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GIS-Based Modeling of Site Suitability and Capacity for Small Hydropower Generation in Edo State, Southern Nigeria

Akpofure Miller Fakpor
Department of Remote Sensing and GIS,
Federal University of Technology, Akure, Nigeria
Olamiposi Caleb Fagunloye
Geosciences Department, Georgia State University, Atlanta, U.S.A.
Titus Endurance Igben
Department of Remote Sensing and GIS,
Federal University of Technology, Akure, Nigeria
Dada Emmanuel
Department of Geography and Planning Sciences,
Adekunle Ajasin University, Akungba Akoko, Nigeria

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Abstract

The study evaluates the suitability of sites for small hydropower development in Edo State, Nigeria, as a renewable energy source. The assessment integrates Geographic Information System (GIS) techniques with hydrogeological and remote sensing data, including precipitation, stream order, geology, slope, land use/land cover, and soil texture. A Multi-Criteria Decision Making (MCDM) approach, specifically the Analytical Hierarchy Process (AHP), was used to rank potential SHP sites based on their suitability for hydropower generation. The analysis identified three highly suitable locations for SHP development. The estimated gross annual energy outputs for these sites were 5.8 MW, 5.65 MW, and 6.1 MW, respectively. These findings indicate significant potential for SHP as a sustainable energy solution in the region. However, further considerations - such as the specific hydropower yield, the river course location, environmental sustainability, socio-cultural factors, and compliance with government policies - are crucial for successful development. The study underscores the importance of SHP in enhancing electrification efforts while promoting environmentally friendly and sustainable energy generation.

Keywords: Small Hydropower (SHP), Suitability, GIS, Dam

Introduction

Energy consumption is rising globally as the world's population continues to increase, particularly in less developed countries like Nigeria. Harnessing a renewable and sustainable energy source will prove reliable and, therefore, be required to address this need. Hydropower is regarded as one of the pillars of energy systems that are sustainable, harnessing more renewable energy options. It is efficient, flexible, and reliable, with low greenhouse gas emissions and long-lasting infrastructure, and it can provide multiple-use benefits such as water supply and mitigating flood impacts (Osokoya et al., 2013). Compared to large hydropower projects, studies indicate that a well-designed small hydropower (SHP) system is a renewable, more sustainable energy source with minimal adverse environmental impacts, providing cheap, clean, and reliable electricity (Emeribe et al., 2016; Fraenklel, 1991). Indeed, some legislatures have labeled "large hydro" as either non-renewable or not sustainable (Osokoya et al., 2013).

Furthermore, it has been observed that small hydropower is known across the world to be well-suited in rural environments of less developed countries and offers a solution to both the absence and inconsistent electricity supply in many parts of Nigeria, endowed with favorable terrain and river systems (Odiji et al., 2021). Edo State, Nigeria, has been observed by Emeribe et al. (2016) as having several such surface water resources with the potential of being harnessed for small hydropower development.

Despite the capacity of SHP as a renewable energy source to address the energy needs in Edo State, the current situation is seen to be characterized by poor power development and management. Power is generated from large hydropower plants and gas turbines situated across the country, which contribute to a national grid that is connected through distribution systems to different regions and states. In Edo State, only a few communities are connected to this national grid, which, unfortunately, has experienced multiple collapses due to inadequate and poor infrastructure maintenance. Thus, many residents experience total power blackouts or frequent power outages affecting households and businesses. Additionally, many rely on fossil fuels such as gas, diesel, and premium-motor-spirit (used mostly in household and industrial generators) for electricity generation, contributing to environmental degradation (Webb, 2024; Nyambuu and Semmler, 2023) and high energy costs.

Past scholarly works, such as Emeribe et al. (2016), assessed selected rivers in Edo State for their capacity for small-scale hydropower generation, determining their hydropower yield annually and on a monthly basis. The study limited its data to flow analysis of the rivers in estimating the highest monthly hydropower yield for each selected river and their annual yield, forming a basis for classifying their suitability for different hydropower schemes. Odiji et al. (2021) identified and selected suitable locations for the development of a small hydropower dam in the upper Benue River watershed using Geographic Information Systems as an integrated system for analyzing the data. Karakuş and Yıldız (2022) reported that remote sensing (RS), geospatial techniques, and artificial intelligence are suitable approaches that have emerged in dam site selection. Thus, remote sensing and GIS methods are effective, reliable, save time, and reduce costs in decision-making involving earth and environmental systems. In spite of this advantage, however, in Nigeria, the use of GIS in the selection and modeling of potential hydropower sites is low.

A capacity of not more than 10 megawatts of electricity is a standard for small hydropower (SHP) systems (Odiji et al., 2021; Khare et al., 2019). SHP could be categorized further into different generating capacities: Pico (generating below 10 kilowatts), micro (from 10 to 100 kilowatts), mini (above 100 kilowatts to 1 megawatt), and small systems (above 1 megawatt to 10 megawatts generating capacity) (Chiyembekezo et al., 2012). Thus, the SHP installed systems are quite advantageous in supporting diverse energy requirements of various populations or institutional types (Ang et al., 2022).

Therefore, this study integrates the use of remote sensing, GIS techniques, and certain hydrogeological criteria - precipitation, stream order, geology, slope, land use/land cover, and soil texture - to determine highly suitable sites for small hydropower generation. The study estimated the gross hydropower energy output for highly suitable sites in assessing their potential for electrification in the study area of Edo State, Nigeria.

Materials and Methods

The Study Area

The study area is Edo State, a central part of Southern Nigeria with coordinates of longitudes and latitudes of between 6º04'E and 6º43'E and 5º 44'N and 7º34'N, respectively (Fig. 1). It's predominantly tropical rain forest with some northern portions in the derived savanna zone and a few mangrove swamps in the south. The land area is between 17,802 and 19,187 square kilometers, with an elevation of approximately 500 feet in the southern part and 1,800 feet in the northern part. The population is projected to be about 4,777,000 by 2022 (Citypopulation, 2023).

The climate is humid tropical and has two seasons: the wet period from April to October and the dry period from November to March, with a cold harmattan spell in the months of December and January (Emeribe et al., 2016). The highest mean monthly temperature is 29.1°C, recorded in March, while the lowest is 24.4°C in June (World Bank Climate Change Knowledge Portal, n.d.). The mean annual rainfall occasionally exceeds 2000 mm in the northern part, with a bimodal distribution (the first peak occurs in July with monthly rainfall of 344.7 mm, while the second occurs in September with 457.2 mm) (NIMET, 2007).

Fig. 2 shows the drainage network of Edo State. Other important features of the study area are the Afenmai Hills, Orle Valley Basin, Esan Plateau, and the Benin Lowlands. The Ikpoba River rises from the Esan Plateau, where many Ishan communities live. Benin City is the state's capital and also the largest urban center in the state; it is noted for its historical landmarks and monuments. Edo State was chosen due to its combination of favorable topography, persistent power deficits, and the presence of perennial rivers and rainfall patterns conducive to small hydropower development.

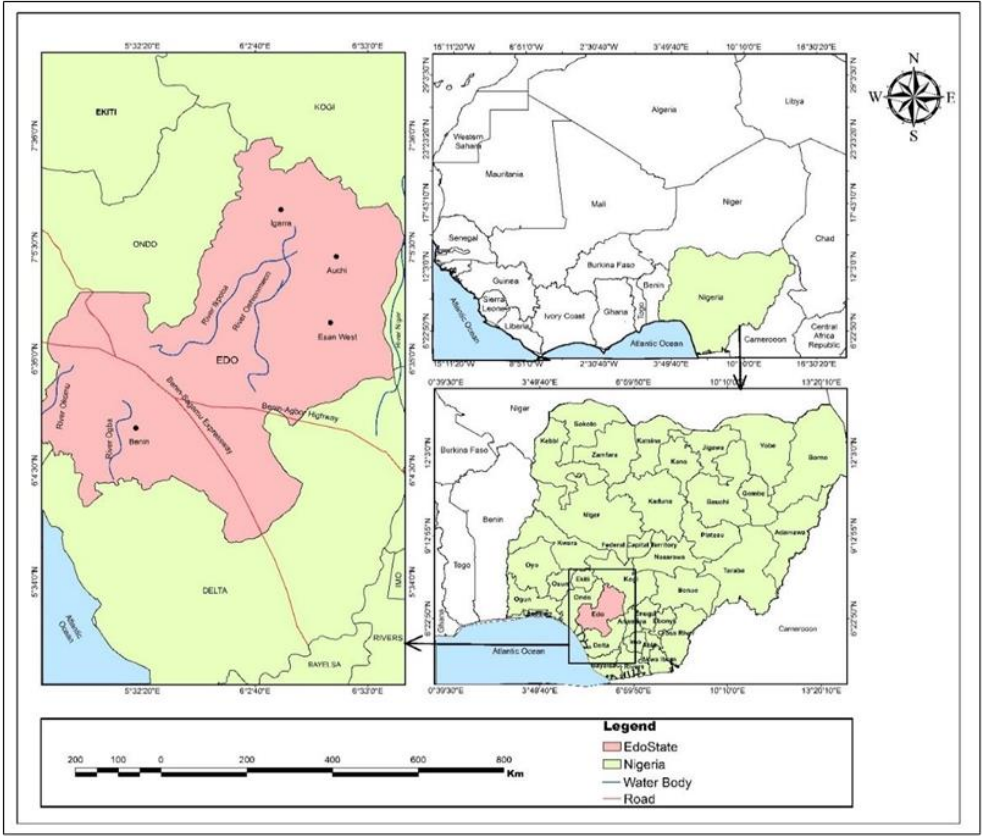

Fig. 1. Edo State Map showing the case study area - Edo State, Nigeria (on the left) - and the two inset maps show the map of West Africa, focusing on Nigeria (upper), while the second is the map of Nigeria, focusing on Edo State (lower).

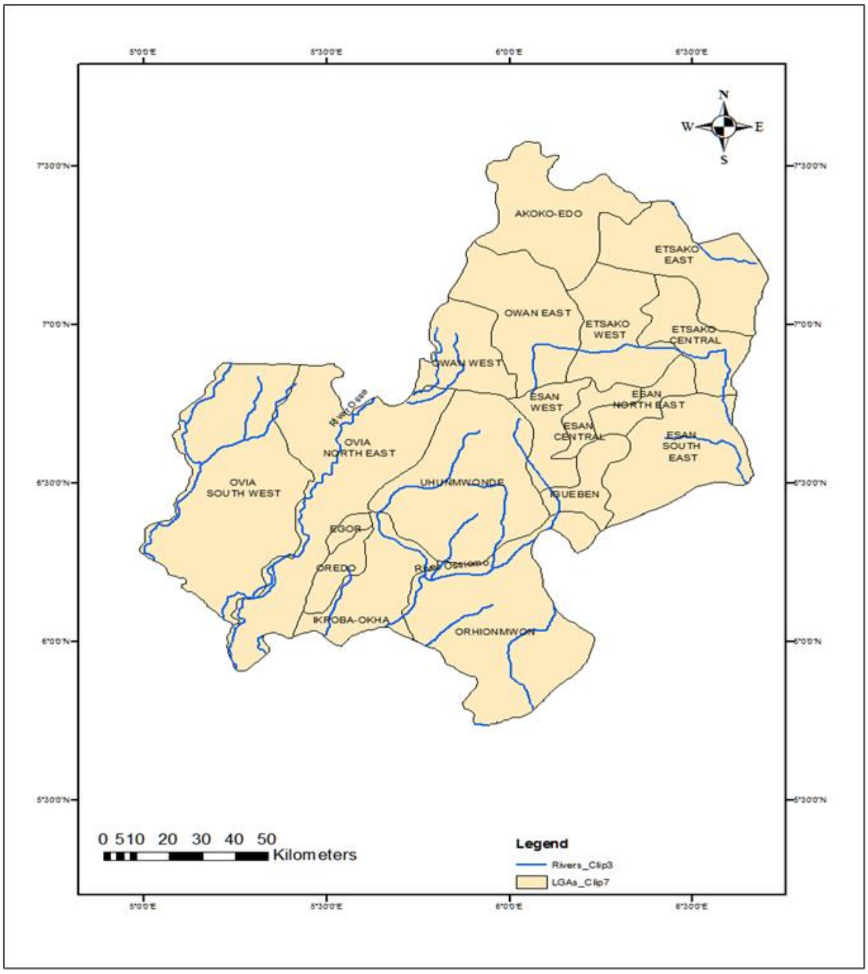

Fig. 2. Drainage system of Edo State

Materials and Methods

The data used in this research consisted of a soil map derived from the Africa Soil Properties dataset (Africa Soil Profiles Database, n.d.), a geological map of Edo State, and precipitation data downloaded from Google Earth (using seven (7) synoptic gauging sampling stations picked at random and interpolated). The rainfall data spanned 10 years (from 2010 to 2020). A Landsat 8 image of 30 meters resolution with path 189, row 56, and Digital Elevation Data (DEM) from Shuttle Radar Thematic Mapper (SRTM) of 2020 was obtained from the United States Geological Surveys (USGS). The software used for the study includes ArcGIS 10.5, Microsoft Excel 2019, and the Analytical Hierarchy Process (AHP) Calculator.

The study area was classified into built-up/bare land, river/wetland (Fig. 4.), rock outcrops, and vegetation using the maximum likelihood algorithm in ArcGIS. Land cover can greatly modify the effect of rainfall, affecting soil erosion and runoff properties (Adinarayana, 1995). Areas with high soil erosion create a weak foundation for dams (Baban and Wan-Yusof, 2003).

Soil data

The soil properties were obtained from Africa Soil Information Services (AFSIS) data sets. Based on their textural properties and their different infiltration rates, the classes of soil types we have in Edo State are Sandy Loam, Sandy Clay Loam, Loam, and Clay Loam of different preference values. Based on the classification, clay loam, which is the soil type with the lowest infiltration rate, was found southwest of the study area. Essentially, soil acts as a pervious medium, providing multiple passageways that allow water to move to the surface. The degree to which soil can pass water through a drainage channel is a function of the size of soil particles, arrangement, and extent of aggregation between them, making soil the major controller of the hydrological response of a catchment (USDA, 2004).

Geologic data

A very vital factor that affects dam construction when considering natural factors is the geology. The geologic map for the area of study was digitized from the Arc Geological Map of Nigeria, Nigeria Geological Survey Geologic Map of Nigeria 2006 (Geological Maps, n.d.).

Surface hydrology and stream network analysis

Surface hydrology and stream network analysis were carried out in ArcGIS using the sample hydrologic analysis extension. The shape of a surface determines how water flows across it. Hence, a DEM was used as input to make it possible to delineate the drainage system and characterize it. The upslope area, which contributes to a point in a stream network, and the downslope path that water would follow can then be determined. Figure 3 is the hydrological analysis flowchart adopted for the study.

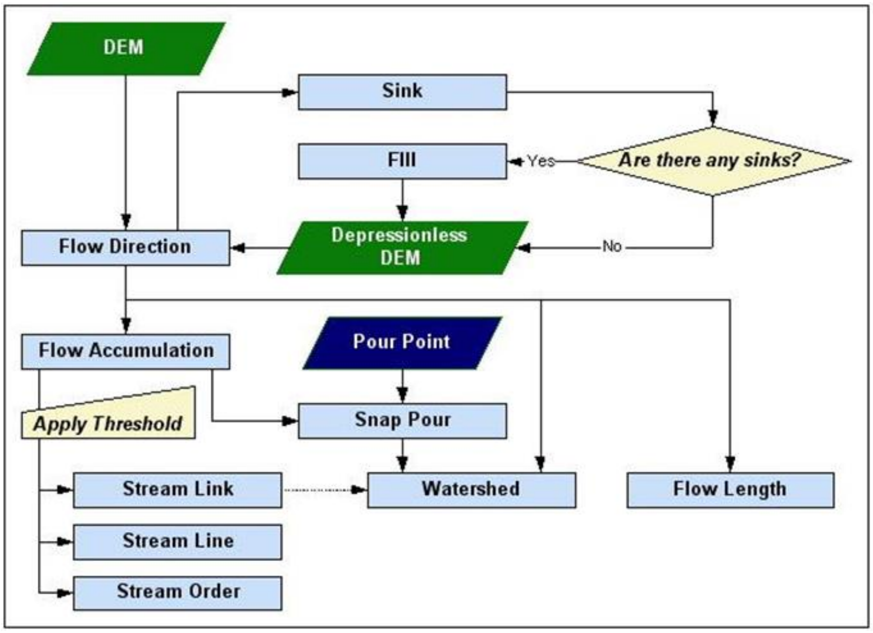

Fig. 3. Hydrological analysis flowchart used for the study

Rainfall Data

Precipitation data utilized for the study were obtained from the Google Earth weather parameters extension. It was used to derive a total of 7 rainfall gauging stations (2010-2020), which were interpolated for the entire study area using Inverse Distance Weighting (IDW) in ArcGIS to estimate the spatial distribution of rainfall amount.

Estimation of Runoff Depth

The Soil Conservation Service-Curve Number (SCS-CN) method was employed in estimating runoff depth [13] - [15]. To achieve this, Curve Numbers were derived by reclassifying the land use/land cover map and soil texture map into the hydrological soil group using the United States Department of Agriculture land use and land cover classification system (Class A, B, C, and D) (Melesse, 2002; Valiantzas, 2012; Prasad et al., 2014). The runoff curve number (CN) was estimated on a pixel basis during image analysis. Runoff depth was calculated based on Equations 1 and 2 according to Prasad et al. (2014) below, where Q = runoff depth (mm), P = rainfall depth (mm), retention after runoff (mm), S = potential maximum retention after runoff begins (mm), and Ia = initial abstraction (mm) assumed as 0.25:

$$Q = \frac{(p-Ia)2}{(p-Ia)+s} \quad \text{.............. Equation 1}$$

$$\boldsymbol{S} = \frac{25400}{CN} - 254\,mm \quad \text{........... Equation 2}$$

Slope

Slope analysis was done in ArcGIS using SRTM data. Gradients of slopes play a critical role in the suitability of locations for dam construction, especially when considering runoff generation, as it affects the recharge and infiltration rate of an area. Thus, catchments that have steeper slopes are more efficient in ensuring high runoff. Usually, slopes greater than 5% (2.86) increase runoff and soil erosion rates (Wang et al., 2023; Mahoo, 1999). Slope is categorized as gentle (less than 5 degrees), moderate to steep (5 to 18 degrees), and steep to very steep sloping (more than 18 degrees) (Adinarayana, 1995). Slope ratio was calculated using Equation 3 below:

Slope ratio = Tan (slope in degrees) * 100% ……………… Equation 3

Multi-Criteria Analysis (MCA)

The study employed multi-criteria analysis using AHP. Odiji et al. (2021) noted that AHP is a useful tool in decision-making where several criteria are to be considered at the same time. In this process, each criterion is given relative weight. Thereafter, two or more alternatives are compared.

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) was used to assign relative importance to the six decision-making criteria relevant to hydropower site selection: Stream Order, Slope, Precipitation, Geologic Layer, Soil Type, and Land Use/Land Cover. AHP is particularly suited for integrating both qualitative judgments and quantitative data, offering a structured way to handle multi-criteria problems involving both tangible and intangible factors.

Pairwise Comparison and Weight Justification: A pairwise comparison matrix was constructed based on Saaty's 1–9 scale, guided by a structured expert elicitation process and informed by literature on hydropower site suitability (Saaty, 2008; Mardani et al., 2015). The experts evaluated each criterion's relative importance based on their hydrological significance and practical impact on mini-hydro project development. Stream Order received the highest weight (0.382) because it directly influences streamflow magnitude, which is foundational to energy output. Slope (0.250) followed due to its correlation with hydraulic head, affecting the potential energy available for conversion. Precipitation (0.159) was assigned significant weight due to its contribution to catchment water yield and flow continuity. Geologic Layer (0.100) was valued for its implications on construction feasibility and structural stability. Soil Type (0.064) was factored in for its role in infiltration and runoff dynamics. Land Use/Land Cover (0.0428) received the least weight due to its relative ease of modification during project implementation and lower hydrological sensitivity. Table 1 shows the criteria, their identifiers, and weights as used for the study. This hierarchy of weights reflects a balance

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between physical water availability, terrain potential, and technical feasibility, as commonly adopted in similar studies (Feizizadeh et al., 2014; Machiwal & Jha, 2008).

Table 1: Criteria identifier and weights

Criterion No	Criterion	Criterion Weight
C1	Drainage order	0.382
C2	Slope	0.250
C3	Precipitation	0.159
C4	Geologic layer	0.100
C5	Soil type	0.064
C6	Land use and Land cover	0.0428

Consistency Verification: To ensure the reliability of the pairwise comparisons, the consistency ratio (CR) was calculated. The resulting CR value of 0.092 indicates acceptable consistency, as it falls below the threshold of 0.10 recommended by Saaty. This confirms that the judgments used to assign weights were logically coherent.

Suitability analysis was carried out based on all classified criteria. According to Saaty (1977), the normalized weights in the AHP used in the suitability analysis are calculated using Equation 4 below, where the intensity of importance is criteria i when compared to criteria j, and the reciprocal value is assigned to criteria j as intensity of importance. After all possible comparisons between all criteria pairs, the weight (W) of criteria i that is subsequently utilized in the suitability analysis is then calculated from the equation.

$$Wi = \sum_{j=1}^{n} \frac{Pij}{(} \sum_{i=1}^{n} \sum_{j=1}^{n} Pij) \text{.................. Equation 4}$$

Sensitivity Analysis: Although a full sensitivity analysis using tools such as Monte Carlo simulation was beyond the scope of this study, a qualitative assessment was conducted. Each criterion's weight was varied by ±10% to assess the impact on the final suitability ranking. The rankings of top sites remained relatively unchanged, indicating that the model is reasonably robust to small variations in weights.

Reclassification Process

To prepare data used for the multi-criteria analysis, all input raster layers were reclassified using a common scale ranging from 1 (least suitable) to 4 (most suitable), serving as a preference value. This value was further scaled proportionally to a range of 0 to 100 in the ArcGIS environment using linear normalization. This ensures a standardized scale ideal for GIS-based decision models. It is an approach that standardizes diverse data types into a unified preference structure, ensuring compatibility across criteria layers.

Rationale for the 1–4 Scale: The initial 1–4 scale was selected for its balance between granularity and interpretability. A wider scale (e.g., 1–9), although commonly applied in standard AHP practices, was considered inappropriate in this case due to the relatively low resolution and variability of some input datasets. Research by Malczewski (1999) and Feizizadeh & Blaschke (2013) suggests that smaller scales can improve coherence and reduce overfitting in GIS-based multi-criteria evaluations where data differentiation is limited. Thus, the 1–4 scale used in this study ensures both methodological clarity and data-aligned sensitivity.

Criteria for Assigning Reclassification Values: Reclassification thresholds were defined based on both expert knowledge and literature:

- Slope: Higher slopes (e.g., >12°) received a score of 4 due to their potential for generating higher hydraulic head. Gentle slopes (<2°) were scored 1 due to limited energy generation potential.
- Precipitation: Areas with mean annual rainfall above 185 mm were scored 4, reflecting high runoff potential. Lower precipitation zones were scored progressively lower.
- Stream Order: Higher stream orders (e.g., 5th order) were assigned higher scores based on greater expected discharge.
- Soil Type and Geologic Layer: Classes were rated based on permeability and stability. For example, granitic formations and loamy soils scored higher due to their structural suitability and moderate infiltration.
- Land Use/Land Cover: Vegetated areas (e.g., forest) scored higher due to their lower ecological impact and greater infiltration capacity. Built-up areas and barren lands received lower scores or were excluded.

The reclassification involves subjective judgments, thresholds, and scores that were developed in consultation with hydrologists and GIS specialists and cross-referenced with existing studies (Baban & Wan-Yusof, 2003; Mahoo, 1999). By applying a consistent rule-based approach, the influence of subjectivity was minimized and documented transparently to allow for replication. Table 3 shows the preference values used for reclassification of the various criteria used in the study.

Table 3: Unified preference values for reclassification

Slope (Degree)	Preference value	Unified Preference value
0 – 2.0	1	25
2.0 – 5.0	2	50
5.0 – 12.0	3	75
12.0 – 46.0	4	100
Precipitation (mm)		
140 – 156	1	25
156 – 170	2	50
170 – 185	3	75
185 – 202	4	100
Soil Type		
Sandy loam	1	25
Loam	2	50
Sandy clay loam	3	75
Clay loam	4	100
Geologic layer (Rock resistivity)		
Low resistivity	1	25
Moderate resistivity	2	50
High resistivity	3	75
Land use/Landcover		
Built up & bare Land	0	0
Rock outcrops	0	0
River and wetlands	3	50
vegetation	4	100
Stream order		
1	1	25
2	2	50
3	3	75
4	4	100

Estimation of Gross Hydropower Energy Outputs

The gross hydropower potential was further estimated for the highly suitable sites by calculating gross annual hydropower energy outputs. The measure of hydropower that can be achieved at any given location is determined by the head of the turbine and the corresponding flow rate (Kurse et al., 2010; Soulis et al., 2016).

The gross hydropower potential was calculated with the formula in Equation 5 below. It is estimated as the power available from falling water. In the equation, P is power in watts, η is the dimensionless efficiency of the turbine, ρ is the water density in 1000 kg/m^3, Q is the flow in m^3/s or water discharge that will pass through the turbine, g is the acceleration due to gravity = 9.8 m/s^2, and h is the height difference between inlet and outlet in meters, which in this context represents the gross head (Emeribe et al., 2016; Adejumobi et al., 2013).

$$P = \eta \rho Q g h \text{ ………………………… Equation 5}$$

The values of gross head represent differences between the inlet and the outlet or the difference in elevation between the conveyance points or pipe, which is the penstock. The head value, or change in elevation, is calculated for each of the hydropower sites by applying Equation 6, where HD = horizontal distance traveled between the inlet and the outlet, which represents the length of the penstock.

Elev. Change = HD * slope ratio …………………… Equation 6

The penstock's length varies with design considerations and physical properties of the location to be developed. The penstock length used in estimating the gross hydropower potential for the highly suitable areas identified in the study was purposely assigned a value of 50m. This value is suitable for areas with moderate elevation drops to hilly terrains found at these sites (Audu et al., 2022; Emeribe et al., 2016). The nature of hilly terrains and the combination of lowlands with moderate slopes (using this penstock length) allows for sufficient head (height difference) to generate power efficiently without requiring extensive civil works, excessive excavation, or structural support. A 50m length strikes a balance between achieving the necessary head and minimizing energy loss due to pipe resistance. It is also cost-effective, as a longer penstock increases material, installation, and maintenance costs (Ibegbulam et al., 2023). A relatively shorter penstock such as this will be more environmentally friendly as it requires less land clearing (Audu et al., 2022).

Turbine (system) Efficiency: The efficiency of the system depends solely on the type of turbine used for the hydropower generating system. There are various types of turbines with varying magnitudes of efficiency and circumstances in which they are more suitable. Table 4 shows these types of turbines and when they are most suitable for usage. The Kaplan turbine is most suitable for low heads, which is characteristic of the proposed hydropower sites in the study area. The Kaplan turbine has an efficiency of approximately 90%. Therefore, the efficiency (η) value in this study is substituted as 0.9 in Equation 4 above to calculate for gross hydropower potential (Emeribe et al., 2016; Adejumobi et al., 2013).

Table 4. Types of turbines and head specifications

Turbine Type	Head Range (H)
Kaplan and propeller	$2 < H > 40$
Francis	$10 < H > 350$
Pelton	$50 < H > 1300$
Banki-Michell	$3 < H > 250$
Turgo	$50 < H > 250$

Results and Discussion

Land Use and Land Cover

The results of the land cover analysis in Fig. 4 show an abundance of rock outcrops in the northern and northeastern parts of the study area, with settlements splattered around the habitable fringes of the rock outcrops. It shows that built-up and bare ground occupied 24%, river covered 6%, rock outcrops consisted of 35%, and vegetation occupied 35% (Fig. 5).

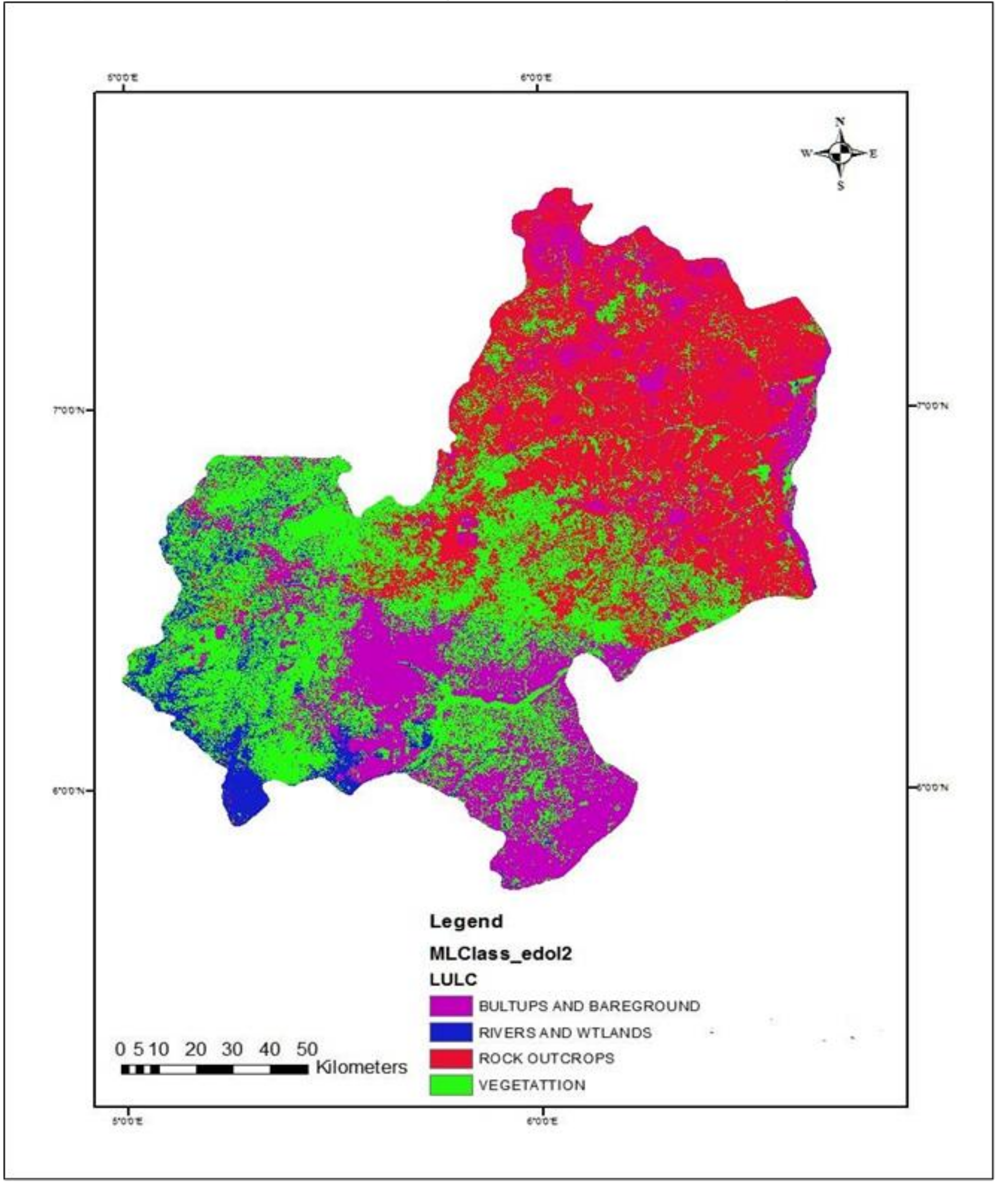

Fig. 4. 2020 Land use/Land cover in the studied area

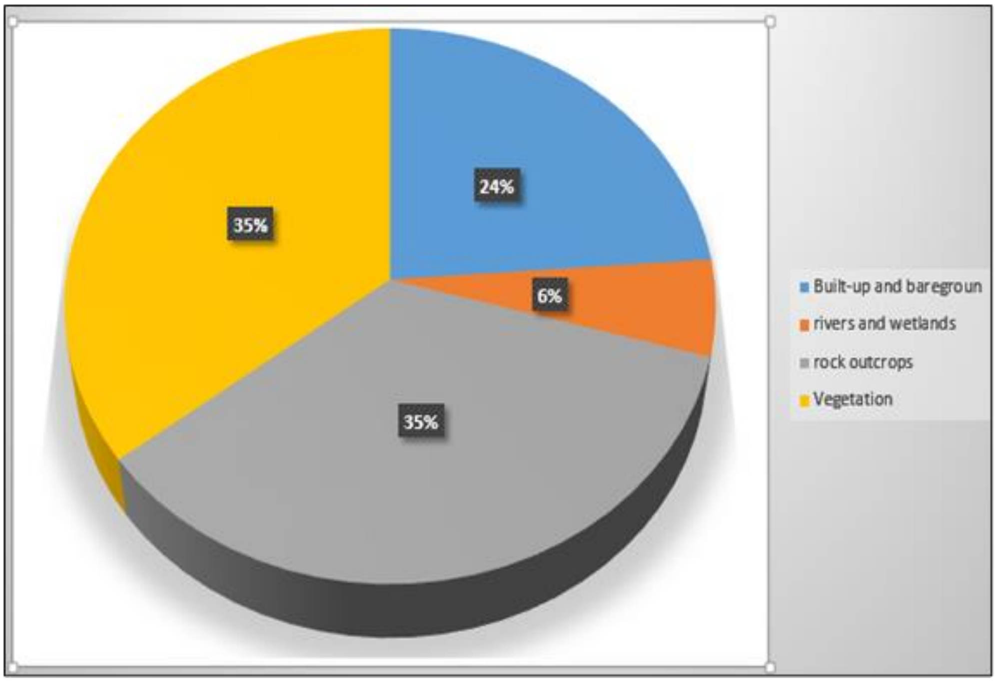

Fig. 5. Percentage pie chart of 2020 Land use/Land cover for the studied area

Soil Map layer

Analysis of the soil texture of the study area shows that sandy loam is dominant, covering 48% of the area (Figs. 6 and 7). The next soil type that covers most of the study area is the loamy textural class. It covers 47.7% of the study area and is usually characterized by medium texture, which is well-drained. The other two textural classes, which are sandy clay loam and clay loam, cover very small areas of the study area. They comprise 4% and 0.3% of the study area, respectively. They both have low infiltration rates due to the presence of clay and possess high runoff capabilities.

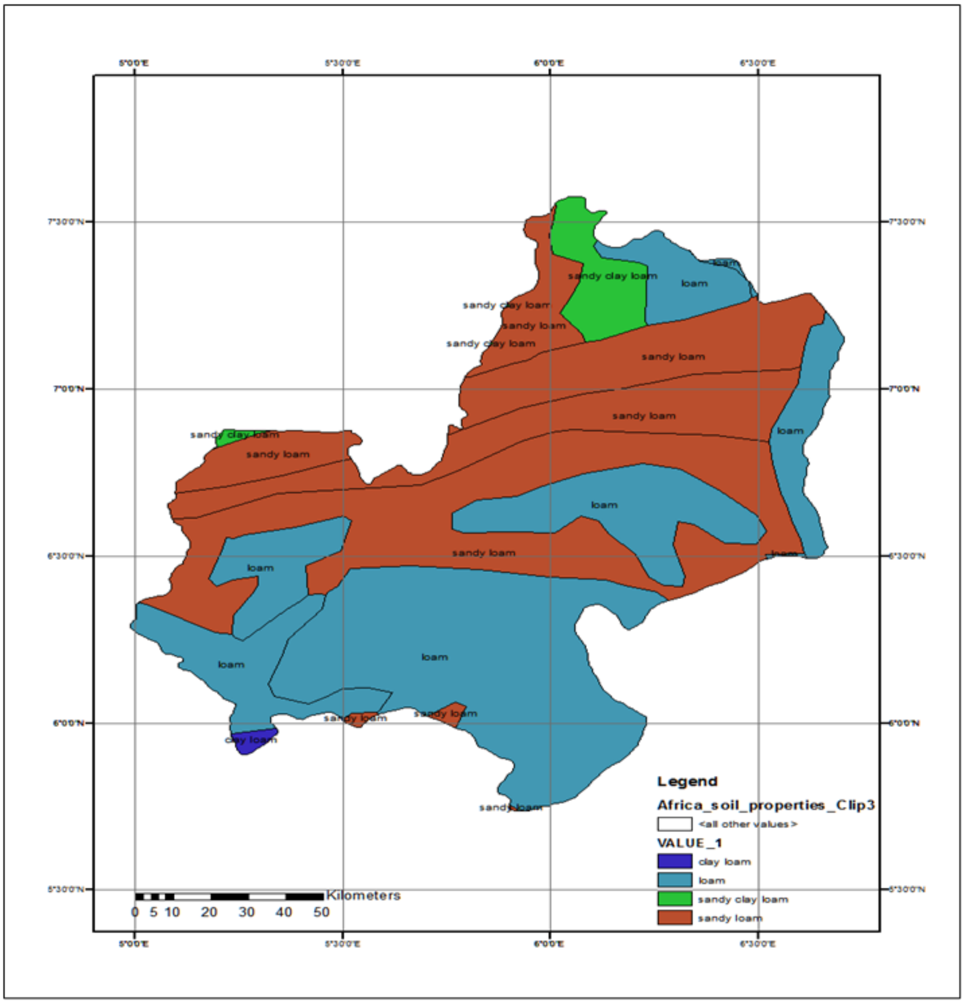

Fig. 6. Soil texture in the studied area

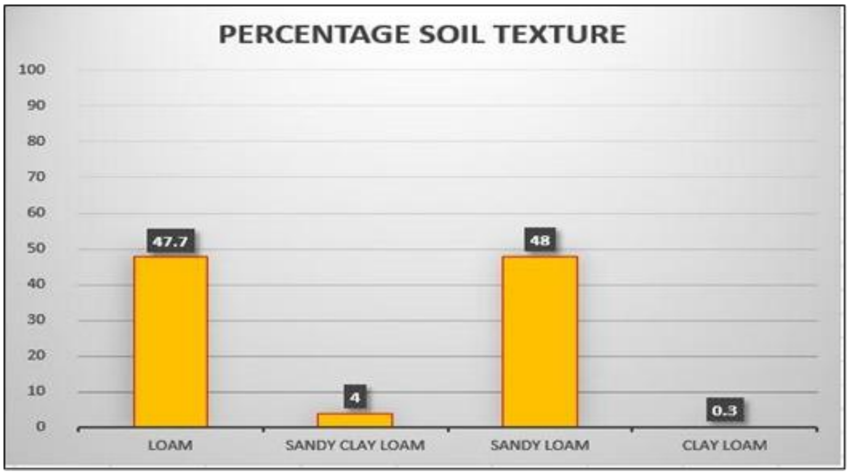

Fig. 7. Percentage of soil composition in the study area

Geologic Map layer

The study shows that most regions of the study area are composed of sedimentary rocks, and these are observed as one goes southward in the region. However, metamorphic rocks (e.g., migmatite, gneiss, and others) are also substantially distributed towards the northern region of the area (Fig. 8). Rocks with relatively high resistance to erosion, percolation, and pressure are suitable rock foundations (USACE, 1986). In this regard, Baban and Wan-Yusof (2003) identified rock (igneous rock type), quartzite rock (metamorphic rock type), thick-bedded sandstones, flat-lying sandstones, and limestone rock (sedimentary rock type) as examples of the most satisfactory materials.

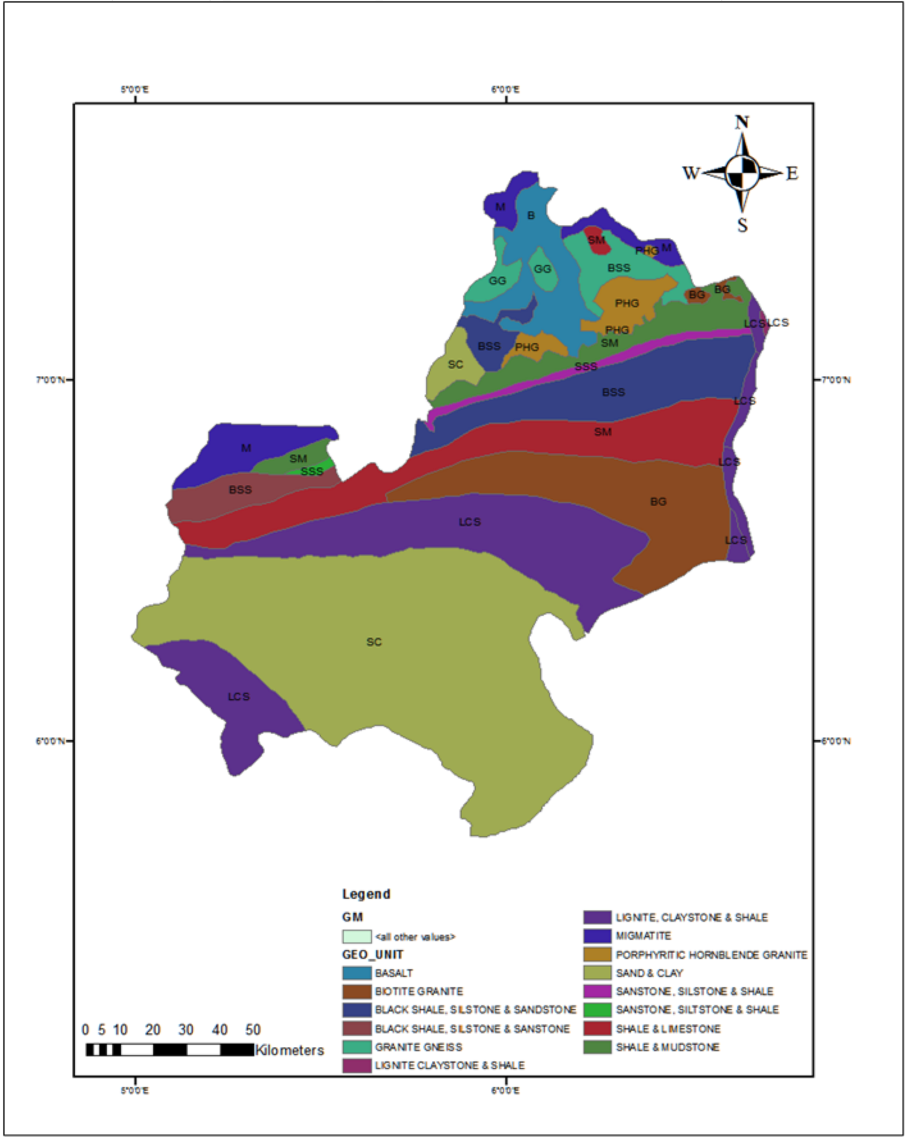

Fig. 8. Geologic map of the studied area

Resistivity map

It can be deduced from the resistivity analysis that high resistivity occurred in the northeastern part of the study area, with a small proportion in the central and western parts. Central and southern parts depict moderate resistivity, while the larger part of the study area from north to south contains low-resistivity rocks (Fig. 9).

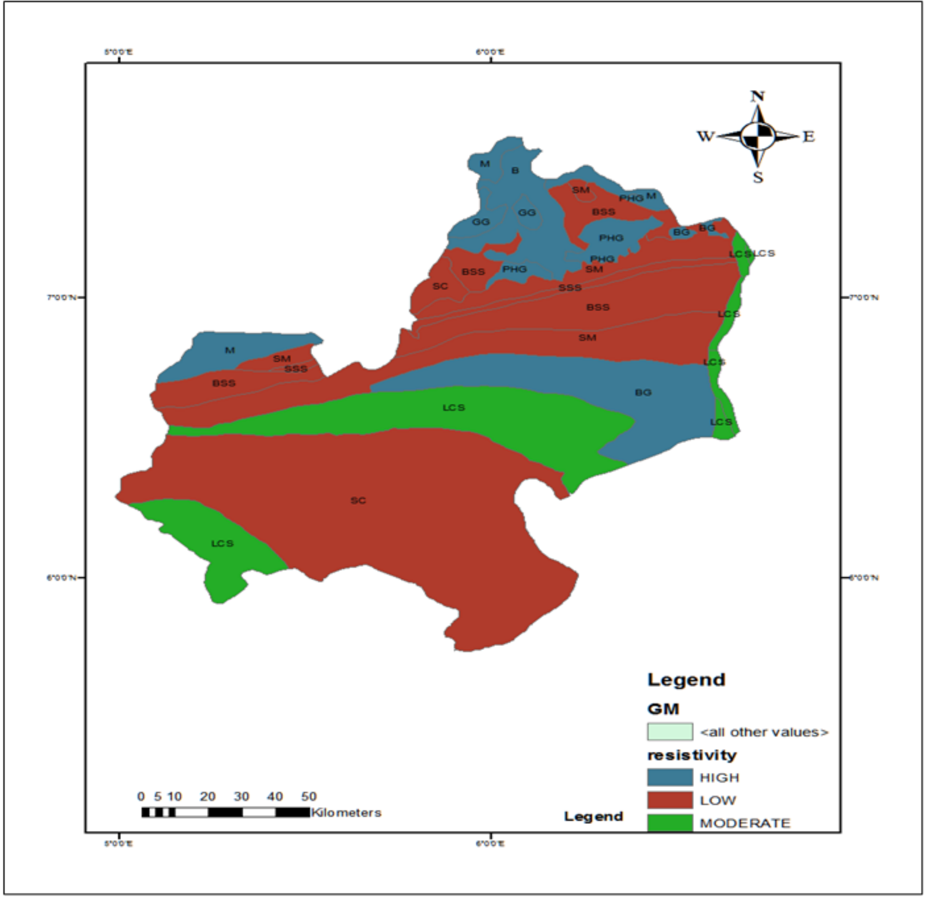

Fig. 9. Resistivity in the study area

Slope Map

Analysis of the slope map of the study area for hydropower generation revealed that larger parts of the study area are dominated by gentle to moderate slopes, except in the northern part where the slopes are steep and deep due to the fact that the region is a hilly and rocky terrain (Fig. 10). The northern part of Edo State has the most suitable slope for hydropower generation, which ranges from steep to very deep slope. The regions surrounding the proposed highly suitable hydropower spots all have slopes ranging from 3 to 5 degrees. Therefore, the slope average is calculated for this range as equal to 4°, used in calculating the slope ratio.

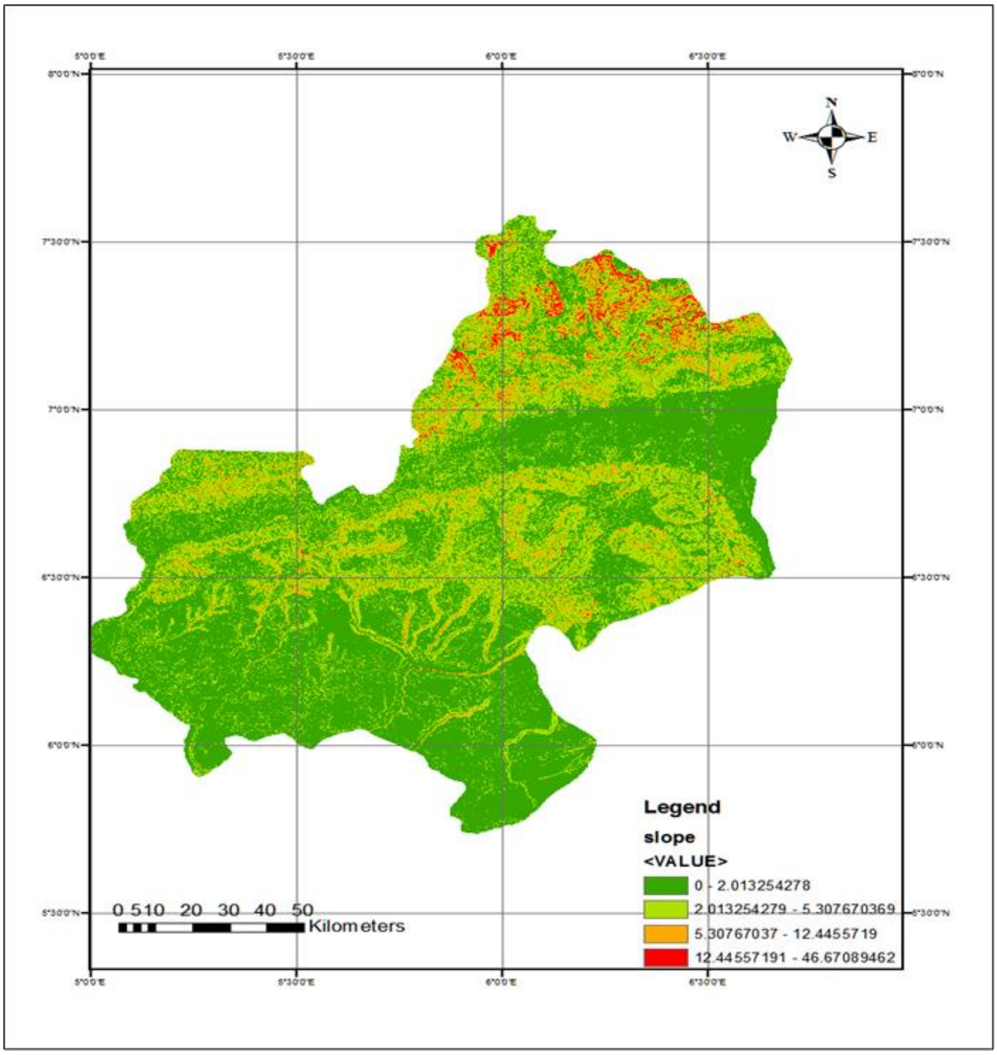

Fig. 10. Slope in the study area

Precipitation and Rivers/Basin Map

Rainfall distribution amount varies considerably across the study area, with the southwestern part of the area receiving much more rainfall than the northern and northeastern parts (Fig. 11). The maximum amount of mean annual rainfall ranges between 147 mm to 210 mm, while the low range of mean annual rainfall is between 140 mm/year and 193 mm/year. The river basin map of the study area shows that the major rivers in the area are located in the southern part of the area, including the Ovia River, the Ose River, and the Ossiomo River (Fig. 12). These rivers are suitable for hydropower generation and are a major contributing factor to the suitability of small hydropower generation.

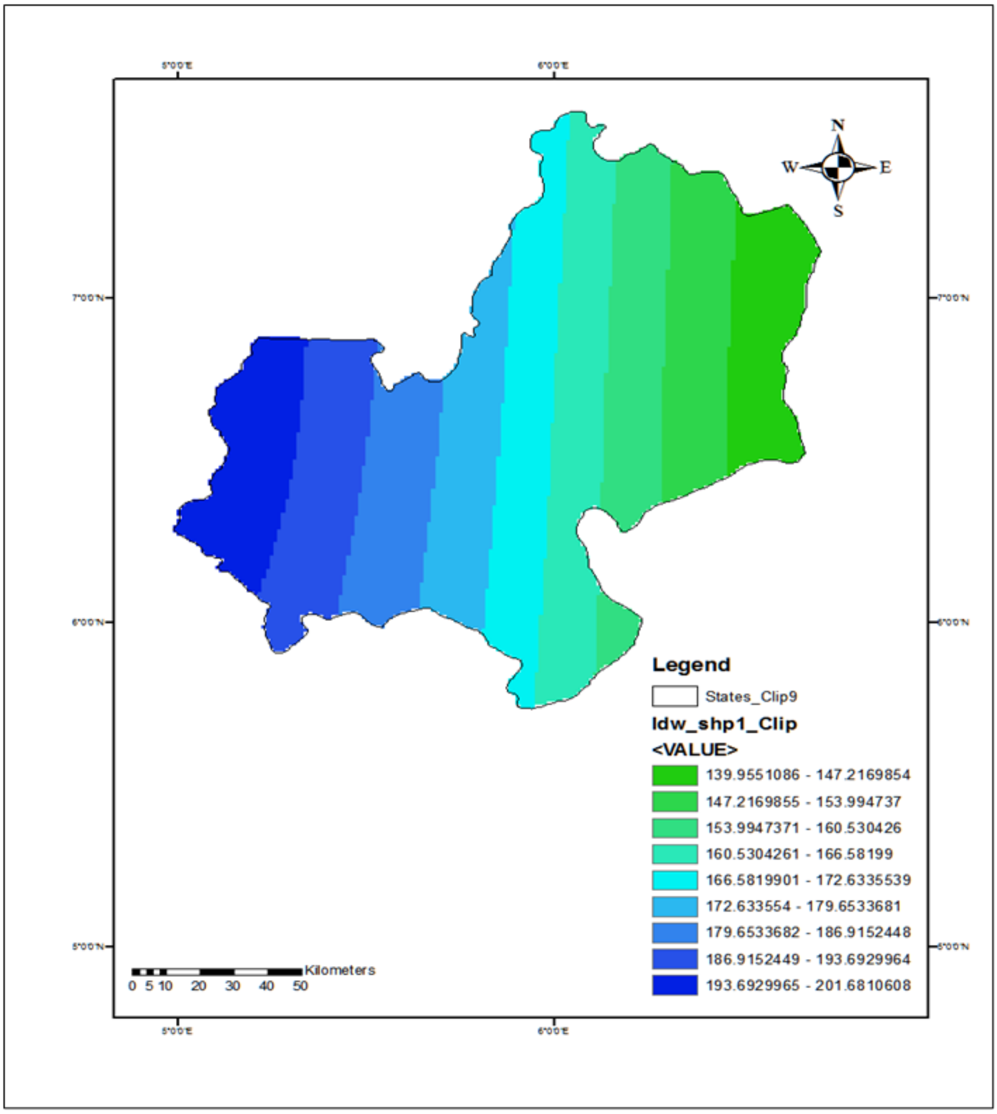

Fig. 11: Precipitation Distribution in the studied area

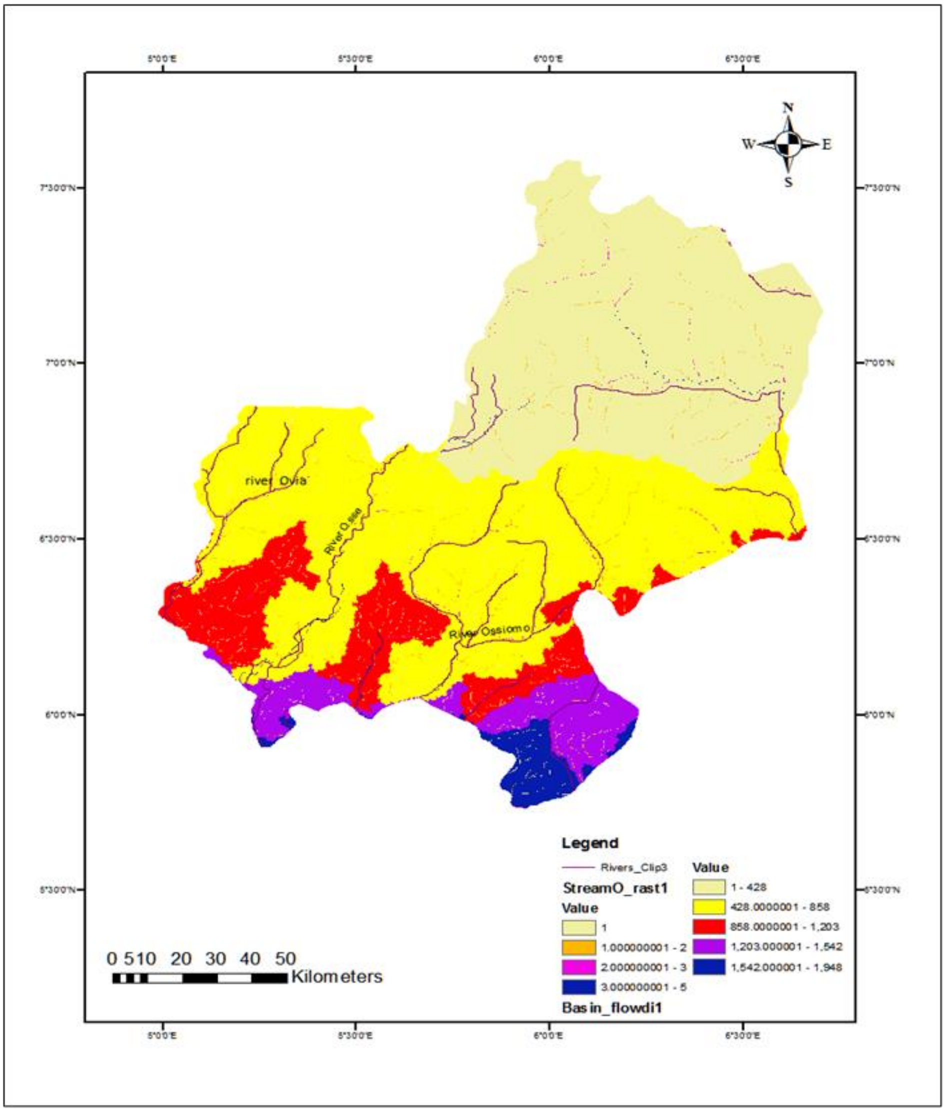

Fig. 12: Rivers & Basin in the studied area

Suitability map

The overall result of the suitability analysis for the study shows a distribution of suitable sites for small hydropower dams in the study area, Edo State, Nigeria. The results reveal a total of 337 sites, out of which 155 (46%) are of low suitability, while 179 (53%) are of moderate suitability, and only 3 (1%) are of high suitability. Figure 13 shows the distribution of the different classes of suitability across the study area, while Figure 14 shows the highly suitable areas for siting a dam for a small hydropower plant for the purpose of power generation in Edo State. The highly suitable points are located in the south-western part of the state almost along the Ose River channel.

Nevertheless, other moderately suitable sites could be considered for development based on varying factors and policies.

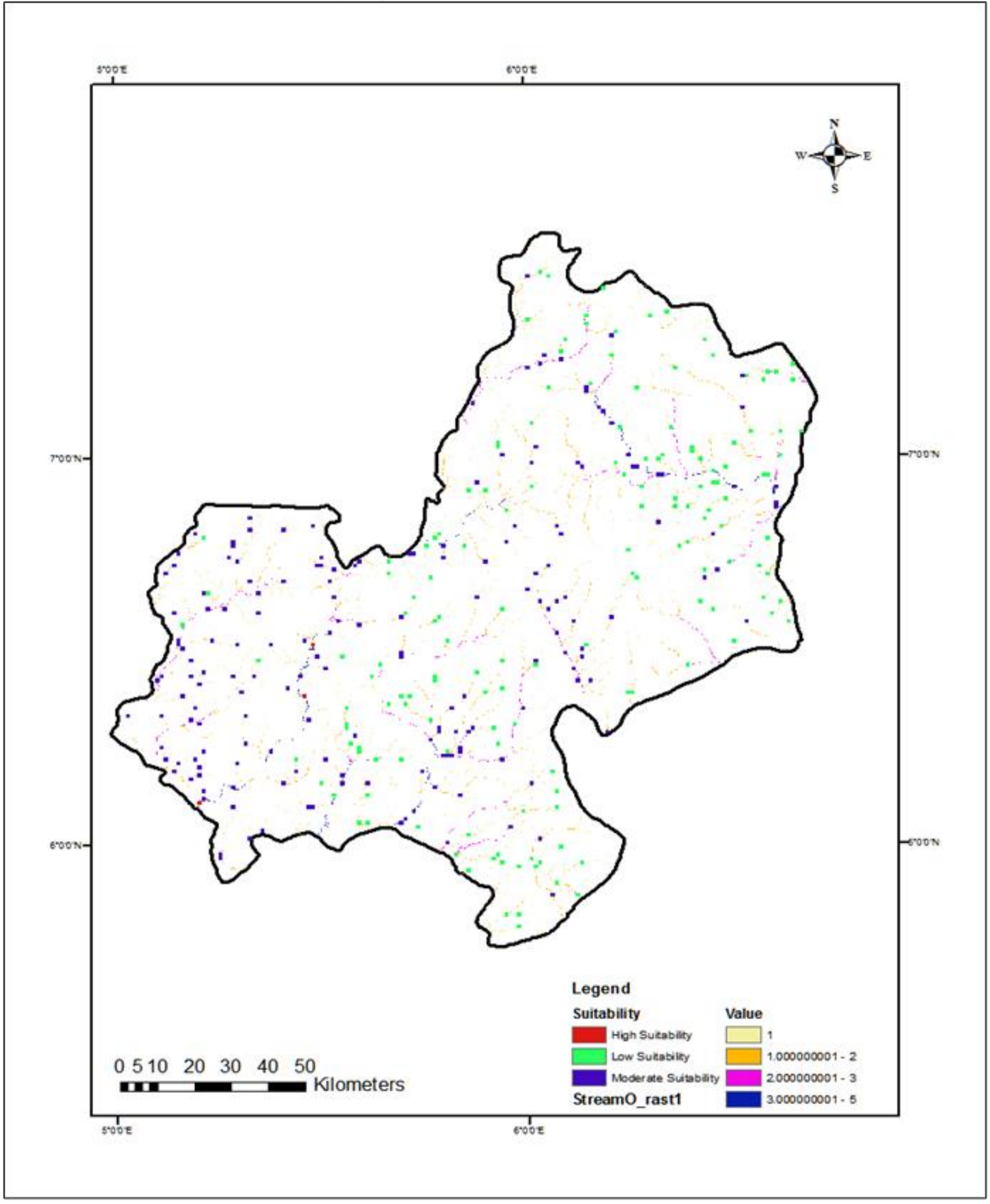

Fig. 13. Distribution of Suitability for Small Hydro Power (SHP) dam in the studied area

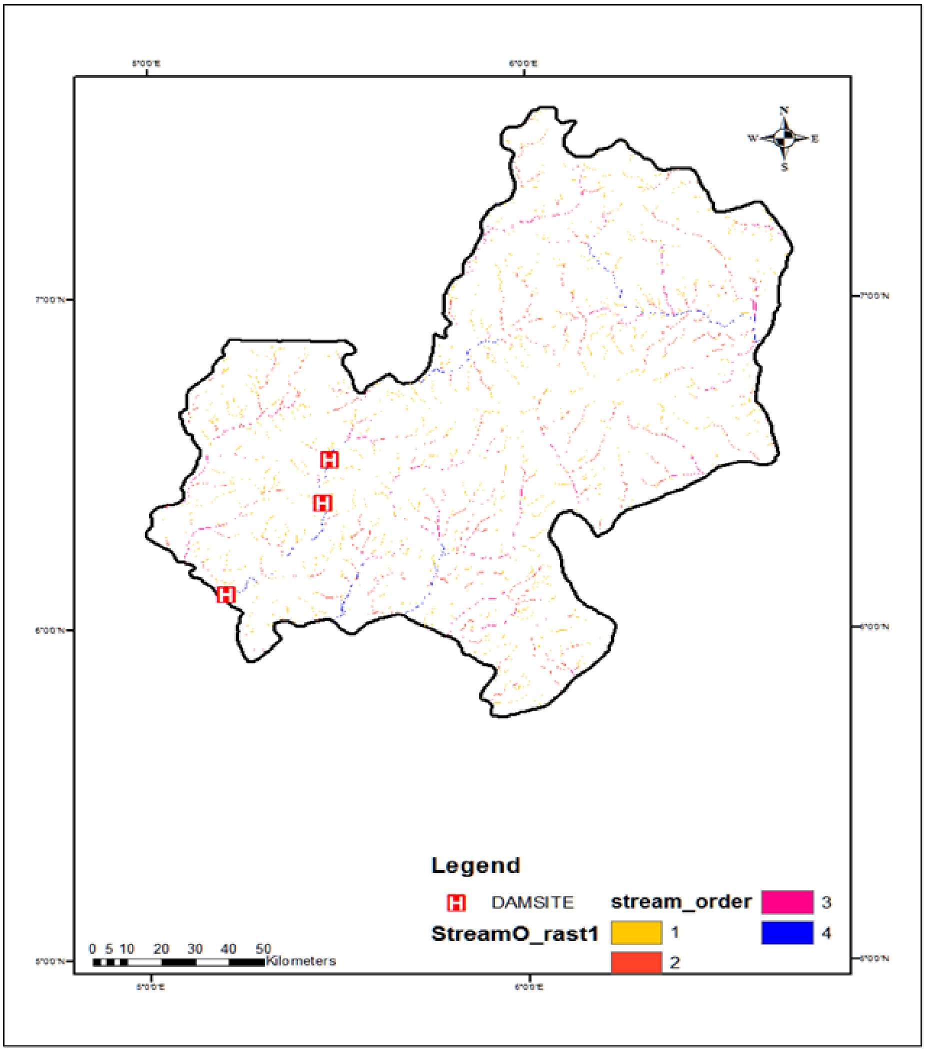

Fig. 14. Proposed Hydropower Damsites (of Highly Suitable points depicted with the symbol "H" on the map) for the studied area.

Run-off Depth

The runoff values for the three suitable dam sites contain curve number values of 65 for the first site, 60 for the second site, and 98 for the third site (Table 5). The average monthly precipitation ranges from 190.5 mm in the 1st suitable site and 190.5 mm and 198 mm for the 2nd and 3rd sites, respectively. The first, second, and third sites contained 5.38 mm, 6.67 mm, and 0.2 mm as the potential maximum retention after runoff starts, with 1.08, 1.33, and 0.04 as the initial abstraction values lost before runoff is generated due to infiltration, evaporation, and water interception by vegetation. The runoff depth consisted of 189 mm, 183 mm, and 197.7 mm for the first, second, and third suitable dam sites, respectively.

Table 5: Runoff values for each SHP site

Dam Site	CN Value	Avg Precipitation	S	Initial Abstraction (la) mm	Runoff (Q)
Dam 1	65	190.5	5.38	1.08	189
Dam 2	60	190.5	6.67	1.33	183
Dam 3	98	198	0.2	0.04	197.7

Gross Hydropower Energy Outputs

The gross hydropower potential was estimated for the three most suitable sites by calculating their annual energy outputs. The analysis, as shown in Table 6, provides both locational data and gross energy output from each site. The results revealed that the volume of water runoff (Q) is a primary factor in determining the power generation capacity at each hydro site. Specifically, hydro site 1, with a runoff of 189 m^3/s, can generate approximately 5.83 MW of power annually. Hydro site 2, with a runoff of 183 m^3/s, has a gross power capacity of 5.65 MW per year. Hydro site 3, with the highest runoff of 197.8 m^3/s, can produce about 6.10 MW annually.

It is important to emphasize that these values are theoretical estimates and do not reflect the exact power generation that may be realized when the hydropower plants are operational. Actual energy outputs can vary due to several factors, including weather changes, seasonal variations in water flow, and design or engineering considerations. For instance, the head (the vertical distance between the water source and the turbine) may fluctuate throughout the year based on rainfall or drought conditions. The values presented in Table 6 are average annual estimates that provide a general indication of the hydropower potential at each site.

Hydro Site 1: A site with coordinates 5° 28' 6.5" E and 6° 6' 34.7" N is identified for small hydropower generation with a runoff rate of 189 m^3/s, generating an estimated 5.83 MW annually.

Hydro Site 2: A second site with coordinates 5° 27' 27.2" E and 6° 23' 11.5" N has a slightly lower runoff of 183 m^3/s and is estimated to produce 5.65 MW of power annually.

Hydro Site 3: The third and most powerful site, with coordinates 5° 12' 6.5" E and 6° 6' 34.7" N and a runoff of 197.8 m^3/s, has a capability of generating 6.10 MW annually.

These sites were selected based on their suitability for hydropower development and provide a promising opportunity for renewable energy generation in the region. However, further site-specific evaluations are needed to refine these estimates and account for real-world conditions.

Table 6: Location and Potential Gross Annual Approximate Output

Site	Latitude	Longitude	Head	Q(Runoff)	Gross Power (watts)	Gross Power (Mw)
1	5° 28' 6.5" E	6° 6' 34.7" N	3.5	189	5,834,430	5.83
2	5° 27' 27.2" E	6° 23' 11.5" N	3.5	183	5,649,210	5.65
3	5° 12' 6.5" E	6° 6' 34.7" N	3.5	197.8	6,104,851	6.10

Conclusion

This study examined the suitability of sites for small hydropower (SHP) development in Edo State, Nigeria, using GIS and multi-criteria analysis techniques. The results identified three highly suitable locations for SHP development, with estimated gross annual energy outputs of 5.8 MW, 5.65 MW, and 6.1 MW. These sites offer a promising contribution to the region's energy supply, particularly in supporting rural electrification efforts and reducing dependence on the national grid.

However, the study highlights that further study and considerations are necessary before development. These include evaluating the specific hydropower yield, the segment of the river where each site is located, environmental and ecological impacts, socio-cultural implications, and adherence to government policies. While the focus of this research was on the most suitable sites, moderately suitable locations also hold potential but may require more investment or yield lower energy output.

In conclusion, the development of SHP in Edo State presents a viable path towards sustainable and renewable energy generation. With proper planning and consideration of key environmental and other relevant policy factors, these sites could significantly enhance local power generation capacity and contribute to broader electrification initiatives in Nigeria. These findings are intended to guide government agencies and private sector actors seeking reliable alternatives to centralized power systems. Future work should include site-level engineering and environmental feasibility studies to operationalize the mapped hydropower potentials.

Conflict of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data Availability Statement

Data publicly available in a repository:

- Geologic data is available at http://ngsa.gov.ng/geological-maps/. Landsat and SRTM data are available at https://earthexplorer.usgs.gov/. Precipitation data are available at https://developers.google.com/earth-engine/datasets/tags/precipitation, soil data is available at https://osf.io/86qcy/.

Data cannot be shared openly, but is available on request from the authors:

- Additional data sets to the above-listed, generated during the current study, are available from the corresponding author on reasonable request.

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