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ELECTRICAL & ELECTRONIC ENGINEERING | RESEARCH ARTICLE

Parametric study of a proposed small hydropower project at Gurara-Nigeria

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Abstract: The energy crisis in developing is increasing by the day due to immigration and an increase in population. Hydroelectricity has been spotted to be the cheapest alternative energy option that can be financed by the government and private investors. In this research, a parametric investigation on the proposed small hydropower project was carried at Gurara, Nigeria. This project aims to incorporate a 4 MW hydropower plant within the waterfall neighborhood that already serves as a tourist center. The remote sensing dataset was used to map out the study location's elevation and determine the possibility of a sustainable reservoir based on the rainfall pattern in the geographical location. It was observed that an average rainfall of 400 mm at efficiency between 0.65 and 0.75 would enable optimal energy generation. Also, it was found out that the bank elevation of the water path is equally important as designing the head-section of the hydroelectricity dam. Hence, the study location has enormous potentials to serve energy demands in Nigeria.

Subjects: Renewable Energy; Technology; Electrical & Electronic Engineering

Keywords: hydroelectricity; energy; dam; remote sensing; head of dam

1. Introduction

Alternative energy sources include biomass energy, wind energy; solar energy; geothermal energy; hydroelectric energy, etc. Sustainable energy sources like solar energy – solar energy is a sustainable energy source because the sun is always there; the sun is readily available to give out energy (Tian & Zhao, 2013). The definition of alternative energies changes over time; generally, what is defined, as an alternative source of energy is any other energy source other than fossil

ABOUT THE AUTHOR

Emetere Moses Eterigho is an expert in energy and environment. He has worked extensively on Sustainable Development Goals 7 (SDGs-7) and have proposed several blue-print on how to overcome energy crisis in developing countries. He has doctorate degrees in Solid State Physics and Industrial Physics. The motivation for this study is to optimize waterfall in rural areas for tourism and energy generation.

Moses E. Emetere

PUBLIC INTEREST STATEMENT

The growing energy demands in third world country are huge, that is owing to population, technological and poverty increase. The study area has fundamental challenges in accessing the listed alternative energies based on the availability, affordability, and accessibility. Based on the above, the hydroelectric energy is recommended for the study area to meet up with the growing energy needs. This study suggests the waterfall at Gurara, Nigeria could be modified to serve tourism and energy generation demand at the same time. The paper highlights specific parameter that would make this proposal a workable document.

fuels, and does not contribute to global warming (Ebrahimian, 2003). Energy obtained from organic materials like wood and plants can be said to be biomass. Energy from biomass can be tapped via burning or heating it directly or processing it first into biofuels like ethanol and methane. One of the reasons biomass is renewable is its short carbon cycle (Boocock et al., 1996). The use of biomass does not add to the greenhouse effect; it can be replenished and sustainable. Solar energy is a form of alternative energy gotten from the sun; this is the most secure form of alternative energy source because the sun will always be there, and therefore solar energy will always be available. Solar energy is also the most popular form of alternative energy. Most modern inventions use solar energy; good examples of inventions that work on solar energy are solar cookers, solar chargers, and boiling water using solar energy. Wind energy is the form of energy gained from the wind's speed as it spins the turbines. Wind turbines are usually placed near the top of the hill because the wind is affected by topography (Hasternrath, 1990). The wind comes from the difference in the local and global scale of motion. The main challenge of solar and wind energy is its dependency on the weather; hence, it is now significantly altered by climate change (Emetere, 2016b; Emetere & Akinyemi, 2015). The study area has fundamental challenges in accessing the listed alternative energies based on the availability, affordability, and accessibility. Based on the above, the hydroelectric energy is recommended for the study area to meet up with the growing energy needs.

There are significant risks to consider when citing a small hydropower plant in an unknown geographical location. This risk may be hydrological, construction risk, risk of design flaws, and environmental risk. One or more of the risks mentioned above can crumble hydropower developers and investors, leading to litigations and unnecessary finance drainage. Construction risk and plant design flaws could be corrected with extra budgeting and expert counsel; however, hydrological and environmental risks are most time unredeemable. This paper aims to seek efficient ways of minimizing the hydrological and environmental risks in the bid to construct a small hydropower plant in waterfall without affecting its tourist attraction.

The world is under the siege of air pollution caused by fossil fuel; hence, the need for alternative energy sources has arisen (West et al., 2013; Zani et al., 2015). As a result of this, alternative energy sources have been adopted as new energy options. Developed countries about today have explored into the multi-faceted application of alternative energies. Research has shown that non-renewable energy sources are significant causes of climate change (Emetere, 2016a). Alternative energy resources limit the risk concerning ozone layer depletion because such reduces the emission of carbon monoxide in the atmosphere. A good advantage of alternative energy supply is reducing carbon monoxide via biomass (Haas et al., 2001; Yusoff et al., 2014). However, there is the challenge that some bio-fuels may introduce another kind of pollution, such as nitrogen oxides, as its main component.

Geothermal energy is obtained from the heat in the earth; geothermal energy is renewable because it is inexhaustible – it cannot finish. This form of energy provides more electricity than solar energy and about the same as wind energy. It is not expensive and does not pollute the environment—it is environmentally friendly. Unlike solar and wind energy, it is not dependent on the nature of the weather. Another alternative energy sources that do not depend on the weather are hydroelectric energy. Hydro generally means water; therefore, hydroelectric energy is the energy obtained by the force of water that is energy from waterpower. When using hydroelectricity, the kinetic energy from the falling water is converted to electricity. This form of energy reduces the emission of greenhouse gases (Gulliver John & Arandt Roger, 1991).

Africa is currently plagued with an energy crisis, partly due to the increasing population, inadequate energy planning, etc. This study's importance is to enlighten energy specialists in Africa on the need to concentrate on the hydropower project. Figure 1 shows how widely used are hydropower projects across the globe. The hydropower dam is basically divided into three sections, i.e., head, turbine, and generator (Wood, 1984). The last two sections are primarily

Figure 1. Global hydropower generation.
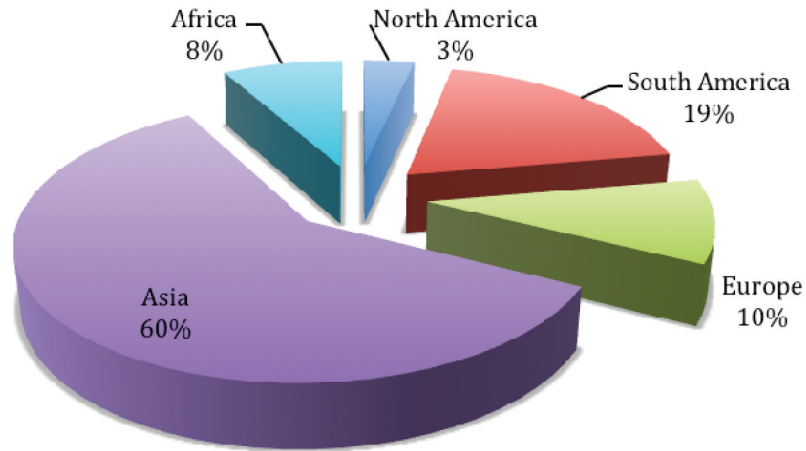
dependent on imports from companies. The most crucial section as regards to this paper is the head section. The head section relates to the vertical profile of the hydro dam itself. Africa, like other challenged regions of the world, is endowed with rivers and other waterbodies. Most salient among these qualities is the topography of the region that can trigger a vertical profile gradient for the flowing water (Bozhinova & Hecht, 2012). This paper aims to seek simple ways of evaluating the potential of hydropower dams via the head-section. The head section is the height difference between the water level in the reservoir and water level entering the turbine, as presented in Figure 2.

In this paper, the focus is on the hydroelectricity energy project. There are three main sections in the hydro dam, i.e., the head, turbine, and generator. This paper theoretically looks into several challenges relating to the head-section of the hydro dam. Several hydropower models would be modified to actualize this study. Good hydropower models are adjustable and flexible to be modeled out, rearranged, and possibly have solutions using mathematics methods. Several known models are adopted to solve problems or design hydropower station (Fang et al., 2008; Nicolet et al., 2007). Therefore, using models to provide a solution to this type of problem involves

Figure 2. Definition of the head section.
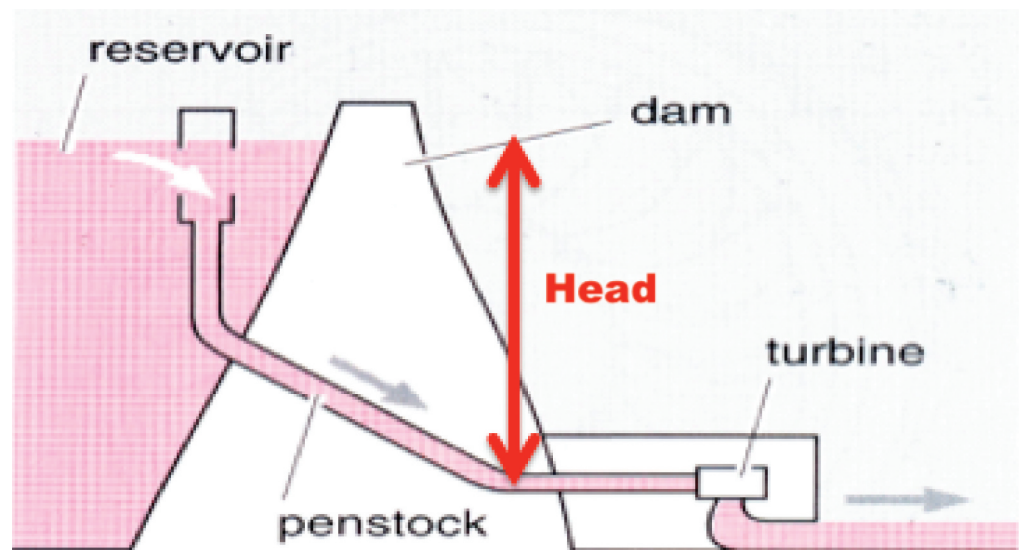
a model that must be designed, and then the many technical scenarios are considered, which forms the technicality of the model. The guiding principles of any energy system are its adherence to the law of conservation of energy that can exist in several forms; potential energy, mechanical energy, vibrational energy, electrical energy, heat energy (Gansel et al., 2014). That means that the total energy of a system remains the same. The second law of thermodynamics states that the energy of a system increases with time; it is implied that the energy sources have different qualities in terms of usability. It is upon this basis the several modifications to known models would be applied in this study. The new model design is expected to enhance better energy generation. However, the incorporation of two reservoirs in the design was not implemented due to specific logistic challenges. The limitation of this work is the topography of the study site. More funds may be required to construct the proposed hydropower dam to fit the recommended parameters.

2. The study area of the proposed hydropower plant

The study area is the Gurara falls in Nigeria. Gurara is a tourist attraction on Gawu-Kafin-Adunu-Beni Road, Gurara, Niger state, Nigeria (Figure 3). The research location has an area of 954 km2. It is mainly an agro area with little development. The research site is located on latitude and longitude of 9.3418° N and 7.0498° E. The research site is known for the presence of a waterfall that is about 30 meters in height, and it lies on the Gurara River. The river is located on the Gurara inter-basin that lies between latitudes 8°-l 1°N and longitudes 7°30′-8°30′E. Its vegetation is savannah, i.e., southern Guinea Savannah zone. It is also characterized by grassland interspersed with remnants of tropical forests.

3. Geology of study area

Gurara is located on the Precambrian Crystalline Basement Complex rocks of North Central Nigeria. The rock formations in the area consist mainly of granite gneiss, schist, and migmatite. Generally, there had been significant localized faulting and folding along the granite gneiss and migmatites that occupy the entire downstream area. The geological survey of Gurara has been conducted in different phases. Ilesanmi et al. (2013) found that a portion of the phase II Gurara project (which was situated about 62 km northwest of Abuja and 58 km southeast of Minna) was characterized by

Figure 3. Research location.
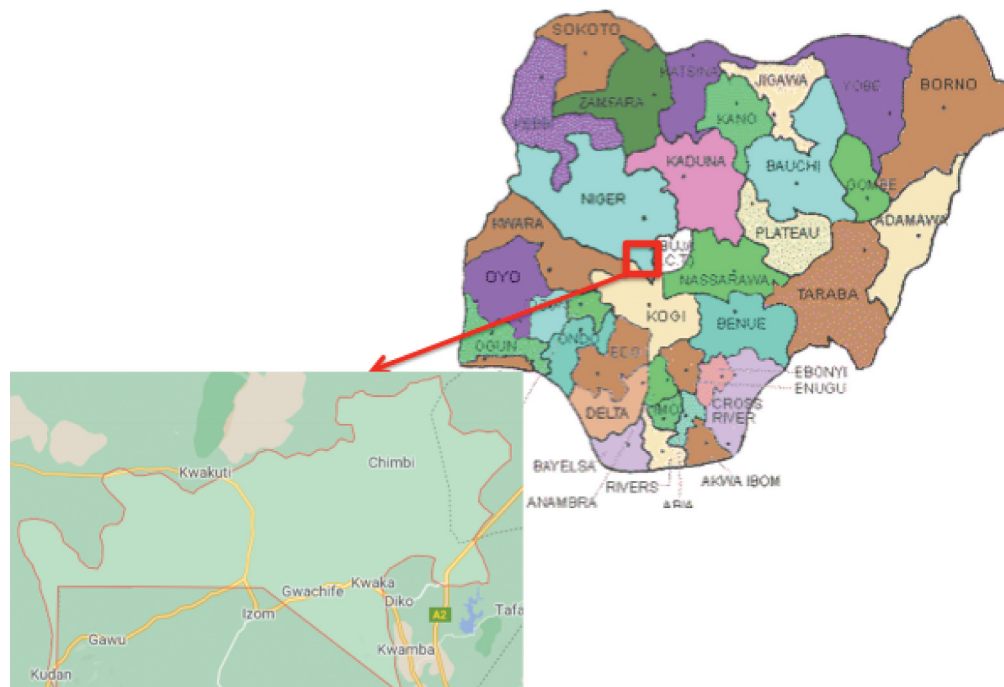
significant fracturing of the bedrock with possibilities for seepage. Okunlola et al. (2014) noted that fracturing intensity controls the groundwater in basement terrains.

4. Remote sensing survey

The satellite imagery of the research site is presented in Figure 4. The preliminary site analysis plan is shown in Figure 5. The particular area we are considering is a rectangle with a perimeter of approximately 1,957.5 m, and an area of 237,051.34 m^2 around the waterfall itself. Sixty points arranged in a regular pattern on the perimeter of and inside the rectangle was taken. Here, using the data provided by Google Earth, we would be recording the co-ordinates and elevation at each point specified by the white dots.

Starting from the top left, we name the horizontal lines A—F, while the points on each line have several 1–10 moving from left to right, such that the point at the top left corner is A1, the top right corner is A10, the bottom right is F10, and so on. These points would guide the recommendation for criteria like the size of the dam and the kind of power it could generate. The vertical profiles for each horizontal line are presented in Table 1–6.

Figure 4. An overhead view of the waterfalls via Google Earth.

Figure 5. The site area with the points specified.

Table 1. Vertical profile along with horizontal line A			
S/N	Latitude	Longitude	Elevation (m)
1	9°18'58" N	7°01'07" E	349
2	9°18'58" N	7°01'09" E	345
3	9°18'58" N	7°01'11" E	341
4	9°18'58" N	7°01'13" E	334
5	9°18'58" N	7°01'16" E	329
6	9°18'58" N	7°01'18" E	332
7	9°18'58" N	7°01'20" E	336
8	9°18'58" N	7°01'22" E	337
9	9°18'58" N	7°01'23" E	341
10	9°18'58" N	7°01'24" E	342

Table 2. Vertical profile along horizontal line B			
S/N	Latitude	Longitude	Elevation (m)
1	9°18'55" N	7°01'07" E	347
2	9°18'55" N	7°01'09" E	344
3	9°18'55" N	7°01'11" E	339
4	9°18'55" N	7°01'13" E	334
5	9°18'55" N	7°01'16" E	327
6	9°18'55" N	7°01'18" E	329
7	9°18'55" N	7°01'20" E	333
8	9°18'55" N	7°01'22" E	335
9	9°18'55" N	7°01'23" E	337
10	9°18'55" N	7°01'24" E	340

Table 3. Vertical profile along with horizontal line C			
S/N	Latitude	Longitude	Elevation (m)
1	9°18'53" N	7°01'07" E	344
2	9°18'53" N	7°01'09" E	341
3	9°18'53" N	7°01'11" E	337
4	9°18'53" N	7°01'13" E	332
5	9°18'53" N	7°01'16" E	322
6	9°18'53" N	7°01'18" E	321
7	9°18'53" N	7°01'20" E	324
8	9°18'53" N	7°01'22" E	331
9	9°18'53" N	7°01'23" E	335
10	9°18'53" N	7°01'24" E	339

Table 4. Vertical profile along with horizontal line D			
S/N	Latitude	Longitude	Elevation (m)
1	9°18'50" N	7°01'07" E	342
2	9°18'50" N	7°01'09" E	339
3	9°18'50" N	7°01'11" E	335
4	9°18'50" N	7°01'13" E	329
5	9°18'50" N	7°01'16" E	312
6	9°18'50" N	7°01'18" E	306
7	9°18'50" N	7°01'20" E	312
8	9°18'50" N	7°01'22" E	322
9	9°18'50" N	7°01'23" E	328
10	9°18'50" N	7°01'24" E	334

Table 5. Vertical profile along with horizontal line E			
S/N	Latitude	Longitude	Elevation (m)
1	9°18'47" N	7°01'07" E	338
2	9°18'47" N	7°01'09" E	333
3	9°18'47" N	7°01'11" E	329
4	9°18'47" N	7°01'13" E	321
5	9°18'47" N	7°01'16" E	305
6	9°18'47" N	7°01'18" E	300
7	9°18'47" N	7°01'20" E	308
8	9°18'47" N	7°01'22" E	318
9	9°18'47" N	7°01'23" E	324
10	9°18'47" N	7°01'24" E	327

| Table 6. Vertical profile along with horizontal line F			
S/N	Latitude	Longitude	Elevation (m)
1	9°18'44" N	7°01'07" E	331
2	9°18'44" N	7°01'09" E	324
3	9°18'44" N	7°01'11" E	320
4	9°18'44" N	7°01'13" E	311
5	9°18'44" N	7°01'16" E	299
6	9°18'44" N	7°01'18" E	301
7	9°18'44" N	7°01'20" E	311
8	9°18'44" N	7°01'22" E	318
9	9°18'44" N	7°01'23" E	321
10	9°18'44" N	7°01'24" E	323

The elevations defined in Table 1–6 are used in the modified model that would be discussed in the next section.

5. Theoretical calculations

Based on the elevations estimated in Table 1–6, the slope of the falls was measured using the middle points A5—F5 at the center of the river (Figure 6). Figure 6 reveals how steep the construction of the dam can go without much digging. Hence, the hydropower dam may follow

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Figure 6. A graph showing the slope of the falls.
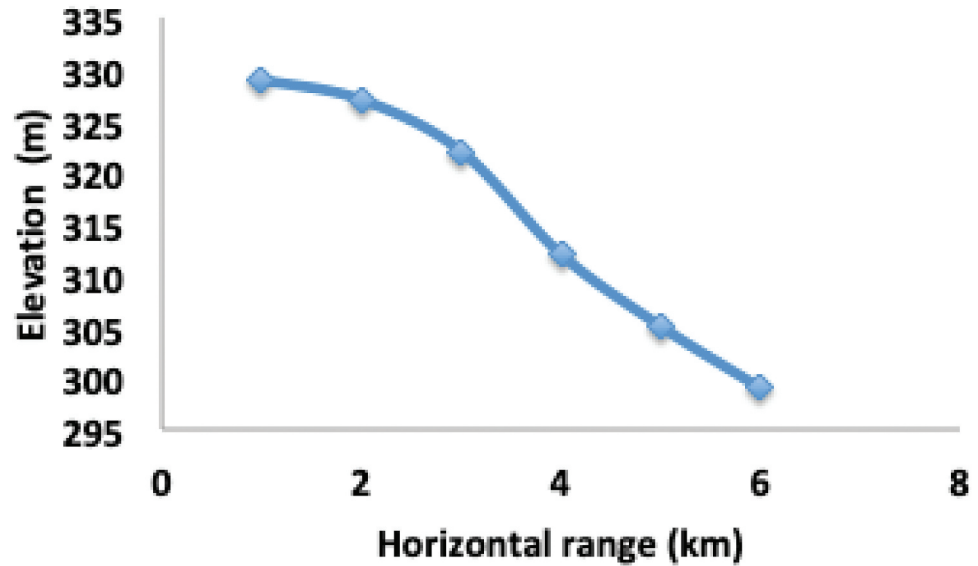
the design below. The volumetric calculation between the heights of the dam to the reservoir can be mathematically written as

$$h1 = Z_0 + \alpha\left(\frac{V}{Vi} - 1\right)^{\beta} \tag{1}$$

where $h1$ is the water level in the dam that flows into the reservoir, V is the volume of water in the reservoir, Z_0 is the nominal water level in the reservoir, α, β are positive parameters, Vi is the minimum water volume in the reservoir.

The adopted hydro dam system is described in Figure 7, where there are expected to be two reservoirs in the region whose annual rainfall is led than 300 mm.

Figure 7. Adopted hydro dam system.
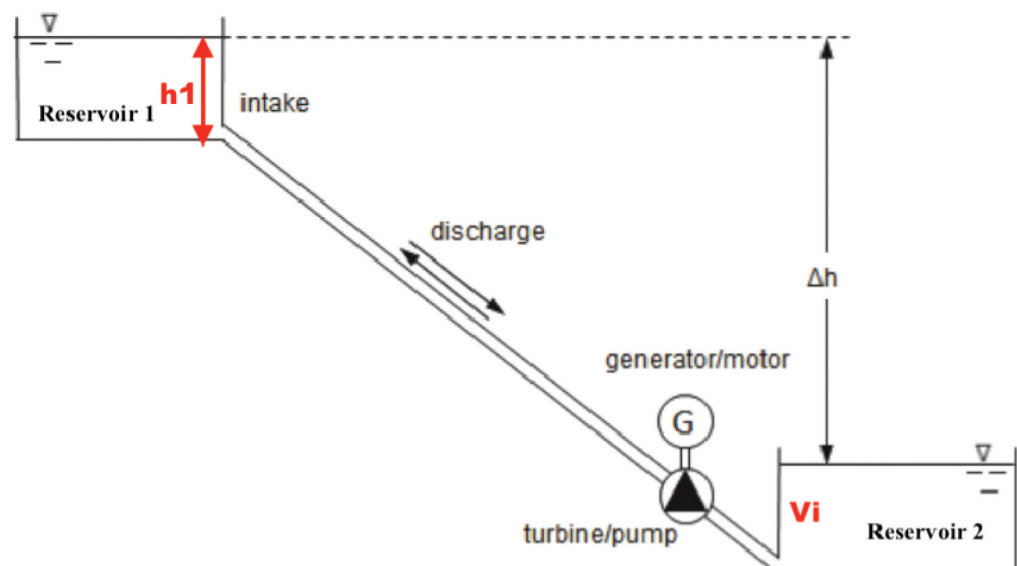
The expected power that can be generated under this circumstance (White, 1999) is given as

$$p = \frac{\eta \lambda V h}{1000} \tag{2}$$

where P is the generator output in (kW), *V* is the water flow through the turbine in (m^3/s), Δh is the net head of water (m) (the difference in water level between upstream and downstream of the turbine), η is the Station Efficiency and γ is the specific weight of water (N/m^3)

Since we are more interested in the head section, the potential energy (White, 1999) that can be generated by design is given as:

$$E = \rho \, \dot{V} g \, x (h1 - h_m) \tag{3}$$

where h1 is the elevation of the point above a reference plane (in the positive z-direction) as described in equation (1) and Figure 7, h_m is the elevation of the research site, ρ is the density of the fluid at all points throughout the fluid (Kg/m^3), g is the gravitational acceleration (m/s^2), V is the volumetric flow rate (in cubic metres per second), $(h1 - h_m)$ is the deviation of elevation from its average elevation around the study location.

If equation (2) is substituted into (3), then

$$\dot{V} = \frac{1000(h1 - h_m)}{h\eta} \tag{4}$$

Based on the modified equation presented in equation (4), the station efficiency based on the elevation location can be found.

The deviation of the elevation, as calculated above, is given in Table 7 and 8. The results show that the maximum *h* can be obtained on longitude and latitude 7°01′07″ E and 9°18′47″ N, respectively.

It was observed that the hydropower dam could not be located between longitude 7°01′13″ E—7°01′24″ E. Hence, the longitude mentioned above is not used to estimate the dam's approximate volumetric flow rate as given in equation (4).

The approximate volumetric flow rate was plotted against the elevation, as depicted in equation (4). The station efficiency is assumed to be between 65%-85%. At longitude 7°01′07″ E, the volumetric flow rate is expected to be more stable than other longitudinal analysis. It observed that the maximum volumetric flow rate was at midpoint elevation, i.e., the center of the river. Secondly, it is observed that the proposed dam's stability would be at the highest elevation that is not located along the river path (Figure 8). Technically, this result means that if the dam is repositioned from the center of the river path, there may be more stable hydropower generation throughout the year.

The volumetric flow rate analysis at longitude 7°01′09″ E is presented in Figure 9. Like in Figure 8, it also affirmed that the highest volumetric flow rate could only be found at the center of the river. However, the highest elevation around the river at this longitude reveals that the elevation at the riverbank has a huge influence on the stability of the dam.

The volumetric flow rate analysis at longitude 7°01′11″ E is presented in Figure 10. The information was almost as revealed in Figure 9. However, the smoother curves at the highest elevation further affirm that the elevation at the bank of the river has a huge influence on the volumetric flow rate.

Table 7. Deviation of elevation around the research site

	9°18'58" N (measured in meter)	9°18'55" N (measured in meter)	9°18'53" N (measured in meter)	9°18'50" N (measured in meter)	9°18'4.7" N (measured in meter)	9°18'44" N (measured in meter)
7°01'07" E	10.40	10.50	11.40	16.10	17.70	15.10
7°01'09" E	7.56	8.67	9.67	14.89	14.67	9.78
7°01'11" E	4.50	4.75	6.88	12.75	12.50	7.00
7°01'13" E	−1.86	0.43	2.86	8.57	6.29	−1.00
7°01'16" E	−7.17	−6.50	−6.67	−7.00	−8.67	−13.17
7°01'18" E	−5.60	−5.80	−9.00	−14.40	−15.40	−13.80
7°01'20" E	−3.00	−3.25	−8.25	−12.00	−11.25	−7.25
7°01'22" E	−3.00	−2.33	−4.00	−6.00	−5.00	−2.67
7°01'23" E	−0.50	−1.50	−2.00	−3.00	−1.50	−1.00
7°01'24" E	0.00	0.00	0.00	0.00	0.00	0.00

Figure 8. Volumetric flow rate analysis along longitude 7° 01'07" E.
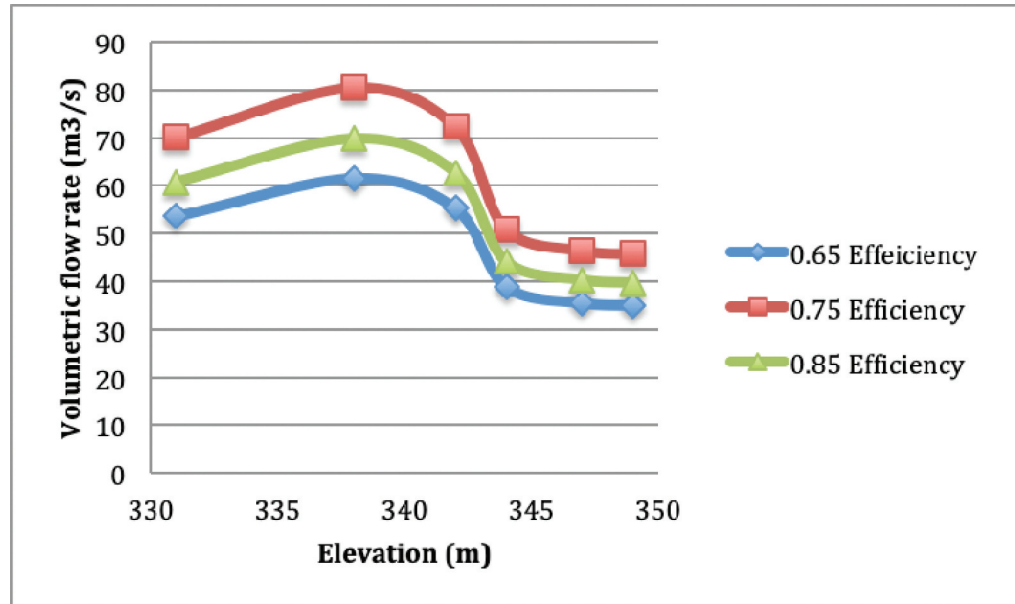
**Figure 9. Volumetric flow rate analysis along longitude 7° 01'09" E.**
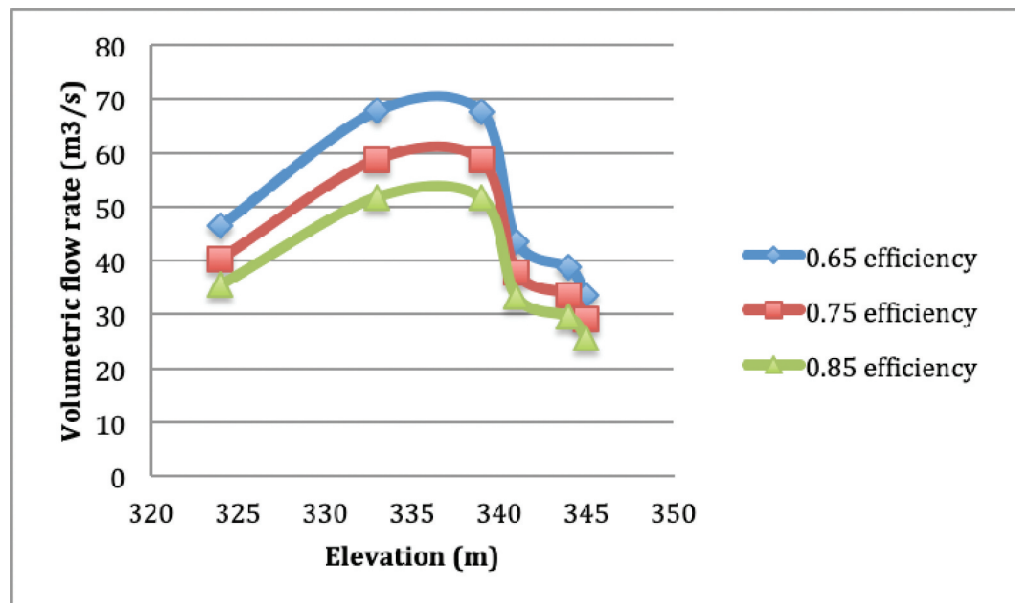
Following the falls' relatively steep slope, we can estimate that the head's height should be above 64.7 m to run the preferred turbine, i.e., Francis turbines. This calculation would solve the challenge of water level fluctuation during seasonal variations. The elevated riverbank would ensure enough water is stored for some running during the dry season.

6. Small hydropower project site design

The small hydropower system is proposed to have 4 MW capacities at a maximum discharge of 80.5 m^3/s. Figure 3 would then be transformed into an image close to Figure 11. Like any hydropower project, this section's emphasis is based on size, head, and local meteorology. The proposed small hydropower plant's equipment is a modified version of Tokyo Electric Power Services Co., Ltd

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Figure 10. Volumetric flow rate analysis along longitude 7° 01'11" E.
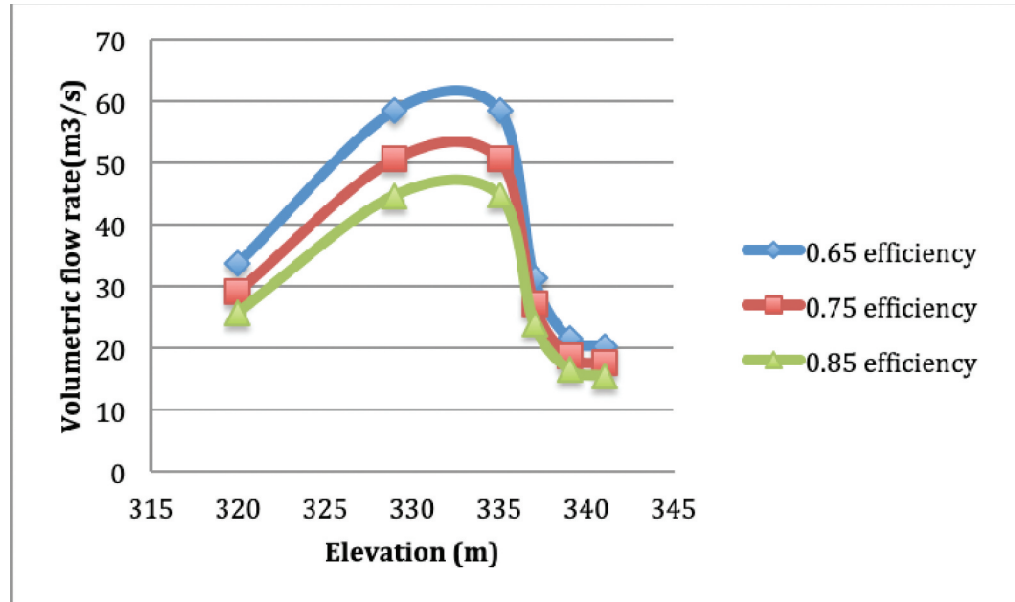
Figure 11. *Cross-section of small hydropower design (*Kaunda et al., 2012**).**
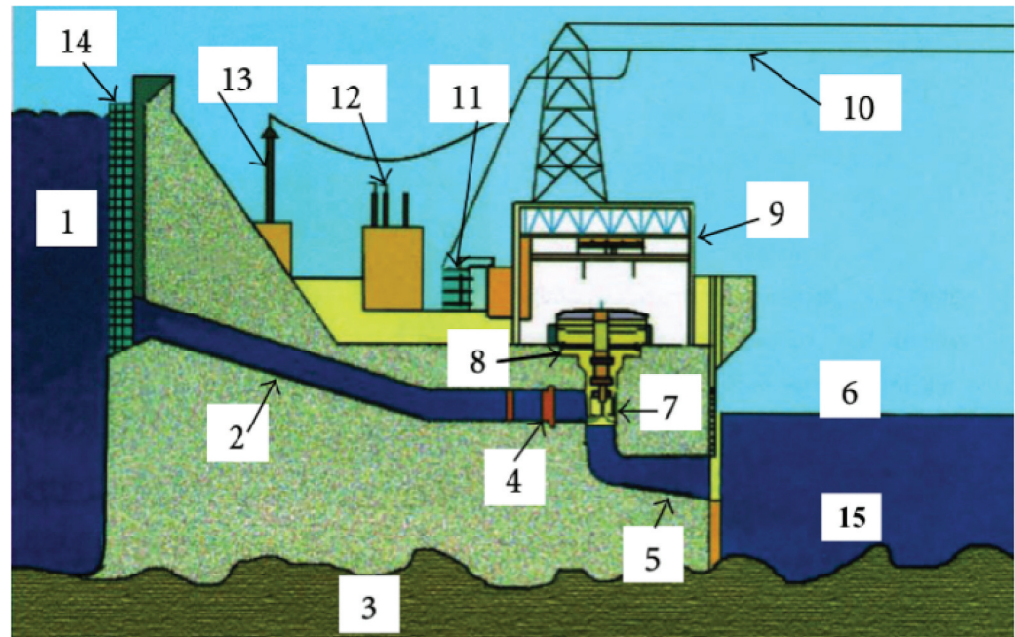
(1) Reservoir 1   (6) Tailrace water   (11) Transformer
(2) Penstock   (7) Turbine   (12) Insulators
(3) Bed rock   (8) Generator   (13) Transmission tower
(4) Valve   (9) Power house   (14) Trash rack
(5) Draft tube   (10) Transmission lines (15) Reservoir 2

Table 8. *Equipment for small-hydropower plant* (TEPS, 2013)	
Equipment	**Specification**
Water Turbine and Generator	**Submerged turbine generator four units turbine: vertical shaft propeller turbine 2.3 MW, 800 rpm Generator: Vertical shaft three phases synchronous generator 2000.5 kVA, 800 rpm**
Controller	**Start and stop the operation of the plant protection stop control voltage, current, output observation automatic synchronizer protection relay isolated operation detecting device**
Main Transformer	**Type: Oil self-cooling three-phase transformer rated capacity: 500kVA Voltage: 22kV/440 V**
Switch Gear	**Three Phase Switchgear with Fuse Transformer for Instrument Current Transformer for Instrument Arrester**

(TEPS, 2013) presented in Table 9. The proposed hydropower plant design will be more effective if a dam is built to produce electricity at a constant rate. This result means that a large reservoir is needed to save water for electricity demand periods. The lake that forms behind the dam can be used for water sports to boost tourist experience.

The reservoir potential in this research was estimated using the rainfall dataset over the region. The reservoir acts much like a battery, storing water to be released as needed to generate power. Several factors are responsible for the loss of live storage in the reservoir, namely geology, ground slopes, climate, drainage density, rainfall pattern, and human activities (Luis et al., 2013). The most potent factor is the rainfall pattern. Northeast trades from the Sahara desert and the Southwest Monsoon from the Atlantic ocean are two driving forces that influence rainfall in the research site and other West Africa (Hasternrath, 1990). The rainfall pattern generally influences the hydro-logical behavior of rivers in the tropics. Hence, the reservoir potential of the proposed hydro station is dependent on the rainfall patterns. The rainfall pattern was investigated using ten years of rainfall dataset (2010–2019) as presented in Figure 12.

The research site's rainfall is high between June and August for the past ten years, with a maximum value of >500 mm. This data, i.e., in conjunction with the topography investigation presented in Figure 5, shows that the proposed hydropower plant could be incorporated into the Gurara waterfall. The local government authorities can still main the funds from tourist activities while generating a sizeable electricity amount. The proposed site plan is presented in Figure 13.

7. Environmental risk analysis

The citing of the small hydropower plants in the Gurara community would undoubtedly create jobs and improve its electricity supply. However, the most dangerous factor is the environmental challenges that investors should endeavour to factor-in during the site survey analysis. The first

Figure 12. Rainfall pattern in research site (a) 2010–2014 (b) 2015–2019.
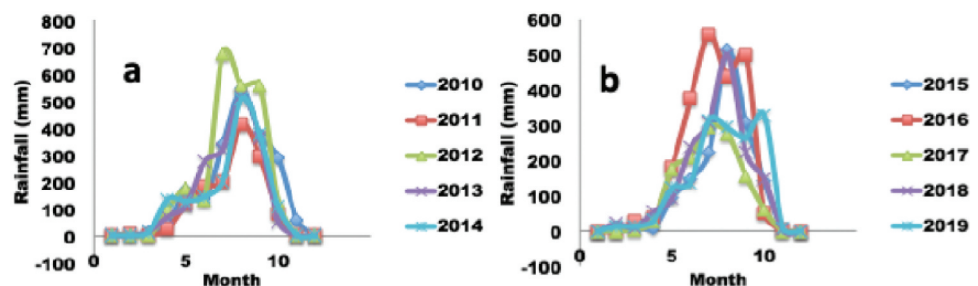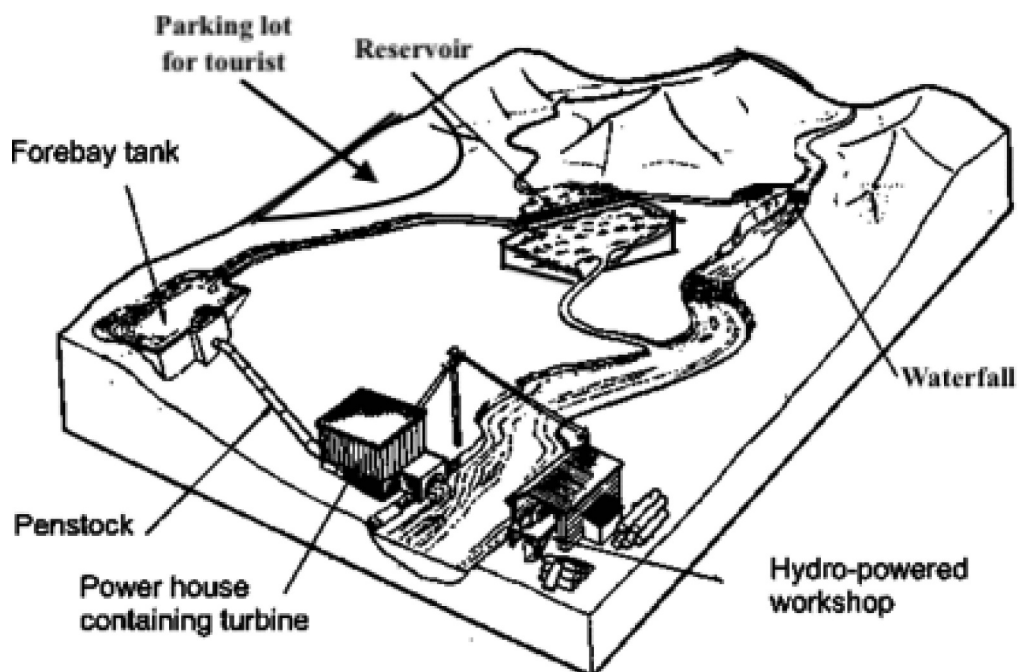
Figure 13. Proposed hydro-power site plan.

disadvantage is the contamination of the Gurara river from construction sites. The Gurara river is significant as it extends to several rivers and dams (Okunlola et al., 2014). This result means that over 300,000 people will be deprived of water during the construction. Also, when the construction is ongoing, the emission of dust particulates increases the aerosol loading over the geographical area. This development means that asthmatic patients are likely to have more difficulty breathing. The noise pollution in the construction site, i.e., from construction vehicles, may affect the area's wildlife demography. More so, humans are affected by noise pollution.

There is a huge possibility that there will be significant disposal of hazardous waste into waterways or the surrounding environment. This action may lead to the death of most aquatic lives in the Gurara river. It could also lead to the spread of water diseases that will claim lives. Due to the construction of the proposed site (in Figure 12), there will be the erosion of riverbanks and roadsides as channels and reservoirs are created. There is the possibility that road accidents may increase due to increased traffic along the Gurara route. There is the possibility that the construction of the hydropower plant will affect the existing farmlands in the area, thereby reducing the food supply and the income of the inhabitants. The construction can also distract tourists from the waterfall. This development would lead to a shortage of local government revenue generation.

The creation of the dam, reservoir, and forebay will disturb aquatic life and lead to their large-scale destruction as they swim into the penstock and power generation turbines where they will be killed. Aside, the death of the aquatic lives, there is the possibility that the mating seasons are altered as water animals may have to swim against the water stream during breeding seasons (Stephen, 2012).

8. Conclusion

In this research, it has been emphasized that hydropower plays a significant part in ensuring reliable electricity service and in meeting customer needs in a market-driven industry. The new design allows for the reclamation of hydropower plants via comprehensive site planning. This development makes hydropower plants the most efficient means of producing electric energy. Developed nations have used this technique to efficiently use today's hydropower plant to about

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90 percent, thereby meeting the needs of growing energy users. In the future, it is recommended that the two reservoirs in Figures 7 and 10 be incorporated for better energy generation.

The longitudinal and latitudinal analysis of the research site, which covers a perimeter of approximately 1,957.5 m, and an area of 237,051.34 m^2, was successful using remote sensing techniques to estimate its elevations. The head's location can be as high as 17.1 m with a volumetric flow rate of above 85 m^3/s. Also, the bank elevation of the water path is equally important as designing the head-section of the hydroelectricity dam. The hydroelectricity dam can be located on longitude 7°01′07″ E and latitude 9°18′58″ N. More so, there is the possibility of many existing small dams and drops in elevation along the route where small generating plants could be installed.

A reservoir-driven hydropower plant has been suggested for the research location to store large amounts of electricity at low cost. There is the possibility that the design plan would not deprive the tourist attraction of the Gurara waterfalls. In addition to sightseeing, tourists have added water sports experience from the lake formed behind the dam.

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