnson et al., 2015). The globally installed SHP capacity is estimated at 78 GW against total estimated potential of 217 GW (UNIDO, 2016) with China leading the SHP developmental agenda. On the continental front, Asia leads SHP development with a total of 50,729 hydropower systems whiles Africa lag with 580 SHP.

In Ghana, the total installed capacity for existing plants is 4132 MW consisting of hydro (38 %), thermal (61 %) and solar (<1%) (Eshun and Amoako-Tuffour, 2016). Since 1965 when the Akosombo Dam, the first hydropower plant was completed, Ghana has rather taken a snail's pace towards exploring and developing its hydropower potentials. The Akosombo hydropower plant is augmented with 400 MW and 160 MW installed capacities from Bui and Kpong hydropower plants respectively (International Hydropower Association (IHA, 2018). According to the strategic development goal of Ghana (IRENA, 2012), the government envisages expanding energy coverage from 20 % in 2018 to 80 % by 2030. However, this energy coverage projection will only remain a myth unless pragmatic efforts are taken to expand the energy network to meet the ever increasing demand. Most of the unmet populations are the rural and peri-urban communities whose energy demand may not have to be hosted by the major hydropower plants but rather considerations of SHP to absorb such loads. This is particularly true since connecting to the national power grid is prohibitively expensive due to the transmission losses. Thus, local hydropower production is an attractive and sometimes viable option (International Hydropower Association (IHA, 2018). Having recognized the need to augment Ghana's energy mix, it thus becomes imperative that lessons are drawn from global best practices with regards to SHP potential exploration. In India, Pandey et al. (2015) assessed the

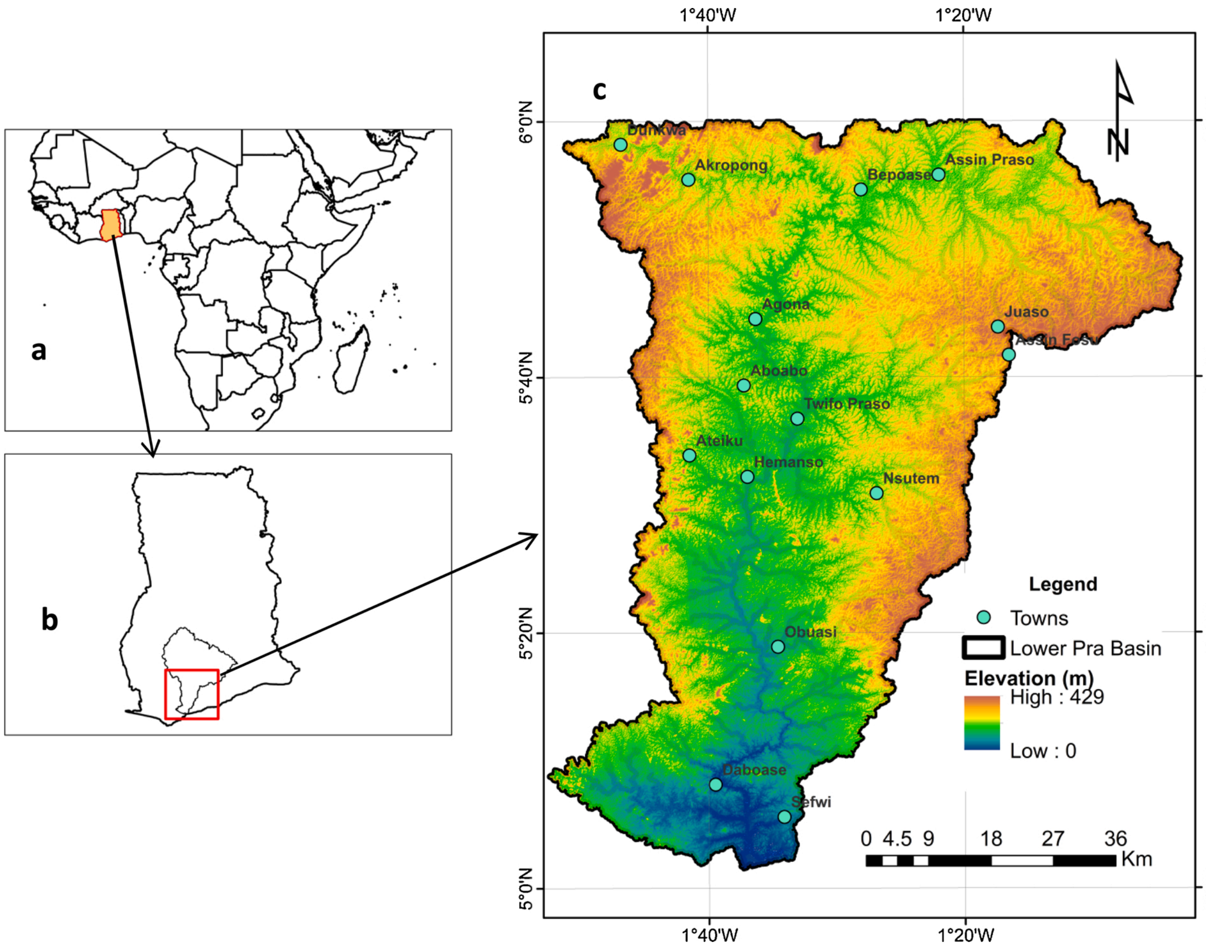

Fig. 1. Contextual location of the Lower Pra River Basin (LPRB) **a** Africa, **b** Ghana and **c** LPRB.

hydropower potential of the Mat River using a set of geospatial technologies together with the Soil and Water Assessment Tool (SWAT). In the Ciwidey subwatershed in Indonesia, Rospriandana and Fujii (2017) also examined the potential for SHP development with geographic information system tools coupled with the SWAT hydrologic model. Similarly, theoretical hydropower potential has been evaluated for the Misamis Occidental (Tarife et al., 2017) and quite recently for the Mindanao River Basin (Guiamel and Lee, 2020) all in the Philippines. The aforementioned discussions reiterate the need to leverage on advances in technology to promote potential hydropower exploration, planning and development with least cost and resources.

In Ghana, earlier investigations indicated that many river reaches have the potential for small hydropower development (Arthur, 2014). Nonetheless, no in-depth studies have been initiated to assess the technical and economic viability of SHPs in Ghana.

On this backdrop, this study sought to investigate the potential for the development of SHP within the Lower Pra River Basin (LPRB) by (i) identifying optimal sites for SHP development and (ii) examining the technical feasibility of the proposed SHP through hydrologic modeling and Geographic Information Systems (GIS) application.

2. Materials and methods

2.1. Study location

The Lower Pra River Basin (LPRB) remain the focus of this study (Fig. 1), however the description given herein is for the whole of the Pra River Basin (PRB). The PRB is located between latitudes 5 °N - 7° 30′ N and longitudes 2° 30′ W - 0° 30′ W in south central Ghana. The drainage network comprises the main Pra River and its major tributaries of Birim, Anum and Offin rivers and their tributaries. The Pra River and its tributaries constitute the largest river basin of the three major south-western basins system (Ankobra, Tano and Pra). The principal Pra River together with its tributaries takes its source from the highlands of Kwahu Plateau in the Eastern Region and flows for 240 km prior to entering the Gulf of Guinea close to Shama in the Western Region (Water Resources Commission, 2010). The drainage area is about 22,106 km^2, with an average elevation of about 300 m and uniformly appearing plateau at elevation ranging from 0 m to 429 m. The Pra River traverses 41 administrative districts. The Pra Basin which lies within the southern forest and transitional climatic zones is characterized by a bi-modal rainfall regime with two rainy seasons, which extends from April to June and also from September to November. The mean annual rainfall increases southwards from 1393 mm to 1779 mm. Due to the high amount of rainfall in the area, the inhabitants are mostly farmers. The area is characterized by uniformly high temperatures with a mean annual temperature of 27 °C from 1988 to 2018.

The main river and its tributaries form a principal source of water supply to communities within the basin. The main tributaries are perennial and make all-year round dependable water source. The basin is one of the most extensively and intensively utilized river basin areas in Ghana with respect to settlement, agriculture, logging and mining. The presence of gold and other mineral resources has encouraged the operations of large mining companies in the basin as well as illegal small scale mining locally referred to as "Galamsey". The increasing forest clearance for mining, settlement and infrastructural development poses substantial loss of soil minerals and accompanying high sediment transport in the Pra and its tributaries. The basin hosts most of the large cocoa growing areas in the Eastern, Ashanti and Central regions. Nevertheless, anthropogenic activities such as logging and mining are having detrimental impacts and deteriorating the surface water resource of the basin. Cocoa and oil palm constitute the major cash crop cultivation in the basin. The basin contains the highest density of settlements both rural and urban in Ghana (Water Resources Commission, 2010).

2.2. Spatial datasets and processes

A 1 arc-second Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM) bounding the Pra River was downloaded from the USGS website (https://earthexplorer.usgs.org). From the DEM, a contour map was generated at an interval of 2 m while the stream ordering was performed using the Strahler method. The ordering of the Pra River into stream network was necessary to determine streams of higher order which would provide sufficient flow for hydropower generation. Using the Fill tool in ArcGIS, the DEM was filled to remove any sinks, followed by flow direction and flow accumulation. From ArcMap, the raster calculator was used to define and generate flow accumulation with minimum accumulated flows of 10,000 cells. The output of the raster calculator was then utilized to order and generate the stream network of Pra River using the stream order tool (Fig. 2).

Rainfall and temperature data for three weather stations in the Pra basin (Daboase, Twifo Praso and Dunkwa-On-Offin) were

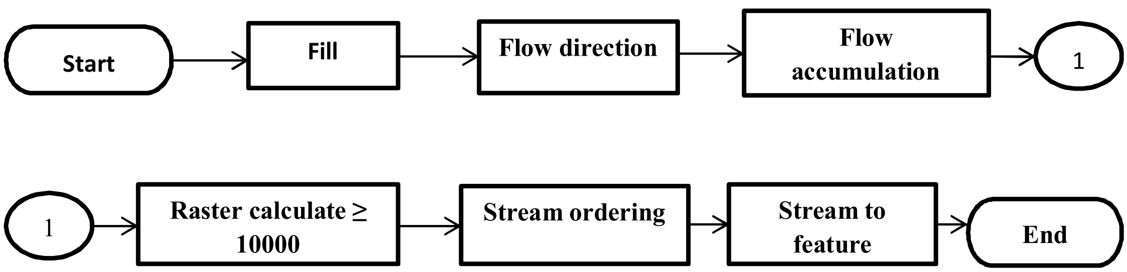

Fig. 2. Flow chart for the generation of Pra stream networks.

obtained from the Ghana Meteorological Agency for the period 1988–2018. Streamflow data for the Daboase hydrological station was also acquired for 1988–2018 from the Hydrological Services Department, Ghana. As a key determinant of hydrological processes, land use characteristics were examined through land cover classification to identify the dominant land cover features in the Pra basin. In performing the land use land cover classification, a Landsat 8 OLI/TIRS scene was used. The downloaded image was acquired on 3rd January 2018. A true colour composite combination of Band 4 (Red), Band 3 (Green) and Band 2 (Blue) were used as well as a false colour composite which consisted of the combination of Normalized Difference Vegetation Index (NDVI), Band 1 (aerosol) and Band 6 (SWIR). The NDVI were extracted based on Eq. 1.

$$\frac{Band4 - Band3}{Band4 + Band3} \text{or} \frac{NIR - R}{NIR + R} \quad (1)$$

The true and false colour composites aided in the identification of various features in the image and the performance of unsupervised and supervised classification. To aid the supervised classification process, a 500 m Moderate Resolution Imaging Spectroradiometer (MODIS) dataset was used in combination with the unsupervised classification to identify the dominant features in the Pra basin for the performance of the supervised classification.

The FAO digital soil map of the world (DSMW-ESRI shapefile format) at a scale of 1:5,000,000 was used in this study. Although this data exist at a very coarse resolution, it is the only dataset available that presents comprehensive information on the study area. In preparing the soil code for the SWAT model, the FAO soil database was imported from MWSWAT. MWSWAT is an extension to MapWindow 4.8.8 which host the FAO soil database.

2.3. Head and flow determination

Hydropower is a function of two main factors: the head and the flow. The determination of reaches or network of Pra River with sufficient flow for hydropower siting was accomplished through stream ordering. Stream ordering is a river classification technique into stream network or reaches which depicts the magnitude of flow at the classified stream network. Among the different stream ordering methods such as the Shreve, Horton and Strahler method, the Stahler method was used in ordering the Pra River due to its extensive application and simplicity. This method is such that there will be an increase in stream order when two streams of equal order meets; for instance the adjoining of two first order streams form a second order stream and so on. Consequently, an increase in stream order results in the relative increase in the magnitude of flow and vice versa (Pandey et al., 2015). In order to ensure that there is sufficient flow available for hydropower generation, only higher (≥ 3rd) order streams were considered in the selection of hydropower sites. A conceptual illustration of the Strahler stream ordering method is shown in Fig. 3.

The determination of available head (i.e difference in elevation: E_{max} - E_{min}) and river reach (i.e distance between maximum and minimum elevation: $D_{max} – D_{min}$) were performed using the SRTM derived contour map of the Pra Basin (Fig. 2). As a consistency check, Google Earth elevation profile technique was used as an alternative tool to verify the head and river reach as determined by the SRTM derived contour. In determining the head, each higher stream order of the Pra River (≥ 3rd order stream) was overlaid on the contour map to determine the head. The available head was determined beginning from the main outlet of the Pra River towards the upstream. Using the contour map, the number of contour lines that passes through a particular reach of the Pra River multiplied by the contour interval (2 m) determines the head. Conceptually, the available head, reach and site spacing is illustrated in Fig. 4.

2.4. Hydropower siting

Siting of locations with hydropower potential along the Pra River was conducted based on criteria adopted from Kusre et al. (2010) and Yuksel (2007). The approaches used by Kusre et al. (2010) and Yuksel (2007) were adopted because of their minimum data

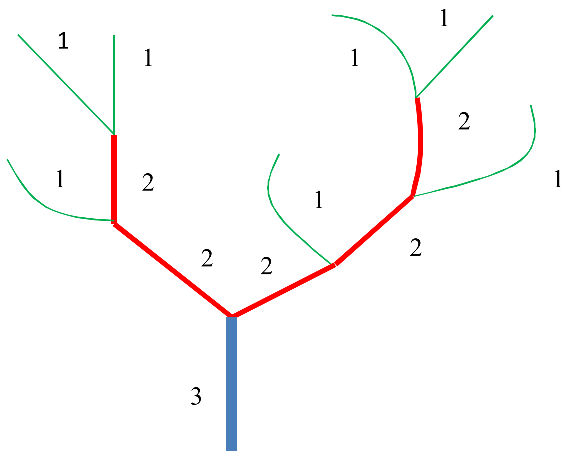

Fig. 3. Conceptualized representation of Strahler stream ordering.

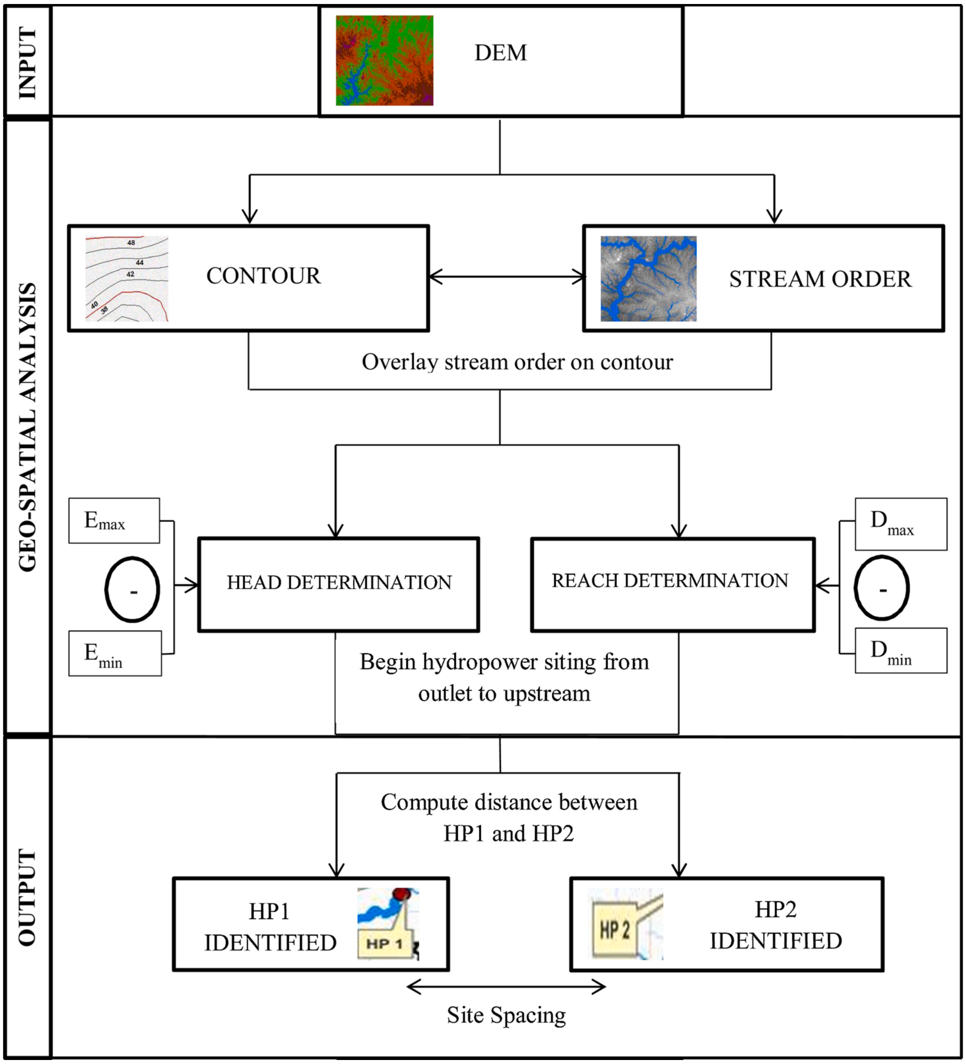

Fig. 4. Conceptualized framework for head and reach determination.

requirements and simplicity but however providing robust and reliable outputs. It is therefore useful for regions with data paucity challenges. The hydropower siting was divided into two distinct stages: preliminary assessment and final assessment (Fig. 5).

In the preliminary assessment, three criteria; sufficient flow, availability of adequate head and maximum stream reach of 3000 m were considered (Kusre et al., 2010). The maximum stream reach was to ensure that the water surface slope of the falling water is not too high or too low for hydropower generation. To guarantee sufficient flow and head for hydropower generation, a minimum of third (3rd) order stream and a minimum head of 8 m were adopted in the preliminary assessment. The minimum head and flow were also to ensure the project considers small to high hydropower generation. The locations on the Pra River that meet the three criteria were designated as preliminary hydropower sites and subsequently subjected to the final assessment.

In the final assessment, all the preliminary hydropower sites were tested against two final criteria, head and minimum site spacing (Yuksel, 2007).To avoid clustering of potential sites as identified in the preliminary assessment, the final suitable sites were selected based on minimum criteria of 10 m and 500 m respectively for head and site spacing. The head criterion was to guarantee the availability of adequate head for hydropower generation whiles ensuring the elimination of unsuitable sites to prevent clustering of final sites. The site spacing is the distance between two successive hydropower sites. The site spacing of 500 m was adopted to evaluate the potential for a cascade hydropower project. The minimum spacing would ensure that the tailrace (tail water elevation) of the upstream site is not affected by the backwater (ponding) of the downstream site. The preliminary hydropower sites that met the two criteria in the final assessment were designated as the final and proposed hydropower sites with the potential for hydropower generation within the LPRB (Fig. 5).

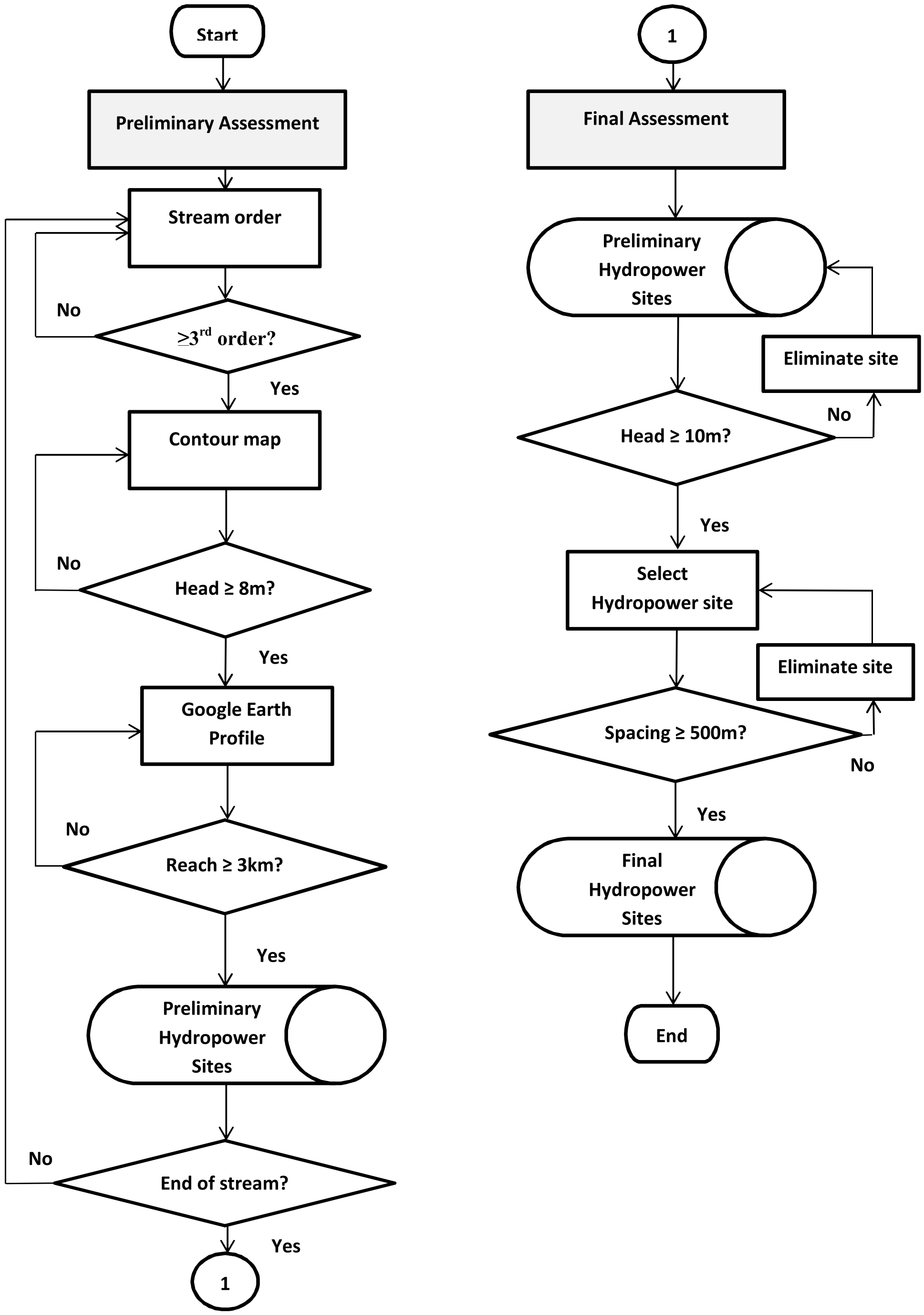

Fig. 5. Flowchart for hydropower siting within the Lower Pra River Basin.

2.5. SWAT model and flow simulation

The Soil and Water Assessment Tool (SWAT) is a small watershed to river basin-scale model widely applied across the world to study hydrology, sediment, in-stream water quality, impact of land use, climate change and various water management interventions on water quantity and quality. SWAT delineates the basin into sub basins and then into Hydrologic Response Units (HRUs) based on homogeneous soil characteristics, land use and topology. The creation of HRUs enhances the prediction accuracy in the sub basin (Neitsch et al., 2002; Williams et al., 2012). It is a distributed hydrological model and can be used to estimate the long term impact of land management practices on runoff, sediment loads and loss of nutrients at different scales. The hydrological simulation of watershed processes in SWAT is premised on the water balance equation formulated as;

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \quad (2)$$

Where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O) and Q_{gw} is the amount of return flow on day i (mm H_2O).

ArcSWAT, an extension to ArcGIS was used in the flow simulation of the proposed hydropower sites. The flow simulations in ArcSWAT were executed using the spatial datasets described under section 2.2. In delineating the river networks for the study area, a threshold area of 103.5 km^2 was considered to zoom into relatively larger streams in the LPRB. In the HRU definition, a multiple land surface slope made up of three land surface slope classes (0–7 %, 7–17 % and 17–87 %) was chosen to define the land surface slopes. The land use data was reclassified according to the crop and urban tables in SWAT2012.mdb database whereas the soil data was reclassified according to the 'Usersoil' table in the SWAT2012.mdb database. With consideration to the HRU definition, the multiple criteria was used with land use, soil class and land surface slope classes set at 2%, 1% and 2% respectively. The threshold levels were set to ensure that all the dominant classes in the land use, soil and land surface slope definition are considered in the creation of the HRUs (Her et al., 2015).

Finally, the simulations were executed for a 30 year period (1988–2018) with the first two years as equilibration period. The output was printed on a monthly timestep.

2.6. Calibration, validation and model performance evaluation

The model was calibrated using both manual calibration (SWAT Calibration Helper v1.0) and automatic calibration with the SWAT Calibration Uncertainty Program (SWAT-CUP). The automatic calibration was performed using the Sequential Uncertainty Fitting (SUFI-2) algorithm. The Daboase stream flow data obtained from the Hydrological Services Department was used for the calibration and validation. The period of data used for the calibration was 01/01/1990 to 31/12 /2010 while that for the validation was from 01/01//2011 to 31/12/2018. The calibration and validation were performed on a monthly time step. Based on the literature, CN2, ESCO, SURLAG, SOL_K, ALPHA_BF, GW_DELAY, GWQMN, REVAPMN, GW_REVAP, RCHRG_DP and SOL_AWC were selected for sensitivity analysis. Sensitive parameters were evaluated based on one-at-a-time and global sensitivity analysis in SWAT-CUP following flow calibration procedure proposed by Neitsch et al. (2002). The initial ranges for the model parameters were attained from the Absolute_SWAT_Values.txt in SWAT-CUP. The parameters were adjusted by method of absolute change (a) and replacement (v).

The performance of the model was adjudged against four objective criteria; NSE, R^2, RSR and PBIAS (Kwarteng et al., 2020; Franco and Bonuma, 2017; Gyamfi et al., 2016a; Moriasi et al., 2007). The model uncertainty was also assessed by the p-factor and r-factor in SWAT-CUP. The optimal value for both NSE and R^2 is one (1) while that for PBIAS is zero (0). R^2 varies between 0 and 1 whiles NSE varies between $-\infty$ and 1. A PBIAS of 0 is optimal and is an indication that the model neither under estimated nor overestimated the observed (Arnold et al., 2012).

2.7. Energy estimation

For each of the proposed sites, a Flow Duration Curve (FDC) and Power Duration Curve (PDC) were constructed. A monthly interval was used for the construction of both the FDC and PDC. In the construction of the FDC, the cumulative frequency (number of flows, N) in descending order was calculated. The flow exceedance probability (dependability) was estimated as;

$$\%Dependability = \frac{Cumulative\ frequency\ of\ flows\ (N)}{Number\ of\ dataset\ (n)} \times 100 \quad (3)$$

Following computation of dependability, FDC at each hydropower site was plotted with discharge (m^3/s) against the percent of exceedance or dependability (%). The PDC was constructed by first computing the power using Eq. 4;

$$Power\ (kW) = \frac{\rho \times g \times H_e \times Q \times \eta}{1000} \quad (4)$$

Where **ρ** is the density of water (1000 kg/m^3)g is the acceleration due to gravity (9.81 m^2/s)H_e is the effective head at the hydropower site (m)Q is the discharge at the proposed hydropower site (m^3/s)η is the overall system efficiency (86 %)

The effective head at each hydropower site was determined from equation 5;

$$H_e = H_g - Head\ Loss \quad (5)$$

H_g is the gross head: the total head determined at each hydropower site. The head loss was taken to be 10 % of gross head (Clarke et al., 2008).

The PDC of each hydropower site was obtained by plotting power (kW) against percent exceedance or dependability (%). For hydropower generation, the firm power and firm flow are often determined at the 90 % dependability (Dudhani et al., 2006). For estimation of the firm energy (kWh) and total Annual Energy Production (AEP), the plant capacity factor (C_f) which represents the ratio of expected output from the plant to the total installed capacity of the hydropower plant was taken as 0.8 (Clarke et al., 2008). This value is so chosen to allow for flow variation, maintenance of old and faulty system and other uncertainties in power generation. Subsequently, the annual firm hydroelectric energy was computed as;

$$Energy\ (kWh) = P_{90} \times T_{90} \times C_f \tag{6}$$

Where P_{90} is the power at 90 % dependability T_{90} is time in hours for a non leap year at 90 % dependability, 7884 hrs and C_f is the capacity factor (0.8)

The AEP was computed by estimating for the area under the PDC. In this case, the resolution of the integral function under the PDC for each site was used in the determination of the AEP.

3. Results and discussion

3.1. Identification of preliminary hydropower sites

The identification of preliminary hydropower sites were based on criteria proposed by Kusre et al. (2010). They include availability of sufficient flow, availability of adequate head and a stream reach of ≤ 3000 m. The minimum head set for the assessment of preliminary hydropower sites was 8 m with a minimum third (3rd) order stream. Based on the above criteria, a total of forty five (45) hydropower sites were identified. The number of preliminary hydropower sites identified included twenty eight (28), thirteen (13) and four (4) hydropower sites on a fifth (5th), fourth (4th) and third (3rd) order streams respectively (Table 1).

3.2. Selection of final hydropower sites

To guarantee small to high energy generation, the final selection of hydropower locations involved a minimum head of 10 m and a minimum site spacing of 500 m. The site spacing is to ensure that the tailrace of the upstream site is not affected by the diversion arrangement of the downstream site and also to ensure that the river ecosystem has enough time to recover (Dudhani et al., 2006). A total of ten (10) hydropower sites were selected after the final assessment. The final hydropower sites selected included seven (7) sites on a fifth (5th) order stream, two (2) on a fourth (4th) order stream and one on a third (3rd) order stream (Fig. 6). The maximum and minimum head of the final hydropower sites are 21 m and 10 m respectively. The maximum head occurs on a third (3rd) order stream whereas the minimum head occurs on fifth (5th) and fourth (4th) order streams. The maximum stream reach of the final hydropower sites is 858 m from hydropower site ten (HP10) which is well below the maximum threshold of 3000 m proposed by Kusre et al. (2010). The minimum site spacing of the final hydropower sites is 548 m from hydropower site six (HP6) which is greater than the minimum threshold of 500 m proposed by Yuksel (2007). The maximum and minimum water surface slopes of the proposed sites are 6.9 % and 1.2 % from hydropower sites five (HP5) and ten (HP10) respectively (Table 2).

Table 1
Preliminary Site Identification.

Str. order	Site ID	Lat.	Lon.	Str. order	Site ID	Lat.	Lon.
5	HP1	5.1598	−1.6456	5	HP25	5.5318	−1.6082
5	HP2	5.1645	−1.6328	5	HP26	5.5569	−1.5680
5	HP3	5.1891	−1.5734	5	HP27	5.5666	−1.5641
5	HP4	5.2089	−1.5655	5	HP28	5.5746	−1.5627
5	HP6	5.2311	−1.5770	5	HP29	5.5905	−1.5557
5	HP7	5.2466	−1.6013	4	HP30	5.6257	−1.5378
5	HP8	5.2507	−1.6013	4	HP31	5.6386	−1.4859
5	HP9	5.2776	−1.5882	4	HP32	5.6693	−1.5683
5	HP10	5.2816	−1.5881	4	HP33	5.6757	−1.5806
5	HP11	5.2880	−1.5958	4	HP34	5.7018	−1.5950
5	HP12	5.3032	−1.5984	4	HP35	5.7077	−1.5992
5	HP13	5.3146	−1.6056	4	HP36	5.7135	−1.5855
5	HP14	5.3325	−1.6114	4	HP37	5.7372	−1.5955
5	HP15	5.3461	−1.6186	4	HP38	5.7496	−1.5823
5	HP16	5.3504	−1.6205	4	HP39	5.8199	−1.5588
5	HP17	5.3661	−1.6285	4	HP40	5.8669	−1.4989
5	HP18	5.3718	−1.6305	4	HP42	5.9099	−1.4276
5	HP19	5.4269	−1.6278	4	HP43	5.9255	−1.4104
5	HP20	5.4574	−1.6059	3	HP5	5.2266	−1.5694
5	HP21	5.4910	−1.6161	3	HP41	5.8906	−1.5154
5	HP22	5.5109	−1.6162	3	HP44	5.9280	−1.6128
5	HP23	5.5209	−1.6157	3	HP45	5.9283	−1.5532
5	HP24	5.5296	−1.5977				

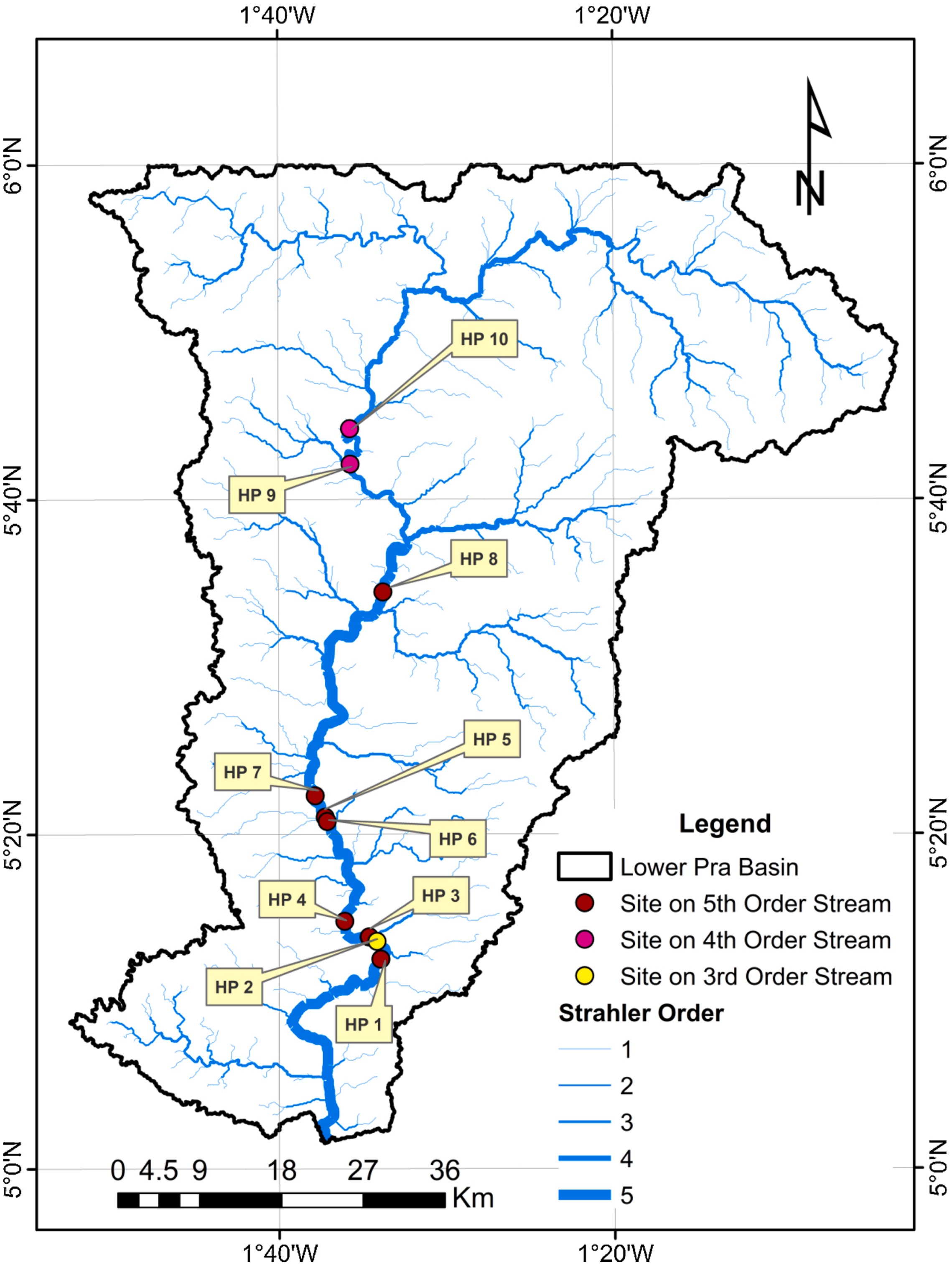

Fig. 6. Final hydropower sites along the Lower Pra River.

3.3. Land use land cover characteristics over the LPRB

The land cover types of the LPRB was characterized into four land use land cover classes to include vegetation, forest, built-up and water (Fig. 7). Vegetation was found to be the dominant land cover type representing 70.2 % of the basin area with forest, built-up and

Table 2
Details of proposed final hydropower sites along the Lower Pra River.

Str. order	Site ID	Lat.	Lon.	Head(m)	Reach(m)	Spacing(m)	Water surface Slope (%)
5	HP1	5.2089	−1.5655	10	330	2820	3
3	HP2	5.2266	−1.5694	21	703	2722	3
5	HP3	5.2311	−1.5770	15	340	3739	4.4
5	HP4	5.2466	−1.6010	10	230	4380	4.4
5	HP5	5.3461	−1.6186	11	159	9380	6.9
5	HP6	5.3504	−1.6205	11	463	548	2.4
5	HP7	5.3718	−1.6305	15	650	984	2.3
5	HP8	5.5746	−1.5627	11	390	31,610	2.8
4	HP9	5.7018	−1.5950	13	250	22,318	5.2
4	HP10	5.7372	−1.5955	10	858	8546	1.2

water constituting 23.6 %, 3.7 % and 2.5 % respectively of the basin area (Table 3).

3.4. Sensitivity analysis and fitted parameter values

Table 4 presents global sensitivity parameters with their corresponding *p*-value and *t*-stats. In global sensitivity analysis, the larger the absolute value of *t*-stat and the smaller the p-value, the more sensitive the parameter (Abbaspour et al., 2004). Given the 5% significance level, the most sensitive parameters were ESCO (t-stat = 126.1; $p < 0$), GW_DELAY (t-stat = 6.1, $p < 0$) and CN2_FOEB (t-stat = 2.2, $p < 0$).

Table 5 shows the most sensitive parameters and their respective fitted values. GW_DELAY defines the time in days taken by the water that exits the soil profile to percolate and recharge the shallow aquifer. The delay in time depends on the water table and the hydraulic properties of the geologic formations in the vadose and phreatic zones (Gyamfi et al., 2016b, 2017). The fitted value of the GW_DELAY from the calibration is 31 days.

Initial SCS curve number for moisture condition II (CN2) was one of the most sensitive parameters that affected the model output. The SCS curve number is a function of the soil's permeability, landuse and antecedent soil water conditions. Impermeability of the surface increases as the curve number increases from 35 to 98. Thus, a high CN value means a high surface runoff and a reduction in base flow (Williams et al., 2012; Gyamfi et al., 2016b). The dominant soil types (Ao1-ab-1046 and Ao7-ab-1067) in the Pra basin belong to the hydrologic soil group D and C which are characterized by high runofff and low infiltration rate. The fitted values of CN2_FOEB_Ao1_ab_1046 (75) and CN2_FOEB_Ao7_ab_1067 (70) indicate that the forest cover in the basin is characterized by moderate surface runoff and moderate infiltration rate.

The soil evaporation compensation factor (ESCO) determines the depth distribution required to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks (Abbaspour et al., 2015). It must range from 0.01 to 1. As the value of ESCO is increased, the model extracts more of the soil evaporative demand from the upper soil layer. The fitted value of 1 (Table 5) shows that most of the basin's soil evaporative demand is met by the upper soil layer.

3.5. Calibration and validation of flow

Fig. 8 and Table 6 shows the model performance statistics for both calibration (01/01/1990−31/12/2010) and validation (01/01/2011−31/12/2018) periods. It is evidenced that all the model statistics fell well within the acceptable limits. The NSE for both calibration and validation periods were well above 0.6. A model with an NSE value between 0.65 and 0.75 shows a good performance (Moriasi et al., 2007). The R^2 values recorded in the model calibration and validation are 0.73 and 0.70 respectively. According to Kwarteng et al. (2020), a model with an R^2 value between 0.70 and 0.75 indicates a good performance. Also, a model with a PBIAS value below 10 % shows very good performance and between 10 % and 15 % in absolute value indicates a good agreement between the observed and simulated flows (Gyamfi et al., 2016b). It is therefore inferred that the model's PBIAS values of 6.76 % and 13.14 % during calibration and validation respectively indicate a very good model performance. The model however underestimated the observed flow. The underestimation in flows compared to the observed data may be attributed to inconsistencies in the weather data (particularly rainfall) and the observed discharge. Hydrologic modelling presents a number of uncertainties due to the complex processes that occurs within a watershed (Abbaspour et al., 2015). In view of this, the goodness of fit and the degree to which the calibrated model accounts for the uncertainties were assessed by the p-factor and r-factor. The p-factor indicates the percentage of observed data that is bracketed by the 95 Percent Prediction Uncertainty (95PPU) envelope and the r-factor is the uncertainty indicator. The p-factor ranges from zero (0) to one (1) and r-factor ranges between zero (0) and infinity (∞). A p-factor of one (1) and r-factor of zero (0) depicts a simulation that corresponds exactly to the observed data (Abbaspour et al., 2004). From Table 6, a p-factor of 55 % (0.55) and 57 % (0.57) are observed in both calibration and validation periods repectively. Based on the criteria espoused by Abbaspour et al. (2004), the 95 Percent Prediction Uncertainty (95 %PPU) envelope of the observed flow is in a satisfactory range. The model's r-factor values of 0.37 in the calibration and validation stages indicate a good reduction of the model uncertainty and thus the acceptability of model results for further hydrological analysis of hydropower potential.

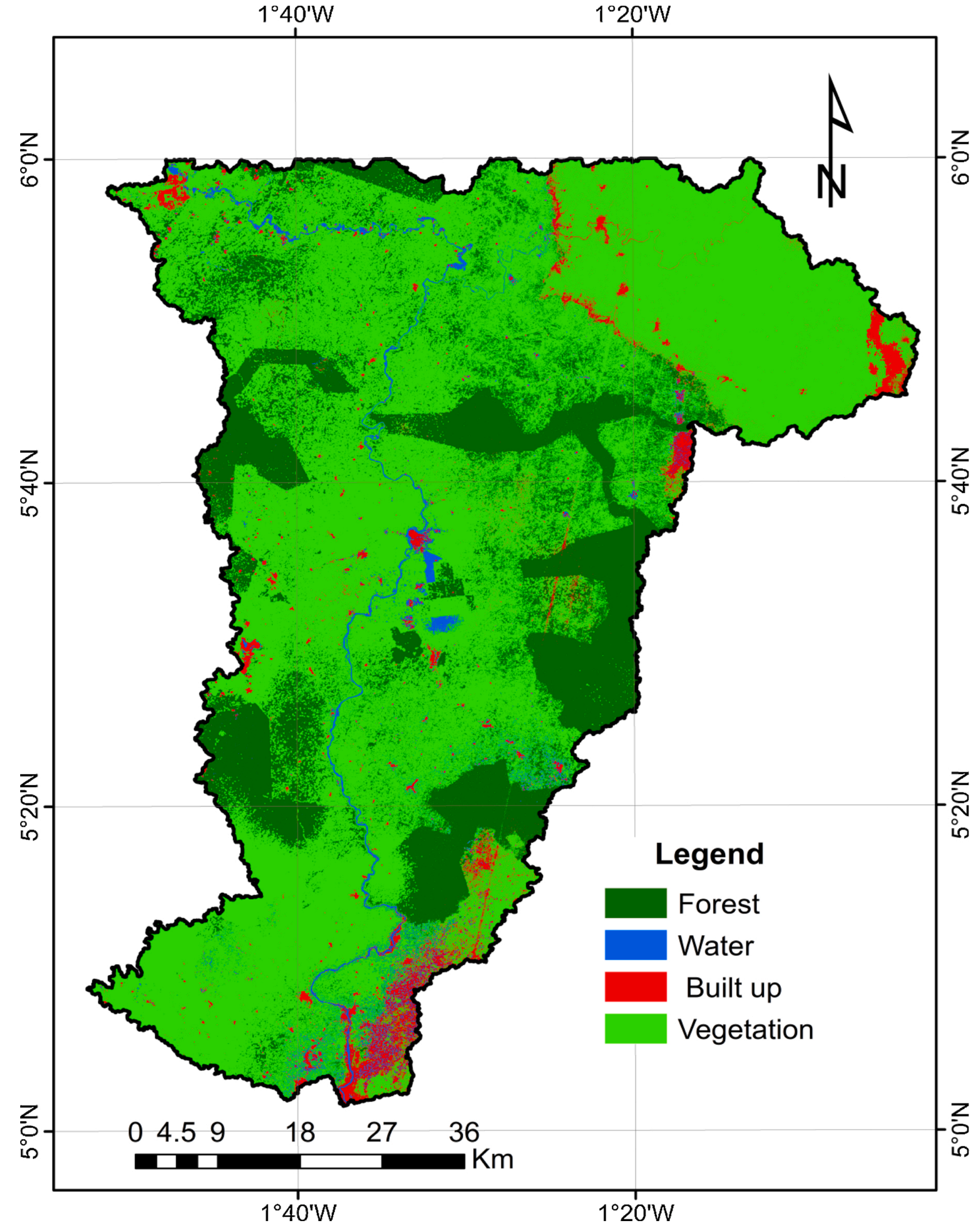

Fig. 7. Land covers class within the LPRB.

3.6. Flow assessment

Fig. 9 depicts that apart from the flow at Daboase stream gauge (180 m^3/s), hydropower site 1 (HP1, 172.9 m^3/s) recorded the highest flow followed by hydropower site 3 (HP3, 165.3 m^3/s). The lowest flow recorded was at hydropower site two (HP2, 5.3 m^3/s).

Table 3
Percentage distribution of land cover classes.

Land cover type	Description	Area (%)
Vegetation	Savanna, woody savanna, grasslands and croplands	70.2
Forest	Forest reserves and evergreen forest	23.6
Built up	Settlement, bare soil, roads and foot paths	3.7
Water	Pra river, tributaries, wetlands and any surface water resource	2.5

Table 4
Global sensitivity of model parameters after final iteration (calibration) in SWAT-CUP.

Parameter	t-stat	p-value
10:V_ESCO.bsn	126.10	0.00
3:V_GW_DELAY.gw	6.11	0.00
5:A_CN2_FOEB.mgt	2.23	0.06

Table 5
Calibrated parameters, their fitted values, minimum and maximum range.

Parameter	Fitted value	Minimum	Maximum
a_CN2_FOEB_Ao1−1046.mgt	75	35	98
a_CN2_FOEB_Ao7−1067.mgt	70	35	98
V_ESCO.bsn	1	0	1
v_GW_DELAY.gw	31	0	500

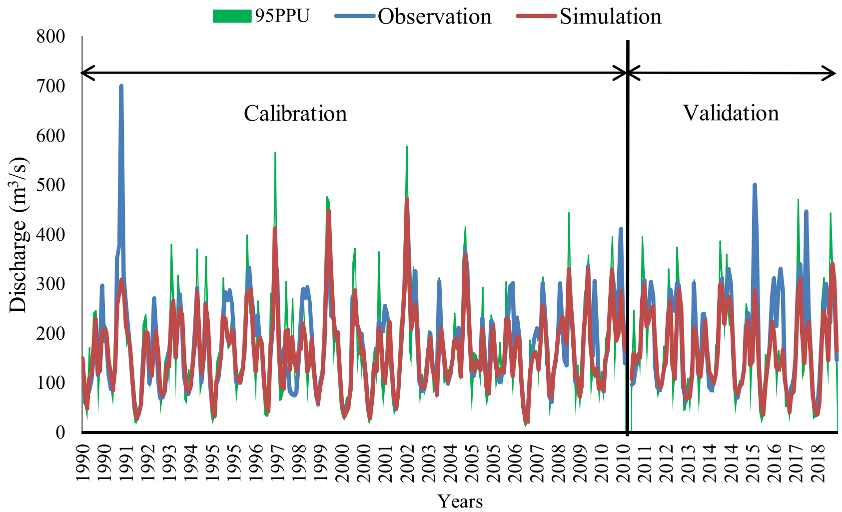

Fig. 8. Observed and simulated flows for calibration (1990 – 2010) and validation (2011-2018) periods.

Table 6
Performance of the SWAT model.

Criteria	Calibration	Validation	Performance range	Performance rating	Reference
NSE	0.71	0.63	$0.65 < NSE \leq 0.75$	Good	Moriasi et al., 2007
R2	0.73	0.70	$0.70 \leq R2 \leq 0.75$	Good	Moriasi et al., 2007
RSR	0.54	0.61	$0.5 < RSR \leq 0.6$	Good	Moriasi et al., 2007
PBIAS	6.76	13.14	$PBIAS < 10$, $10 < PBIAS \leq 15$	Very Good, Good	Moriasi et al., 2007
P-factor	0.55	0.57	$0.5 <$ p-factor ≤ 0.6	Satisfactory	Abbaspour et al., 2004
r-factor	0.37	0.37	r-factor < 0.5	Good	Abbaspour et al., 2004

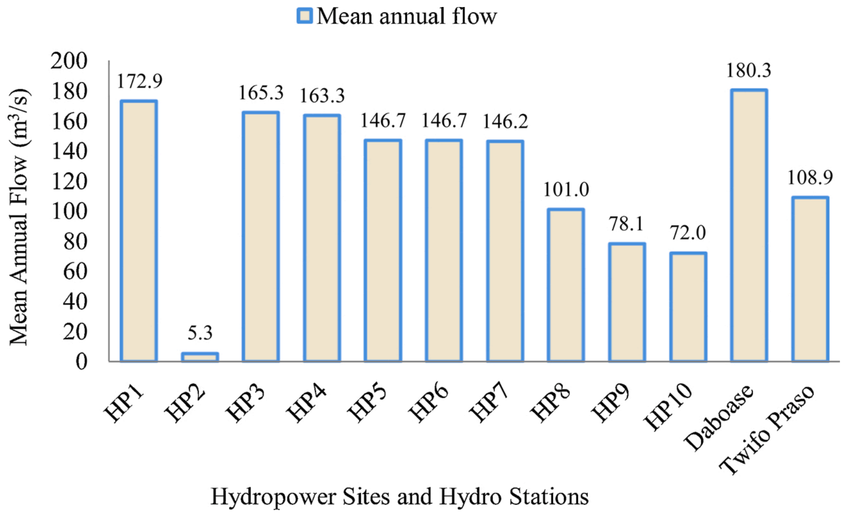

Fig. 9. Long term mean annual flows (1990-2018) at proposed hydropower sites and stream gauges in the basin.

Both HP1 and HP3 are located on a fifth (5th) order stream whereas hydropower site two (HP2) occurs on a third (3rd) order stream. This accounted for the differences in their mean annual flows.

3.7. Power and energy assessment

The firm power, annual firm energy and the total annual energy production with the minimum flow requirements for each of the proposed 10 sites are shown in Table 7. For hydropower development, a dependability of 90 % is often the preferrd choice to establish the firm power (Hidayah and Wahyuni, 2017). Consequently, for this project, the firm power at each proposed hydropower site was established at 90 % dependability. From Fig. 10, it is seen that, the firm power and flow at hydropower sites 1 (HP1) is 12.2 MW and 100.6 m^3/s respectively. Annually, this is the minimum power that can be generated 325 days at the hydropower site. The FDC also shows that, the Pra river is perennial in that even at 100 % dependability, there is still water flowing through the channel. Thus, the firm power guarantees the minimum power that can be produced even in the driest year.

Hydropower site one (HP1) recorded the highest firm power (12.2 MW) about twenty five times the firm power to be generated at hydropower site two (0.49 MW) (Fig. 10). The reason is that, hydropower site one (HP1) occurs on a fifth (5th) order stream and is located 2.7 km downstream of hydropower site two (HP2). Hydropower site two on the other hand occurs on a third (3rd) order stream. Hydropower site three (HP3) has a firm power of 9.94 MW second only to hydropower site one (HP1). Hydropower site nine (HP9) which occurs on a fourth (4th) order stream has a firm power of 4.43 MW with a firm flow of 44.3m^3/s. Thus, from Table 7 and Fig. 10, it is evidenced that the higher the stream flow the higher the power to be generated. Out of the ten (10) proposed hydropower sites, HP1 and HP2 recorded the maximum and minimum firm power respectively.

It is expected that an annual firm energy of 77.1 GW h and total annual energy production (AEP) of 183.8 GW h is to be harnessed from hydropower site one (HP1). The firm energy is the minimum annual energy to be harnessed at 90 % of the time. The total and firm energy were computed considering 86 % system efficiency, 80 % plant capacity factor and 10 % loss in hydraulic head (Clarke et al., 2008). The least annual firm energy expected to be harnessed from the ten (10) proposed hydropower sites is 2.3 GW h at hydropower site two (HP2). This site has a firm power of 0.49 MW and a total annaul energy production (AEP) of 8.5 GW h. Hydropower sites three (HP3) and seven (HP7) also show high hydropower potential with firm power of 10 MW and 9 MW respectively (Table 7). The annual

Table 7
Minimum flow, firm power, annual firm energy and total annual energy production (AEP) of proposed hydropower sites.

HP	H_e(m)	η	Q_{90}(m^3/s)	Firm Power (MW)	Firm Energy (GWh)	Total AEP (GWh)
HP1	14.40	0.86	100.6	12.22	77.10	183.77
HP2	19.11	0.86	3.1	0.49	2.33	8.48
HP3	13.50	0.86	87.2	9.94	47.01	157.67
HP4	9.00	0.86	85.3	6.48	30.65	103.97
HP5	9.90	0.86	76.2	6.36	30.10	104.34
HP6	9.90	0.86	76.2	6.36	30.10	104.34
HP7	13.50	0.86	75.7	8.62	40.77	141.91
HP8	9.90	0.86	54.9	4.58	21.68	73.67
HP9	11.70	0.86	44.3	4.38	20.70	68.80
HP10	9.00	0.86	42.0	3.19	15.09	49.20
AVG	11.99	–	64.55	6.26	31.55	99.62

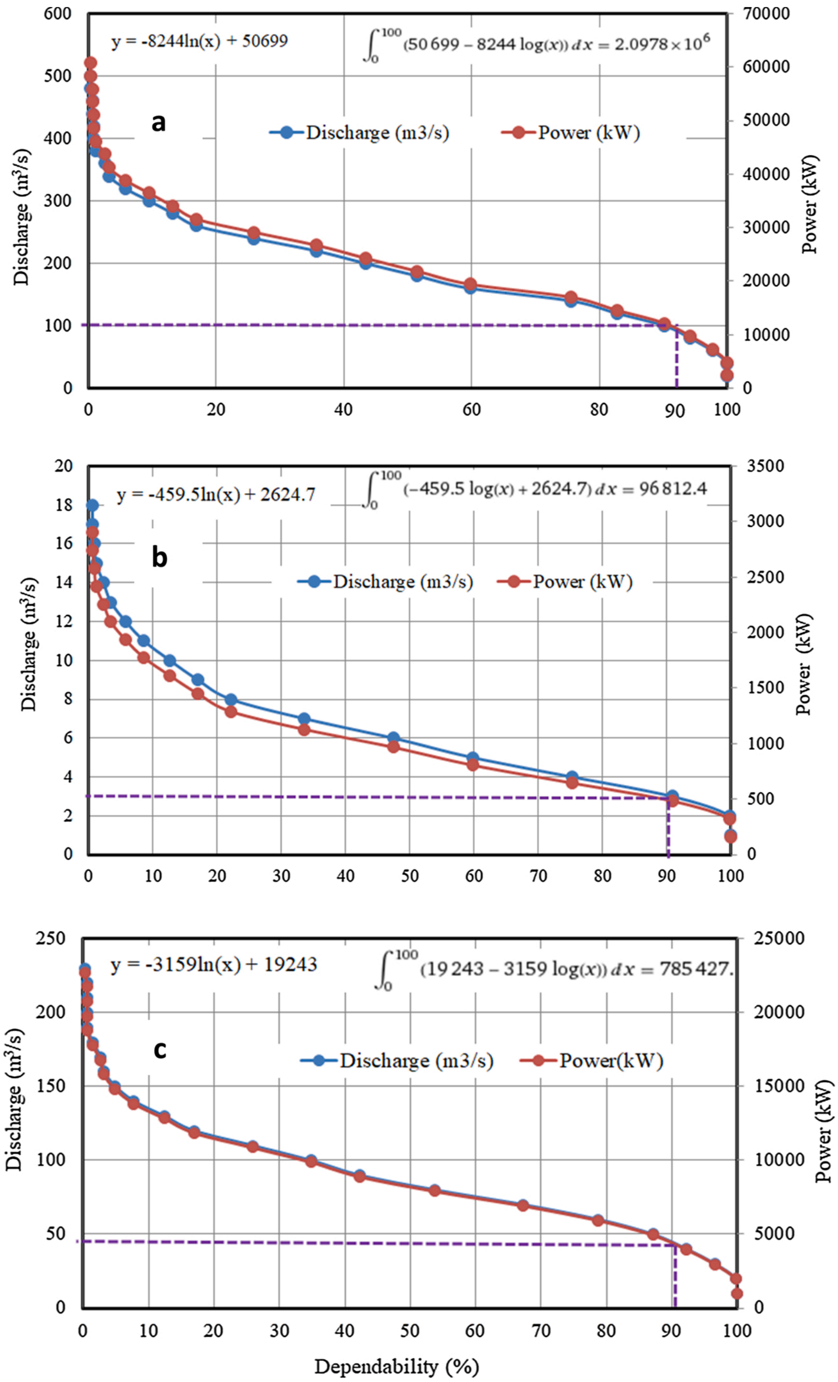

Fig. 10. Sample Flow and Power Duration Curves of hydropower sites, **a** HP1 on 5th order stream, **b** HP2 on 3rd order stream and **c** HP9 on 4th order stream.

firm energy expected to be harnessed from HP3 and HP7 are 47.0 GW h and 40.8 GW h respectively (Table 7). Also, the total annual energy production (AEP) expected to be harnessed from HP3 and HP7 are 157.7 GW h and 141.9 GW h respectively. The average firm power, average annual firm energy and average total annual energy production (AEP) expected to be harnessed from the ten (10) hydropower sites are 6.26 MW, 31.55 GW h and 99.62 GW h respectively (Table 7).

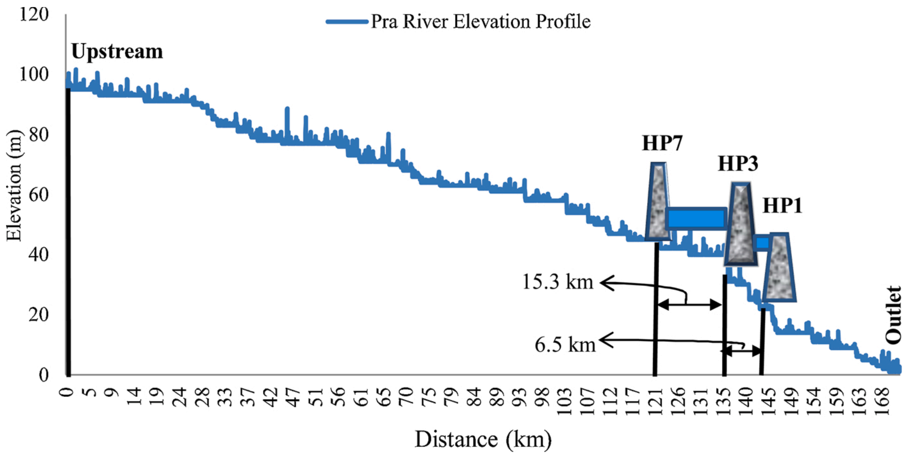

Fig. 11. A proposed cascade system of the three major small hydropower sites identified along the Lower Pra River.

3.8. Proposed cascade hydropower project along Pra River

From Fig. 11, it can be observed that the distance between hydropower site HP1 and HP3 is 6.5 km whereas that between HP3 and HP7 is 15.3 km. According to Yuksel (2007), in order to prevent the backwater or ponding created by a downstream hydropower site from affecting the tailrace arrangement (tail water) of the upstream hydropower site, the minimum distance between successive hydropower sites should be greater than or equal to 0.5 km. This condition is necessary to ensure a successful cascade hydropower project along the same river. Therefore, hydropower sites HP1, HP3 and HP7 can be developed as a cascade project along the Pra River without any interference (Fig. 11). These three sites are proposed to be developed as cascade hydropower project along the Pra River due to the considerable annual firm energy and annual total energy expected to be harnessed when combined. In fact, the combined total annual energy production (AEP) expected to be harnessed from these sites is 483.4 GW h and the combined annual firm energy is 164.9 GW h (Fig. 11).

3.9. Sediment management strategies

Given the current state and catchment characteristics, two notable sediment management techniques; bypassing and sluicing (drawdown routing) are proposed for sustainable operations of potential hydropower developments along the Pra River. Theoretically, bypassing technique diverts some of the sediment through or around the reservoir while sluicing technique removes or rearranges sediment that has already been deposited in the reservoir. In bypassing, a weir constructed upstream of the reservoir diverts sediment laden inflow into a diversion channel which then conveys the sediment laden water downstream of the dam to reconnect with the river. This technique is such that, the weir diverts during peak flows when sediment load is high but ceases during low flows when sediment load is low to allow inflow into the reservoir. This technique has been successfully applied in other jurisdiction for more than 100 years (Sumi et al., 2004).

In sluicing (drawdown routing), the reservoir pool is lowered with the objective of permitting sediment transport through the reservoir at high velocity thus minimizing sedimentation and allowing some already deposited sediments to flush out. This technique is initiated during peak flows and hence requires relatively large dam outlets. It should be noted however that, the adoption and implementation of any of these major sediment management strategies should be informed by feasibility and cost benefit analysis.

Again, given the increased mining activities in the Pra River Basin and the high erosion of finer sediments into the river, turbidity current venting offers further suitable technique for discharging sediments out of the reservoir. Moreover, erosion control strategy involving improvement in vegetation cover along the Pra riverbank will also be utilized to reduce upstream sediment erosion.

4. Conclusion

The Pra River has a potential for hydropower generation. Ten (10) sites with potential for hydropower generation were identified after the final assessment. The maximum and minimum head of the sites are 21 m and 10 m respectively. Statistically, the final model performance proved good with a Nash Sutcliffe Efficiency of (NSE, 0.71 and 0.63), Coefficient of Determination of (R^2, 0.73 and 0.70), Percent BIAS of (PBIAS, 6.76 % and 13.14 %), RMSE standard deviation ratio of (RSR, 0.54 and 0.6), p-factor of (0.55 and 0.57) and r-factor of (0.37 and 0.37) for calibration and validation respectively. The maximum and minimum mean annual flows of 172.9 m^3/s and 5.3 m^3/s were recorded at hydropower sites one (HP1) and two (HP2) respectively. Hydropower sites three (HP3) and four (HP4) also recorded high flows with mean annual flow of 165.3 m^3/s and 163.3 m^3/s respectively.

With regards to hydropower potential, the maximum firm power of 12.22 MW was obtained at site 1 (HP1) while the minimum firm power of 0.49 MW was at site 2 (HP2). The average firm power of the ten (10) hydropower sites is 6.26 MW. Moreover, the highest and lowest annual firm energy expected to be harnessed were 77.10 GW h and 2.33 GW h at HP1 and HP2 respectively. A total annual energy production (AEP) of 183.77 GW h is to be harnessed at hydropower site one (HP1) and is the highest among the proposed sites. The average firm energy and total AEP from the ten (10) proposed hydropower sites are 31.55 GW h and 99.62 GW h respectively. Conclusively, the combined total annual energy production (AEP) expected to be harnessed from hydropower sites HP1, HP2 and HP3 is 483.4 GW h with a combined annual firm energy of 164.9 GW h.

Authorship contribution

Emmanuel Arthur: Data analysis and write-up.
Fred Oppong Kyekyeku Anyemedu: Project conceptualization, structuring and review.
Charles Gyamfi: Data curation and model setup.
Patricia Asantewaa – Tannor: Methodological framework, write-up and review.
Kwaku Amaning Adjei: Software resources and validation of methodology.
Geophrey Kwame Anornu: Model parameterization, review and editing.
Samuel Nii Odai: Overall guidance, review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study was funded by the Regional Water and Environmental Sanitation Centre, Kumasi (RWESCK) at the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, with funding from the Government of Ghana and the World Bank, under the Africa Centres of Excellence project (Grant No: ACE I - P126974-Cr. No. 54230). The views expressed in this paper do not reflect those of the World Bank, Government of Ghana and the KNUST.

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