EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 66 (2025): 18 - 29
Journal homepage: https://eqa.unibo.it/

published by

Geospatial suitability assessment of small-scale hydropower potential (Dam sites) for green energy in North-Eastern Nigeria

Jimoh A. Ibrahim[1*], Bawuro Ibrahim[1], Benison Yason[1], Olabanji O. Aladejana[2]

[1] Department of Geography, Gombe State University, Gombe State, Nigeria.
[2] Geomatics Engineering and Management Department, University of The West, Indies St. Augustine, Trinidad and Tobago.

[*] Corresponding author E-mail: iajimoh@gsu.edu.ng

Article info
Received 20/8/2024; received in revised form 7/11/2024; accepted 15/11/2024
DOI: 10.6092/issn.2281-4485/20218

Abstract
Globally, nations are moving away from the usage of fossil fuels toward cleaner energy sources, hydropower is one of the most significant green energy sources to reduce greenhouse gasses. This study aims to select suitable locations for dam construction in Northeastern Nigeria using geospatial analysis for green energy. The Geographic information system and analytical hierarchy process were used to integrate ten thematics layers: geology, soil, slope, elevation, land use, precipitation, flow accumulation, stream power index, topographic wetness index, and drainage density. To generate a suitability model, ten hydro-physical criteria were used and went through several processing steps. AHP was used to rank and weight each criterion. Five classes were identified from the composite suitability map that was generated: very high, high, moderate, low, and very low. Flow accumulation holds the highest importance, followed by rainfall and drainage density, while slope was the least important in determining the suitability of the region. According to the composite suitability map, roughly 38 % of the region is of the highly suitable category, 54.17 % is moderately suitable while the least was highly suitable class with 0.21 %. Among the six states in the region, Taraba state has the highest potential dam site with three sites while the other has one each except Yobe state with none. Millions of people could have access to green energy by building dams in highly practical and economically viable locations identified. GIS is an effective technique for sustainable dam site location.

Keywords
Geospatial analysis, Green energy, Dam, Climate change, Nigeria

Introduction

Nigeria is the biggest economy in Africa and is one of the world's top producers of oil due to its abundance of natural resources, including oil and gas. The need for energy is rising in tandem with the nation's economy's continued growth. The Nigerian government is working to enhance its residents' access to inexpensive and clean energy through several policies and programs, to achieve universal energy access by 2023 (Word Economy Forum (WEF), 2023). Nigeria boasts of an enormous number of renewable energy resources, including; hydropower, sun, wind, and biomass. According to Moran et al. (2018), hydropower supplies 16.4% of the world's electricity and 71% of its renewable energy. Small hydropower is a signifi-

DOI: 10.6092/issn.2281-4485/20218

cant source of electricity for remote and rural locations. According to the International Energy Agency (IEA), Africa is still wildly underutilized despite having huge potential for producing electricity in rural areas through small hydropower (IEA 2012). Africa has vast potential for small hydropower due to its physical terrain, including topography and climate. The limited comprehensive and current national inventory of suitable locations for small hydropower systems is the main obstacle impeding the growth of SHP systems (Duarte et al., 2010). Nigeria currently has a significant shortage of electricity and primary energy. According to the International Energy Agency (IEA), Nigeria consumes 136 kWh per person annually (IEA, 2007). This is approximately 19 times less than the global average and 4 times less than the average for Africans. More recently, it was reported that 140 million, or roughly 70% of the population do not have access to electric power supply (WEF, 2023). The Nigerian Association of Energy Economists (NAEE, 2015 in Odiji et al., 2021) reported that Nigeria is 90% short in the electrical power supply while availability is almost zero in areas where 50% of the population resides. The inadequate power supply to urban and rural regions in the nation amounts to an albatross on any developmental project (Brimmo et al. 2017). Small hydropower is one of the prospective renewable energy innovations that are appropriate and significant for generating electricity for rural areas because the majority of rural environments have rivers and run-off waters that can support hydroelectric power generation. According to a World Bank report, approximately 55% of Nigeria's population has access to the national grid and the national grid capacity hovered between 4500–6000 MW for a population of greater than 190 million given the untapped opportunity (Ebhota & Tabakov, 2018). The potential of hydropower is still not being used to its full potential as a means of generating electricity in Nigeria despite the nation's enormous water resources being found in every state and local government area. Hydropower contributes at least 90% of the electricity outputs in 23 nations and at least 50% in 63 countries (IEA 2012), making it a significant source of energy for economic and social growth in more than 150 countries. The SHP is a renewable energy source that is adaptable to local conditions and has excellent sustainability prospects. When used effectively, SHP can raise living standards, foster eco-friendly development, provide jobs, and reduce poverty through socioeconomic development. The development of hydropower schemes has numerous oppotunities as a feasible means of producing electricity that will reduce greenhouse gas emissions into the atmosphere (UNIDO 2012 in Odiji et al., 2021). Given Nigeria's abundance of water resources, the hydropower potential is substantial. The country's annual rainfall is approximately 3400 mm in the South-Central Niger Delta, 500 mm over its northern bounder, and 1400 mm over the central Jos Plateau region. Similarly, the eastern ranges of Adamawa and Cameroon boundaries experience elevated precipitation as high as 2000 mm relative to contiguous low areas of the country (Manohar and Adeyanju, 2009). According to the 2010 Survey of Energy Resources, Nigeria's Hydropower capability at the end of 2008 was 43TWh/yr, 32 TW/yr, and 30 TWh/yr for gross theoretical capability, practically exploitable capability, and economically feasible capability respectively (WEC, 2010). The utilization of these hydro-resources would result in decentralized use, implementation, and management enabling self-sufficient rural development through the utilization of regional resources. This might be the most accessible and reasonably priced method of supplying off-grid electricity (Sambo, 2009). Several streams and rivers in Nigeria's eight hydrological drainage systems including the Northeastern River watershed remain untapped. This study aims to evaluate dam site suitability for small-scale hydropower potential in northeastern Nigeria as a renewable energy source. The specific objectives are to (1) assess and map the environmental and hydrological parameters, (2) use weighted analysis and AHP to create a suitability index map, and (3) determine the best location for the dams.

Materials and Methods

Study Area

Northeastern Nigeria is located between latitude 6°30'N–13°45'N and longitude 9°00'E to 14°42'E with an area of over 275872.66 km^2 (Fig 1). The elevation of the area varies from 72 – 2348 m above sea level. River Benue and its tributaries drained the region. The main river, River Benue rises in the central hills of the Cameroon Republic, runs into Nigeria from the east, and empties into River Niger in the southwest. There are two distinct seasons: the dry season which runs from November to March and the rainy season which runs from April to October. The average annual temperature varies from 24 to 27 °C

DOI: 10.6092/issn.2281-4485/20218

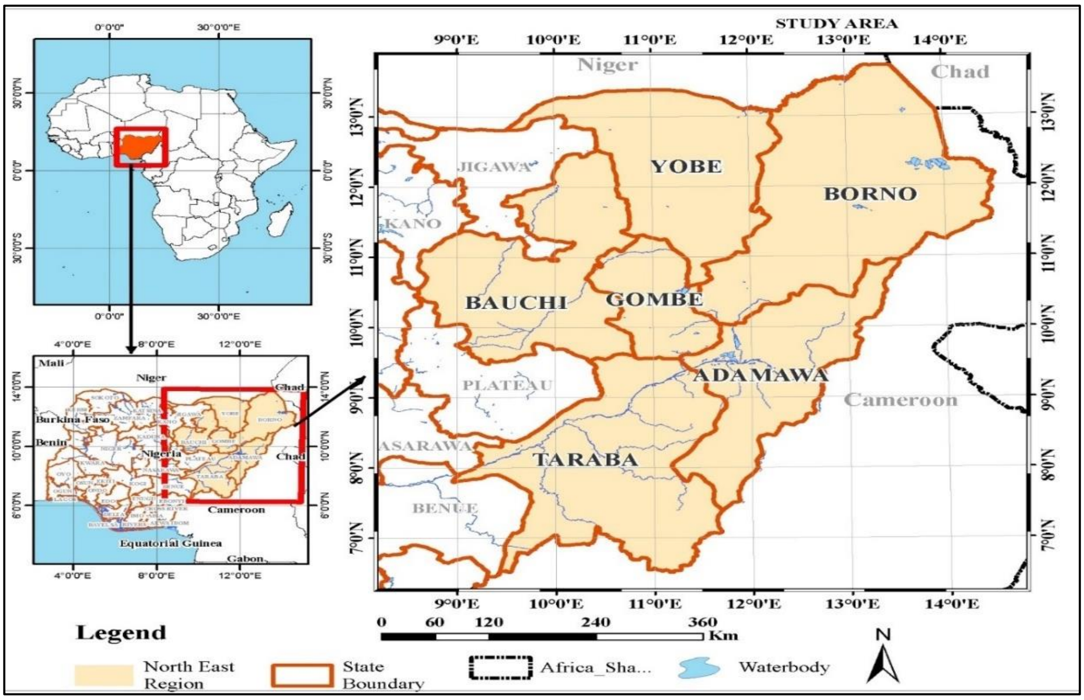

Figure 1
The study area

and the average annual rainfall varies from 700 to 1200 mm, (Ishaku et al., 2015).

Types and sources of data

This research utilizes both primary and secondary data, as detailed in Table 1. The data includes climatic, soil texture, and elevation information from the Shuttle Radar Topography Mission (SRTM). Key parameters such as drainage density, stream power index (SPI), topographic wetness index (TWI), and flow accumulation (FACC) were derived from the SRTM data, each critical for assessing the suitability of dam locations.

Drainage Density represents the total length of streams within a given area and indicates the landscape's capacity to handle water flow. A higher drainage density is typically associated with increased surface runoff, making this factor critical in dam planning (Schumm, 1956).

Stream Power Index (SPI) estimates the potential erosive power of flowing water by combining flow accumulation and slope data. This index is particularly useful in identifying areas where water flow may cause soil erosion, thereby affecting dam stability (Moore et al., 1993).

Table 1. *Types and sources of data*

S/N	Data	Source
1	Mean Annual Rainfall (precipitation)	Nigerian Meteorological Agency (NiMet)
2	Soil (Texture) Data	FAO and UNESCO/ISRIC
3	STRM (Elevation)	Global Landcover Facility (GLCF) (http://glcf.umd.edu/data))
4	Landsat 8 (2019) (Landuse Classification)	(USGS) (http://earthexplorer.usgs.gov))
5	Geology	Nigerian Geological Survey Agency
6	Slope	Generated from SRTM (DEM Elevation data)
7	Drainage Density	Generated from SRTM (DEM Elevation data)
8	Stream Power Index (SPI)	SRTM
9	Topographic Wetness Index (TWI)	SRTM
10	Flow Accumulation (FACC)	
11	Geographical coordinates	Field survey

FAO=Food and Agricultural Organization, UNESCO = United Nations Education, Scientific and Cultural Organization, ISRIC=International Soil Reference and Information Center, SRTM= Shuttle Radar Topographic Mission, USGS= United States Geological Survey.

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Topographic Wetness Index (TWI) is a measure of soil moisture distribution, calculated using slope and flow accumulation. This helps to predict areas prone to waterlogging, which could influence dam design and functionality (Beven & Kirkby, 1979).

Flow Accumulation (FACC) identifies points where water flow converges, directly impacting the availability of water at potential dam sites. This parameter provides a critical understanding of water movement patterns in the landscape (Tarboton, 1997). These parameters were processed using ArcGIS 10.7.1, and their relative importance was ranked based on their significance in dam site suitability evaluation. The weights assigned to these parameters followed established analytical hierarchy processes (AHP) to ensure that the most critical factors were prioritized (Saaty, 1980).

Method of data collection

Climatic data. Mean monthly rainfall data of the region was collected and manipulated in ArcGIS 10.7.1 to produce a rainfall map using the Spatial Interpolation Tool. The map was saved as a Dam climatic map for subsequent overlay analysis (Johnston et al., 2001).

Soil data (Texture). The soil map of the region was digitized from the existing soil map of Nigeria, obtained from the Food and Agricultural Organization and the International Soil Reference and Information Center (ISRIC). The map was digitized using ArcGIS 10.7.1 as polygons, and lines. The fully digitized map was saved as a base map and used for overlay analysis. The different types of soil described on the soil map were considered for generalization.

Shuttle Radar Topographic Mission (SRTM). This is a relief data with 30 30-meter resolution obtained from the United States Geological Survey (USGS). This was subsequently used for overlay analysis. From this data, geomorphology, elevation, drainage, density and slope map were generated using the Surface and hydrology analysis tool in ArcGIS 10.7.1 interface.

Land use. Landsat 8 satellite imageries of 2019 were obtained from the United States Geological Survey (http://usgs.gov/landexplorer). The landuse map was generated with the aid of ArcGIS 10.7.1 software using a maximum likelihood classification scheme to carry out Supervise image classification.

Method of Data Analysis

Software analysis. ArcGIS 10.7.1 was employed for daàta analysis, including the overlay of thematic maps such as rainfall, soil, geology, geomorphology, land use, drainage density, and elevation. The analysis was performed using the Map Algebra and Overlay tool, which allows the combination of multiple raster datasets to identify patterns and relationships (Tomlin, 1990). Assigning criteria weights. To assign different weights to the various criteria presented in Tables 2 and 3 (rainfall, soil, slope, drainage density, geology, and landuse), a pair-wise comparison method developed by Saaty (1980) was applied. This approach helps decision-makers express the relative importance of each criterion in determining the suitability of an area for dam location, facilitating more informed and accurate site assessments (Saaty, 1980). The Analytic Hierarchy Process (AHP) was utilized to generate a composite suitability map, which integrates weighted criteria into a single evaluation framework (Vargas, 1990).

Table 2. *Interpretation of Pair-wise Matrix Comparison (Saaty's AHP)*

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one element over another
5	Strong importance	Experience and judgment strongly favour one element over another.
7	Very strong importance	One element is favoured strongly over another, its dominance is demonstrated in practice.
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation.
2,4,6,8 can be used to express intermediate values		

DOI: 10.6092/issn.2281-4485/20218

Table 3. *Criteria definition of environmental factors for Dam suitability locations*

Thematic Layer	Thematic Layer Weight	Classes	Ranks
Rainfall (mm)	19.20%	0 - 47	**1**
		47 – 75	**3**
		76 – 103	**5**
		104 – 130	**7**
		131 – 160	**9**
Topographic Wetness Index (TWI)	3.20%	(-15.82) – (-11.32)	**1**
		(-11.31) – (-8.73)	**3**
		(-8.72) – (-5.36)	**5**
		(-5.35) – (-1.19)	**7**
		(-1.18) – 12.87	**9**
Stream Power Index (SPI)	5.80%	Less than 0	**1**
		0.01 - 5,248.28	**3**
		5,248.29 - 15,744.84	**5**
		15,744.85 - 36,737.96	**7**
		36,737.97 - 1,338,311.25	**9**
Flow Accumulation (FACC)	24.80%	0 - 0.93	**1**
		0.94 - 1.87	**3**
		1.88 - 2.8	**5**
		2.81 - 3.73	**7**
		3.74 - 4.67	**9**
Drainage Stream Density	15.40%	0 – 1.7	**1**
		1.8 – 3.6	**3**
		3.7 – 5.3	**5**
		5.4 – 7.1	**7**
		7.2 – 8.9	**9**
Geology	12.60%	Basement Complex	**9**
		Sedimentary	**3**
		Younger Granites	**7**
		Migmatite-Gneiss	**5**
Elevation (m asl)	2%	0 – 530	**9**
		531 – 985	**7**
		986 – 1,439	**5**
		1,440 – 1,893	**3**
		1,894 – 2,348	**1**
Slope	8.90%	0–0.81	**9**
		0.82–2.78	**7**
		2.79–5.91	**5**
		5.92–10.2	**3**
		10.21–22.83	**1**
Landuse	3.60%	Urban and Built-Up Land	**1**
		Cultivated Land	**6**
		Grassland	**5**
		Shrubland	**4**
		Savanna	**3**
		Water Bodies	**9**
		Bare Land	**8**
		Forest	**7**
Soil Texture	4.40%	Sand	**3**
		Loamy	**5**
		Clay	**9**

Sources: Adapted from Saaty (1980)

DOI: 10.6092/issn.2281-4485/20218

Definition of suitability criteria based on environmental requirement

In the final stage of the analysis, the study area's ideal dam location was modeled and mapped using all of the thematic layers that were analyzed. Combining and fusing the thematic factors is not appropriate because each factor has a different unit of measurement. As a result, using the natural breaks (Jenks) technique, all thematic layers were standardized by being reclassified into five classes (Chen et al., 2013).

Further, based on a scale of one to nine (1 - 9) each class was assessed regarding a suitable location for construction of the dam. The weighting was determined by using the AHP primary techniques. Determining the weight following the literature and professional judgment is the primary factor in AHP modeling. A new thematic layer weighting was obtained by moderating the combined weight of the two approaches as in (Table 3).

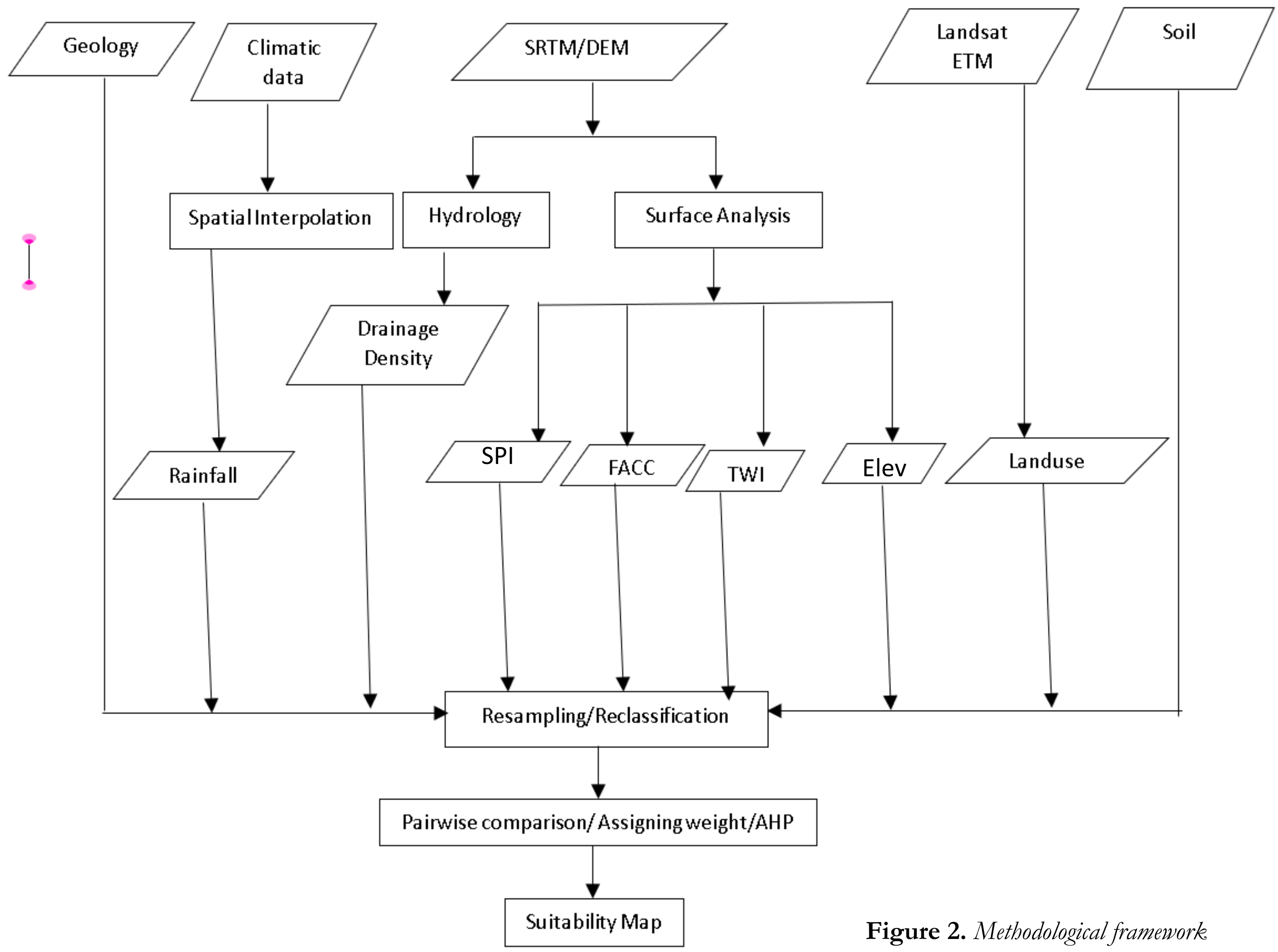

Figure 2. *Methodological framework*

Result and Discussions

DAM suitability mapping

The thematic maps in Figure 3 were used to produce a composite suitability layer and categorized into five classes with the integration of all mapping criteria. As shown in Figure 4, the moderately suitable class has the highest area which makes up 149,451.59 km^2 (54.17%) and is located in the north-central part of the drainage basin, followed by high suitability classes with 104,981.97 km^2 area coverage (38.05%) while the very high suitable class is the lowest with 583.49km^2 (0.21%) located in the north-western and north-eastern part of the watershed. This finding confirms the report of Odiji et al., (2021) who reported the dominance of a moderately suitable class in the upper Benue River watershed. The very low to low suitable class makes up 3359.03 to 17496.58 km^2 (1.2 – 6.3 %) of the region which is located in the southern part, especially in highland areas. By matching varying thematic maps with suitability

DOI: 10.6092/issn.2281-4485/20218

maps, the factors that determine the suitability suitable class were in order of; flow accumulation, topographic wetness index, landuse, soil, stream power index, slope, geology, drainage density, and elevation as the least determinant factor. This confirms the report of Hagos et al., (2022) who reported that mainstream flows alongside topographical parameters carried higher weights when compared to other factors. The areas with low to very low suitability were dominantly determined by the following factors: low rainfall, poor geology, steep slope, high elevation, and low drainage density. The results presented in Table 3 illustrate the weighted criteria for site selection in North Eastern Nigeria for hydro-electric dam construction, derived from pairwise comparisons (Saaty, 2008). Elevation emerges with the lowest priority at 2.00%, indicating its minimal influence on site selection compared to other factors. Drainage Density, Land Use, Rainfall, Soil, Geology, Slope, FACC (Flow Accumulation), SPI (Stream Power Index), and TWI (Topographic Wetness Index) are all significant criteria, with varying degrees of importance ranging from 3.20% to 24.80%. Among the factors, Flow Accumulation (FACC) stands out with the highest priority at 24.80%, indicating its critical role in identifying suitable sites

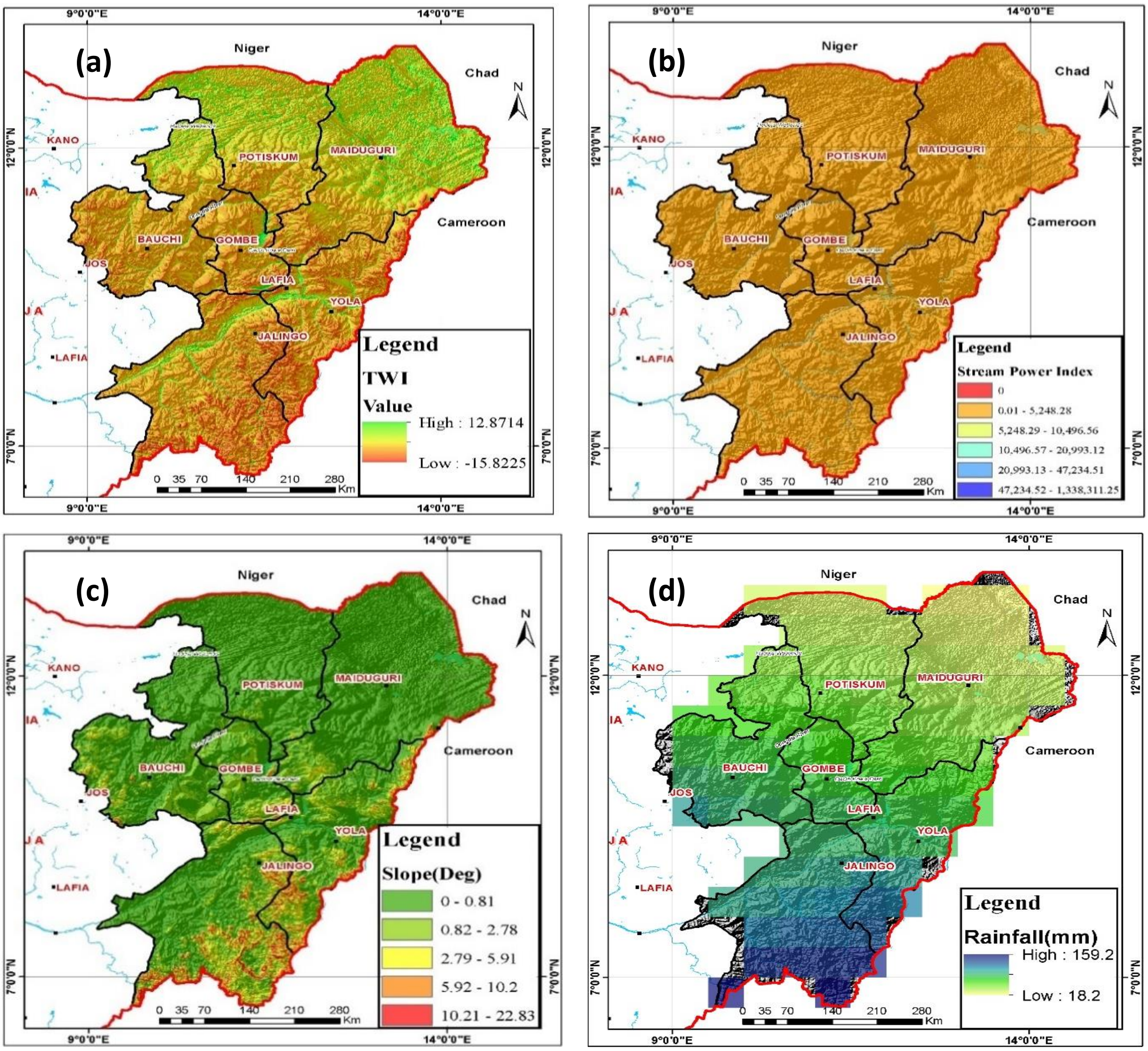

Figure 3. *Criteria for dam site identification* (a) *Topographic Wetness Index,* (b) *Stream Power Index,* (c) *slope,* (d) *rainfall.*

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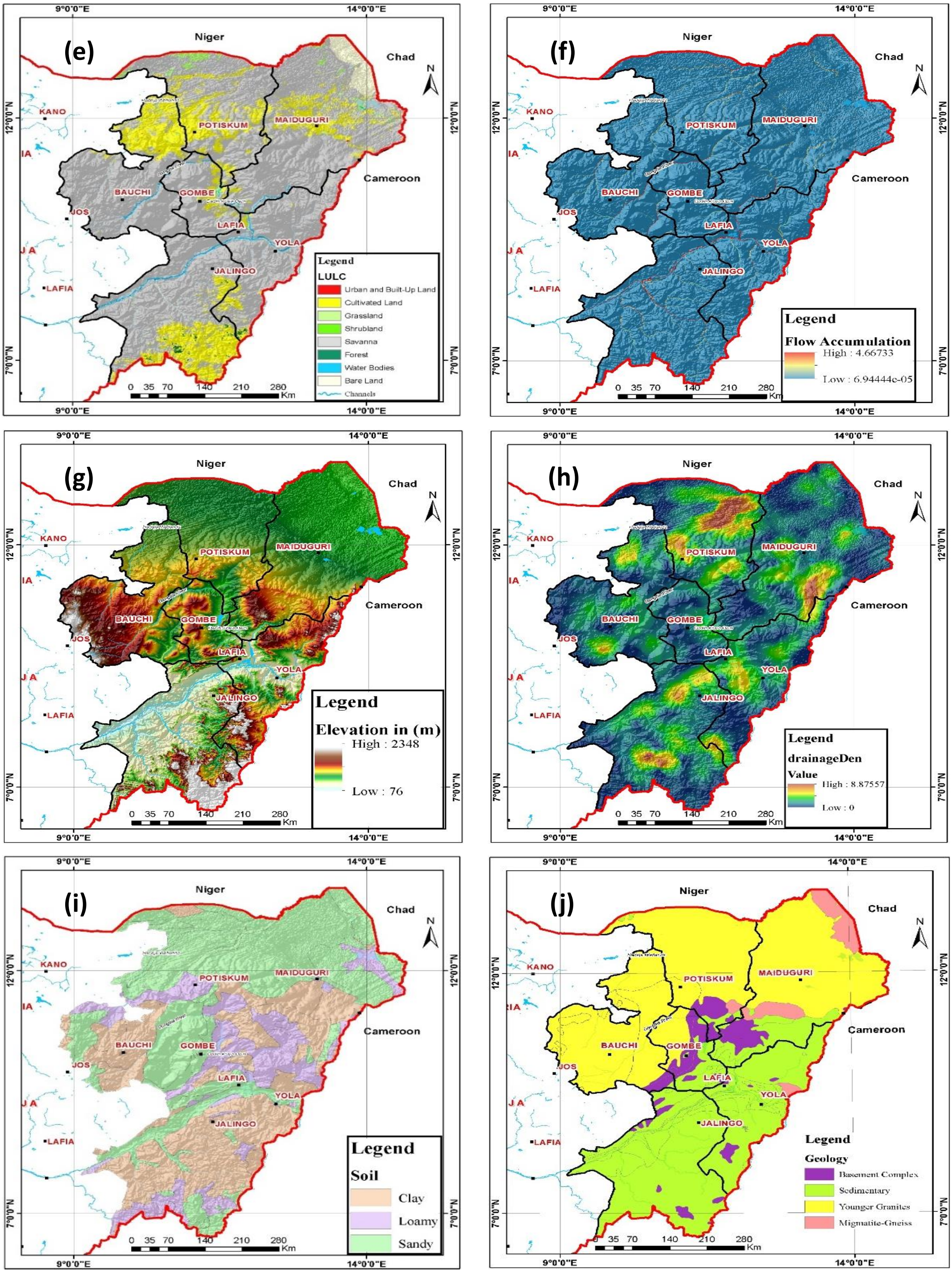

Figure 3 (segue). *Criteria for dam site* (e) *land use,* (f) *flow accumulation,* (g) *elevation,* (h) *drainage density,* (i) *soil texture*, (j) *geology.*

DOI: 10.6092/issn.2281-4485/20218

Table 3 *Resulting weights for the criteria based on pairwise comparisons:*

SN	Criteria	Priority	Rank	(+)	(-)
1	Elevation	2.00%	10	1.10%	1.10%
2	Drainage Density	15.40%	3	8.60%	8.60%
3	Landuse	3.60%	8	1.80%	1.80%
4	Rainfall	19.20%	2	6.00%	6.00%
5	Soil texture	4.40%	7	2.10%	2.10%
6	Geology	12.60%	4	6.60%	6.60%
7	Slope	8.90%	5	4.90%	4.90%
8	FACC	24.80%	1	27.00%	27.00%
9	SPI	5.80%	6	3.10%	3.10%
10	TWI	3.20%	9	1.10%	1.10%

for hydroelectric dam construction. According to Huang et al., (2018), dams ought to be generally located at the watershed or sub-watershed outlet, where the flow accumulation is the largest. This emphasizes the importance of water flow dynamics in determining the feasibility and potential output of hydroelectric projects. Conversely, factors such as Elevation and TWI have relatively minor impacts, suggesting that topographic considerations may have less significance in this context compared to other criteria. Furthermore, the pairwise comparisons reveal a balance between natural and anthropogenic factors, with parameters like Rainfall, Drainage Density, and Soil quality being significant alongside geomorphological aspects like Slope and Geology. These results highlight the multidimensional nature of site selection for sustainable hydroelectric power generation, emphasizing the need for compre-hensive assessments that consider both physical and environmental factors. Overall, these findings provide an understanding for policymakers and stakeholders in identifying suitable locations for dam construction in North Eastern Nigeria, facilitating the development of green energy solutions while ensuring environmental sustainability. Table 4 presents the resulting weights derived from the principal eigenvector of the decision matrix used in the study on sustainable hydroelectric power potential in North Eastern Nigeria. Each cell in the table represents the relative importance of one criterion compared to another, as determined through pairwise comparisons. The values range from 0.11 to 9, indicating the varying degrees of influence each criterion holds in the site selection process for dam construction. The consistency ratio (CR) of 9.9% suggests a reasonable level of consistency in the pairwise comparisons conducted during the deci-sion-making process. A CR below 10% is generally considered acceptable, indicating that the judgments made in comparing the criteria were consistent and reliable. Examining the weights assigned to each criterion, it is evident that Flow Accumulation (FACC) holds the highest importance, with a weight of 9, followed by Rainfall and Drainage Density, each with weights of 6 and 5, respectively. These findings align with the importance of water availability and flow dynamics

Table 4: *Resulting weights are based on the principal eigenvector of the decision matrix:*

	Elevation	Drainage Density	Land use	Rainfall	Soil	Geology	Slope	FACC	SPI	TWI
Elevation	1	0.2	0.33	0.17	0.2	0.2	0.25	0.2	0.25	0.5
Drainage Density	5	1	2	0.5	6	0.5	4	1	4	5
Landuse	3	0.5	1	0.25	0.5	0.25	0.25	0.25	0.25	1
Rainfall	6	2	4	1	5	2	3	1	5	4
Soil	5	0.17	2	0.2	1	0.25	0.5	0.17	0.5	2
Geology	5	2	4	0.5	4	1	2	0.11	3	3
Slope	4	0.25	4	0.33	2	0.5	1	0.33	4	4
FACC	5	1	4	1	6	9	3	1	3	4
SPI	4	0.25	4	0.2	2	0.33	0.25	0.33	1	2
TWI	2	0.2	1	0.25	0.5	0.33	0.25	0.25	0.5	1

Consistency Ration (CR): 9.9%, Principal eigenvalue = 11.326. Source: Authors Analysis (2024)

DOI: 10.6092/issn.2281-4485/20218

in determining suitable sites for hydroelectric projects. Conversely, factors such as Elevation and Topographic Wetness Index (TWI) hold relatively lower weights, suggesting they have less influence on site selection compared to other criteria.

Table 5. *Dam suitability from weighted rank*

S/N	Suitability Rank	Area (sqkm)	%
1	Very Low	3359.03	1.22
2	Low	17496.58	6.34
3	Moderate	149451.59	54.17
4	High	104981.97	38.05
5	Very High	583.49	0.21
Total		275872.67	100.00

Table 6. *Proposed Dam locations per state in Northeastern Nigeria.*

ID	Latitude	Longitude	Mean Elevation (m)	State
1	11.23	11.09	285.20	Gombe
2	12.34	10.37	270.09	Borno
3	11.02	9.06	120.57	Taraba
4	12.62	9.26	163.80	Adamawa
5	10.51	9.69	273.51	Bauchi
6	9.81	8.21	91.00	Taraba
7	10.72	8.13	151.01	Taraba

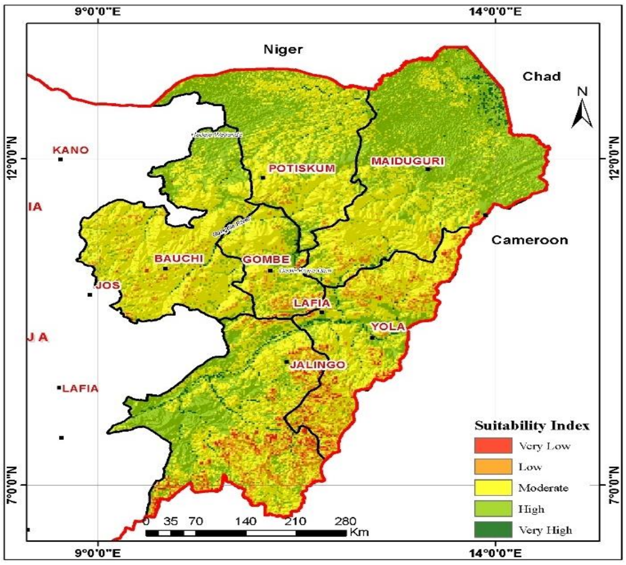

Figure 4. *Site suitability map of Northeastern Nigeria.*

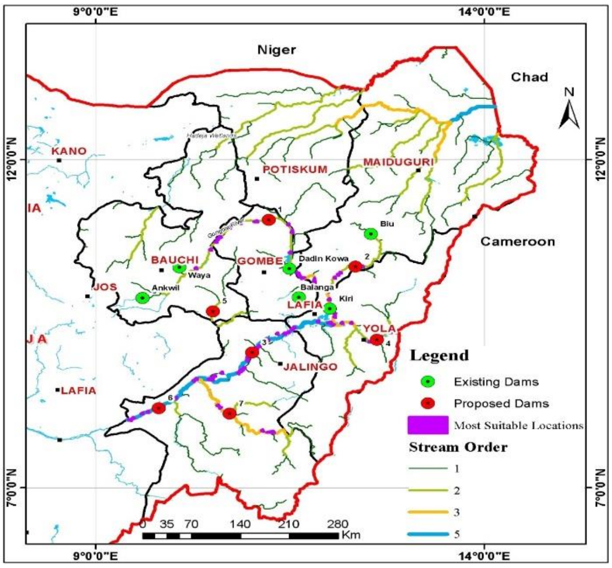

Figure 5. *Locations of potential small hydropower sites in North East Nigeria*

Table 7 shows the mean values of seven numerical criteria for different states in North Eastern Nigeria, along with the number of proposed dam locations in each state as shown also in Figure 5. The criteria include Drainage Density, Stream Power Index, Rainfall, Flow Accumulation, Topographic Wetness Index, Elevation, and Slope. These criteria are crucial in determining the suitability of a location for hydroelectric dam construction. Upon examination of the data, it's evident that Taraba state stands out with relatively high mean values across several criteria compared to the other states. Specifically, Taraba has higher mean values for SPI, Rainfall, Elevation, and Slope compared to other states. These factors signify favorable conditions for hydroelectric dam construction, as higher values of SPI and Rainfall indicate greater water flow potential, while higher elevation and slope can contribute to increased gravitational energy potential. Given Taraba state's favorable conditions across multiple criteria, it's logical that it would have more proposed dam locations compared to other states. The presence of three proposed dam locations in Taraba indicates that multiple sites within the state meet the necessary criteria for hydroelectric development. Conversely, Yobe state stands out with lower mean values across several criteria compared to the other states. Yobe has notably lower values for SPI, Rainfall, and Elevation. These factors suggest less favorable conditions for hydroelectric development within the state. As a result, there are no proposed dam locations in Yobe State. Overall, the distribution of proposed dam locations across the states reflects the varying suitability of each location for hydroelectric devo-

DOI: 10.6092/issn.2281-4485/20218

Table 7. *Mean values of seven numerical criteria for different states in North Eastern Nigeria*

State	Mean Values							Proposed Dams
	DD	SPI	Rain	FACC	TWI	Elev	Slope	
Adamawa	1.58	537.99	85.29	0.02	-10.73	440.55	1.74	1
Bauchi	1.39	278.48	69.00	0.01	-9.80	514.77	0.65	1
Borno	1.46	278.49	38.29	0.01	-7.08	346.60	0.23	1
Gombe	1.20	727.08	70.96	0.02	-10.12	410.93	1.10	1
Taraba	1.57	802.67	112.77	0.02	-10.79	396.16	2.06	3
Yobe	1.99	79.13	37.70	0.01	-7.68	359.26	0.18	0

lopment based on the criteria examined. Taraba state's relatively favorable conditions compared to other states justify the presence of multiple proposed dam locations, while Yobe state's less favorable conditions explain the absence of proposed dam locations within the state.

Conclusion

The study mapped prospective dam development sites in Northeastern Nigeria using geospatial analysis. To generate a suitability model, ten hydrophysical criteria were used and went through several processing steps. AHP was used to weigh and rank each criterion. Five classes were identified from the composite suitability map generated: very high, high, moderate, low, and very low. Flow accumulation holds the highest importance, followed by rainfall and drainage density, while slope was the least important in determining the suitability of the region. About 38% of the region is of the highly suitable class, and 54.17 % is moderately suitable. Among the six states in the region, Taraba state has the highest potential dam site with three sites while the other has one each except Yobe state with none. The locations of the identified dam are both practically and financially suitable for the construction of the dam that could provide green energy. Costructions of more dams in the identified sites will not only gennerates green energy but also reduce the rate of flooding due to dam colapse which destroy lifes and properties. The recent Alua Dam colapse in Borno state Nigeria on 10th September, 2024 affected one million people and the United National Refugee Agency in Nigeria described it as the worst to hit the State in thirty years. GIS has shown to be a potent technology that blends various datasets to produce outputs that enable decision-makers to decide the best/ideal location to build a dam on a sustainable basis.

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