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A suitability modeling based on geographic information system for potential micro hydropower dam site

O. Setiawan[1,*], H.Y.S.H. Nugroho[1], N. Wahyuningrum[1], D. Auliyani[1], K.S. Hardjo[2]

[1] Research Center for Ecology and Ethnobiology, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor, Cibinong 16911, Jawa Barat, Indonesia

[2] Department of Earth Technology, Geographic Information System, Vocational College, Universitas Gadjah Mada, Yogyakarta, Indonesia

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ABSTRACT

BACKGROUND AND OBJECTIVES: Micro-hydropower plants are significant contributors of electricity and clean source of renewable energy. A nationwide or large watershed inventory of potential micro hydropower dam sites is lacking, hindering micro-hydropower development. Traditional ground survey approaches for locating micro-hydropower dam sites are expensive, time-consuming, laborious, and vulnerable to inconsistency. Geographic information system frameworks are commonly used, and they provide significant value to hydropower evaluation. A suitability approach for dam site identification is important in supporting the optimization of hydropower utilization in the context of watershed management and in eliminating the inconsistency of conventional approaches. The objective of this study was to identify potential sites for micro-hydropower dams on the basis of various parameters by using a suitability modeling approach based on geographic information system.
METHODS: The Saddang Watershed was chosen as the study area, it is located in the South Sulawesi and West Sulawesi Provinces of Indonesia, and it is an example of a large watershed. The analytical hierarchy process was used for criterion weighting and to create a dam suitability index map based on the following criteria: geomorphometry, geology, rainfall, soil texture, and land use land cover. The developed dam suitability index map was validated by comparing it with existing dams by using the receiver operating characteristic curve. The identification of potential micro-hydropower dam sites involved overlay and query methods. It considers dam suitability index, proximity from road and settlement, existence of conservation forest, and the potential hydraulic head.
FINDINGS: The dam suitability index map with five suitability classes was obtained, with the high and very high suitability indexes extending to 8.7 percent of the study area. These classes were typified by high drainage density, topographic wetness index, stream power index, low vegetation cover, moderate slope, situated on second or higher stream orders, normal temporal distribution of rainfall, and sandy clay loam soil texture with igneous and sedimentary complex rocks. The developed suitability model was sufficiently effective in determining dam suitability index, as indicated by a value greater than 0.9 of the area under the curve. A total of 635 potential dam locations were identified with high and very high suitability indexes, located on first or second stream orders, within a 4,000 m radius of roads and settlements, outside conservation forest areas, and with a potential hydraulic head greater than 20 meter.
CONCLUSION: Integrating a dam suitability index map and restriction factors into a geographic information system framework, enabled a robust analysis for identifying potential sites of micro-hydropower dams. The proposed approach is expected to contribute to the advancement of renewable energy initiatives and water resource management within large watersheds. It is also expected to serve as a valuable resource for policymakers involved in the implementation of micro-hydropower projects and watershed management to support the achievement of renewable energy development targets.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
56	9	3

Corresponding Author:
Email: ogi.setiawan@brin.go.id
Phone: +62812 424 7658
ORCID: 0000-000 2-8682-4849

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INTRODUCTION

Electricity consumption and availability serve as indicators of the socio-economic development of a particular region. Electricity is also recognized as a catalyst for enhancing various forms of production and as a lever for economic development (Lee and Chang, 2018). Approximately 80 percent (%) of energy consumption is derived from fossil fuels, highlighting society's heavy reliance on non-renewable energy sources (Samimi and Moghadam, 2024). Such dependency has also contributed to the issue of climate change (Harjanne and Korhonen, 2019; Frimawaty *et al.,* 2023). Exploring renewable energy sources is imperative due to possible consequences for developing and developed nations (Hammid *et al.,* 2018). The adoption of renewable sources is also a critical strategy for mitigating environmental effects from carbon dioxide (CO_2) emissions within the energy sector (Olabi and Abdelkareem, 2022). Among renewable energy sources, micro-hydropower plant (MHP) is a prominent contributor to electricity generation (García *et al.,* 2021) and it represents a cleaner energy source (Bayazıt *et al.,* 2017). MHP exhibits the advantage of supporting electricity supplies to remote areas, and thus, it improves energy quality and socio-economic development (Pottmaier *et al.,* 2013). Hydropower also constitutes a substantial portion of global renewable energy development, contributing 71% of the total supply and approximately 16.4% of the world's electricity (Moran *et al.,* 2018). MHP development remains challenging, particularly in regions with rich water resources, such as Asia, and Latin America. One of the primary impediments to MHP development is the absence of the latest national/regional data and information on potential dam sites for MHP initiatives (Odiji *et al.,* 2021). Traditional ground survey methods for identifying potential MHP dam sites are cost-prohibitive, time-intensive, and labor-demanding, necessitating focused investigations in areas that are likely to yield suitable sites. Determining potential locations for MHP dams at the regional scale still uses a data aggregation approach with varying accuracy and is vulnerable to inconsistencies (Ali *et al.,* 2023), resulting in differences and inconsistencies between data and collection methods (Korkovelos *et al.,* 2018). Improving the quality and consistency of dam location identification for MHP is a prerequisite for supporting planning before the structural development. Geographic information systems (GIS)

have emerged as effective tools for spatial data analysis, including the exploration of potential dam sites for MHP projects. GIS-based approaches for hydropower assessment offer several advantages, such as enhancing efficiency and accuracy in the context of data integration, visualization and analysis, and addressing the issues of complex analysis, considerable time consumption, risk assessment, adaptability, and iteration (Zewdie and Tesfa, 2023). GIS approaches have also gained prominence in spatial modeling by conveying valuable and significant information, including the incorporation of remote sensing (RS) and GIS methods for hydropower assessment. The utilization of GIS-based modeling assists in evaluating potential MHP dam sites by considering various parameters that influence site selection (Avtar *et al.,* 2019). Numerous studies have emphasized the utility of RS and GIS techniques in hydropower development. For example, Othman *et al.* (2020) utilized GIS-RS in the selection of appropriate hydropower dam sites in the Kurdistan Region of Iraq by using the Weighted Sum Method (WSM) and Analytical Hierarchy Process (AHP) approaches and by integrating multiple data layers. A study in Thailand incorporated GIS and AHP to assess potential small hydropower sites on the basis of morphometric, climate, lithology, soil type, slope, and land use land cover (LULC) (Ali *et al.,* 2023). Although some studies have explored dam site suitability, limited attention has been given to the explicit elucidation of the spatial identification of potential dam sites with the incorporation of socio-economic factors, conservation forest existence, and technical aspects (potential hydraulic head). Indonesia, the country under consideration, exhibits a remarkable hydrological configuration distinguished by numerous precipitations and a sophisticated river network. The presence of 23.3 million hectares (ha) of state-owned forests (Ministry of Environment and Forestry, 2020) assumes a pivotal role in hydrological regulation, facilitating the provision of the water resources which is integral to advancing MHP initiatives. The country has a hydropower potential of up to 75 Giga Watt (GW), including rivers that drain water from forest ecosystems (Rahayu and Windarta, 2022). MHP development in Indonesia is supported by the National Electricity Company, which aims to develop 0.3 GW MHP in 2016-2025. In accordance with the document of the National Energy General Plan, to achieve a minimum of 23% new renewable energy by 2025, hydropower plants

with a total capacity of at least 18 GW and MHPs of 3 GW, representing 46.4% of the total new renewable energy target, will be built. It shows that both currently and in the future, data and information on potential MHP dam sites in the region/provinces/large watersheds are needed to support the sustainability of national electricity through MHP development. This study addresses the limitations presented in previous research by introducing an approach that identifies stream channel segments with the intersection of the Dam Suitability Index (DSI), proximity from roads and settlements, conservation area boundaries, stream order, and potential hydraulic head. The objective is to enhance the spatial identification of dam sites for MHP development, particularly within large watersheds. This study performed the following procedures to achieve its objective: 1) evaluating and mapping geomorphometry, climate, geology, soil texture,

and LULC factors; 2) applying AHP to generate a DSI map; and 3) identifying potential sites for MHP dam. The study findings will provide resource managers and energy planners, who are constrained by data limitations, with valuable insights for identifying promising locations for MHP dams, mitigating expenditures of time and resources in subsequent field investigations. Suitability modeling is also important for supporting watershed management in terms of micro-hydropower optimization and reducing inconsistency in both data, method, and results. This study was conducted in the Saddang Watershed, South Sulawesi and West Sulawesi Provinces, Indonesia, in 2023.

MATERIALS AND METHODS

The methodological flow chart of this study is presented in Fig. 1. This section elucidates the study area description, the diverse types of utilized data,
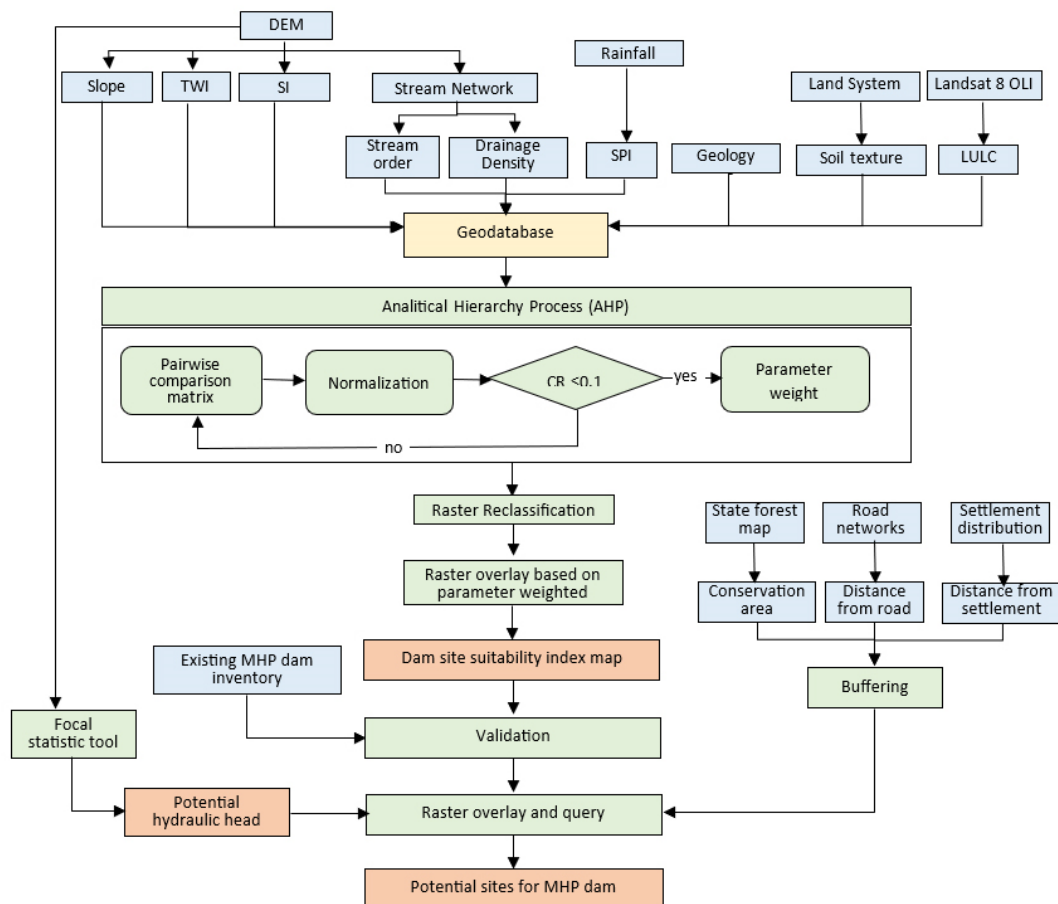

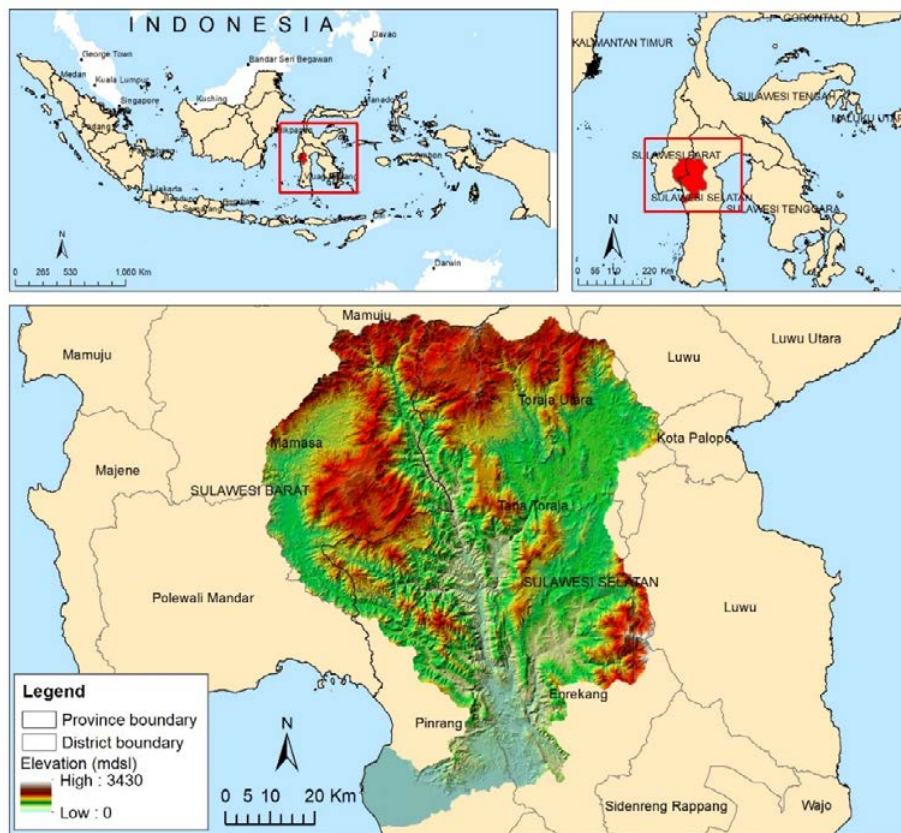Fig. 1: The methodological flow chart of this study

Fig. 2: Geographic location of the study area in Saddang Watershed in west and south Sulawesi Provinces of Indonesia

and the data processing and analysis techniques employed to identify potential sites for MHP dam development. The Digital Elevation Model (DEM) data used in this study were obtained from the Geospatial Information Agency of Indonesia. The spatial resolution of the DEM data is 8.3 meters (m) (Sihombing *et al.*, 2021). The geological characteristics of the study area were extracted from the Geology map of Indonesia, particularly the Sulawesi sheet, with a scale of 1: 250,000 (Villeneuve *et al.*, 2002). The soil texture of the study area was derived from the land system map released by the Geospatial Information Agency. The Landsat Operational Land Imager (OLI) 8, with a spatial resolution of 30 m (Roy *et al.*, 2014) and acquisition year 2022, was downloaded from the United States Geological Survey website and used to obtain the LULC of the study area. This study utilized rainfall data from the Climate Hazards Group Infra-Red Precipitation with Station (CHIRPS) (Funk *et al.*, 2015). The spatial distributions of road networks

and settlements were isolated from Indonesia's Topographic Map with a scale of 1:50,000 produced by the Geospatial Information Agency of Indonesia. The conservation forest situated in the study area was clipped from the State Forest of Indonesia map released by the Ministry of Environment and Forestry of Indonesia (Ministry of Forestry, 2014). The distribution of existing dam sites of MHP in the study area was obtained from Remap Indonesia (Wahyuono and Julian, 2018) for validation purposes.

Study area

This study selected the Saddang Watershed as the object. It is predominantly located in South Sulawesi Province, and a small portion also extends into the West Sulawesi Province, Indonesia (Fig. 2). The watershed covers an area of about 6,630 square kilometers (km^2). The Saddang Watershed is situated between 119°15'20" and 120°03'52" east (E) and between 2°44'20" and 3°46'20" south (S). It

716

constitutes a hydrological basin with a considerable expanse, encompassing Mamuju, Mamasa, and Polewali Mandar Districts in West Sulawesi, and Tanah Toraja, Enrekang, and Pinrang Districts in South Sulawesi. The watershed plays a significant role in shaping the hydrological cycle, ensuring the accessibility and availability of water resources in the context of land governance. Its pivotal role extends to providing essential irrigation for agricultural activities, with effluents discharging at the Bendeng Reservoir, located within the jurisdictions of Pinrang and Sidrap Districts (Irmayani *et al.,* 2018). The climate type of the Saddang Watershed is type C according to the Schmidt-Ferguson classification, corresponding to a slightly wet region. The annual rainfall in the area is 2,155 millimeters (mm), with April experiencing the highest monthly average rainfall and August the lowest. Forest coverage (75%) dominates the LULC of the Saddang Watershed, distributed mainly in the upstream areas (Irmayani *et al.,* 2018). The dominant rock formation is the Talaya Volcano Rock, encompassing 25% of the total area. Mountains/hills landforms dominate the geomorphology of the Saddang Watershed. Most of the watershed areas have slopes between 25% and 45% (Lamada *et al.,* 2022).

Criteria determination for MHP dam site identification

Site selection that is most conducive to establishing MHP structures took into consideration various criteria, including geomorphometry, topography (Ajibade *et al.,* 2020), geology, and climate (Othman *et al.,* 2020). Nine criteria were considered in the DSI mapping within the study area: flow continuity (stream order), geology, slope, soil texture, Drainage density (Dd), Topographic Wetness Index (TWI), Stream power Index (SI), Standardized Precipitation Index (SPI), and LULC. The criteria were adopted on the basis of a comprehensive literature review of previous studies related to hydropower evaluation and data availability consideration.

Flow continuity (stream order)

A crucial criterion for locating an MHP dam is the amount of water flow that is reliably accessible all year round. An adequate water discharge must be available to operate MHP effectively. Flow potential in this study was represented by the stream order criterion in which higher order specifies flow

accumulation. A high flow accumulation value of a particular region is expected to represent water bodies more precisely, such as rivers, ponds, and lakes (Korkovelos *et al.,* 2018). Stream order criterion aids in identifying streams where water flow is likely to exceed a certain minimum threshold throughout the year. The stream network was generated from DEM by using a threshold accumulation value of 1,000 in the GIS environment and the Strahler stream order method. Fig. 3a depicts the stream order in the watershed being studied, and it ranges from first to eighth order. The length of the first order stream reaches 51% of overall stream length in the watershed.

Rainfall

Rainfall intensity exerts a significant influence on peak discharge. An increase in the amount of rainfall directly effects increased river discharge, including peak discharge. The potential for electricity generation in an area depends on rainfall volume, intensity, and spatial distribution (Zhao *et al.,* 2019). In this study, the rainfall criteria were represented by SPI. SPI assesses the deviation of precipitation data from its long-term average, thereby providing insights into the variability and intensity of precipitation events. It also considers the temporal distribution of precipitation and is applicable over various timescales (Gidey *et al.,* 2018). SPI was calculated for periods of the dataset using Eq. 1 (Livada and Assimakopoulos, 2007).

$$SPI = \frac{x_i - \bar{x}}{\sigma} \qquad (1)$$

Where; x_i represents monthly rainfall, $\bar{x}$ represents mean monthly rainfall, and σ denotes the standard deviation of rainfall. The resulting SPI calculation for the entire study area is presented in Fig. 3b. The temporal distribution of rainfall in the study watershed shown by SPI ranged from 0.49 to 0.97. This result indicated that rainfall distribution is normal (SPI = -0.99 to 0.99) and spread throughout the year (Anshuka *et al.,* 2019).

Geology

The geological substrate that underlies a dam structure represents a critical determinant that is integral to a dam's foundation. Geologically strong materials, (e.g. hard rock formations), are highly
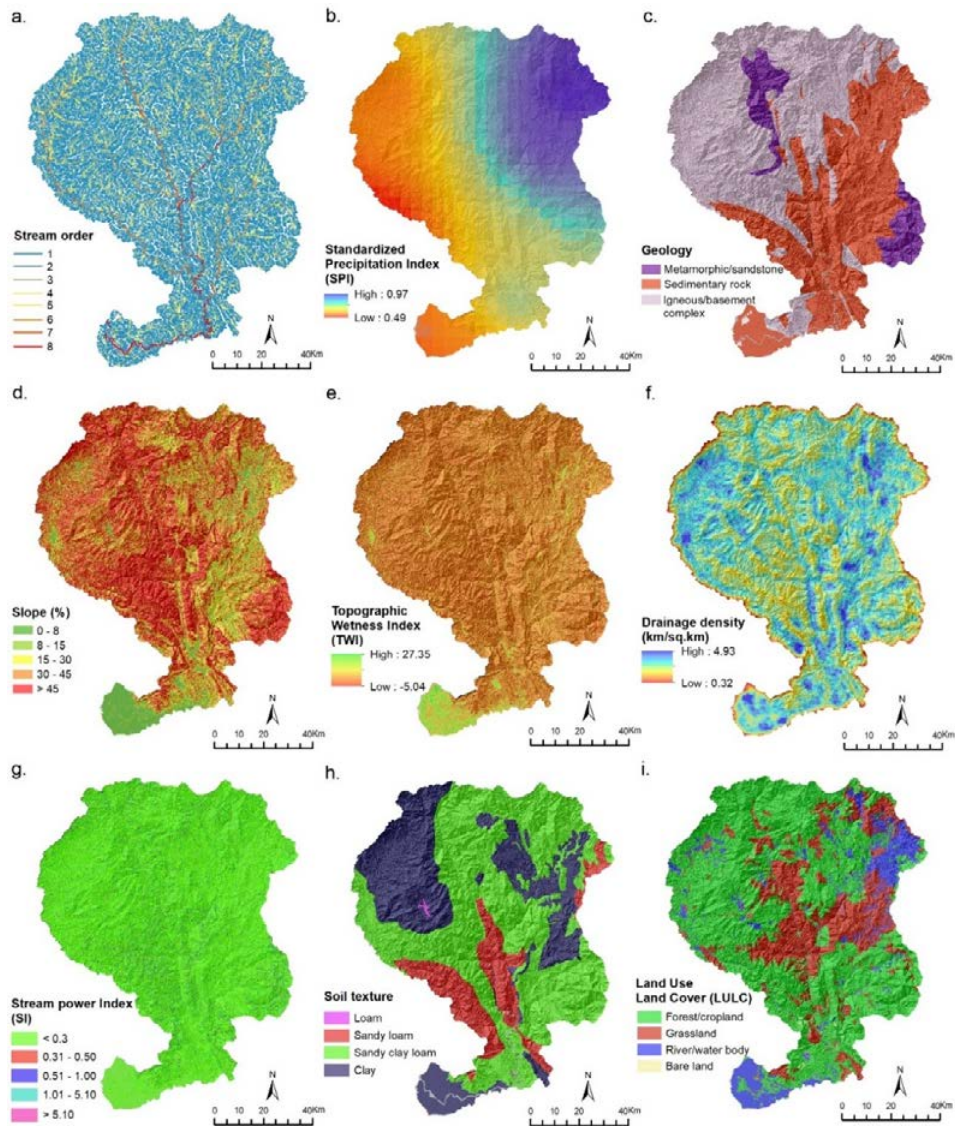
Fig. 3: Maps of criteria used in the analysis: stream order (a), SPI (b), geology (c), slope (d), TWI (e), Drainage density (f), SI (h), soil texture (h), and LULC (i).

suitable materials for dam construction (Sissakian *et al.,* 2020). The geological feature under MHP dam must possess the requisite strength to support the weight of the dam structure and water reservoir. The geological landscape of the study area can be generally categorized into three distinct formations: igneous/basement complex, sedimentary rock complex, and metamorphic/sandstone formation. The spatial distribution of geology in the study area is presented in Fig. 3c.

Slope

Slope exerts a profound influence on the pattern and magnitude of surface runoff. An escalation in slope steepness corresponds directly to an augmentation of river flow velocity (Yu *et al.,* 2022). Slope is also an elemental determinant of hydropower initiation, where a greater slope gradient creates a heightened power yield, and conversely, a reduced gradient diminishes power output. The slope layer in this study was generated from the DEM dataset. Fig. 3d

provides a graphical depiction of slope characteristics, revealing predominant steepness in the northern part with gradual inclinations discernible in the central and southern regions of the study watershed.

Topographic wetness index

TWI functions as a representation metric for identifying regions that accumulate runoff potential. It is employed in elucidating the dynamics of water flow and accumulation (Meles *et al.,* 2020). TWI values were extracted from the DEM using Eq. 2 (Hojati and Mokarram, 2016).

$$TWI = \ln\left[\frac{A}{\tan(\beta)}\right] \tag{2}$$

Where; A is the catchment area, and β is the slope gradient in degrees. Fig. 3e shows the TWI distribution in the study area. The TWI values in the study watershed were between -5.04 and 27.35. The higher values predominantly correspond to the central watershed, especially along the primary river network and in the southern part of the study watershed.

Drainage density (Dd)

Drainage density denotes the total stream lengths per watershed area. It serves as an indicator of the tendency for surface runoff and groundwater presence within a specified area. Regions marked by elevated drainage density are characterized by a heightened susceptibility to surface runoff and groundwater occurrence, making them amenable to hydropower generation applications (Allafta *et al.,* 2021). Stream network data were used to generate drainage density through the spatial analysis method, specifically the line density tool. The drainage density in the study area was between 0.32 km/km^2 and 4.93 km/km^2 (Fig. 3f).

Stream power index (SI)

SI is a valuable tool for quantifying the potential for flow erosion at a specific location on a topographic surface. The corresponding rise in the volume of water contributed by the upslope catchment area and the velocity of water flow are followed by an increase in the upslope catchment area and slope gradient (Andualem *et al.,* 2020), resulting in an increase in the SI values and the potential erosion effects. Eq. 3 was utilized to calculate the SI value based on the

DEM dataset (Papangelakis *et al.,* 2022).

$$SI = \ln[A \cdot \tan(\beta)] \tag{3}$$

Where; A is catchment area, and β is the slope gradient in degrees. Fig. 3g presents the SI map of the study area. SPI values varied between -6.07 and 15.65 within the study area.

Soil texture

Soil texture correlates closely to the infiltration process and runoff generation. The textural composition of the soil is a pivotal factor in identifying an appropriate site for MHP dam construction, particularly in the context of dam foundation (Al-Ruzouq *et al.,* 2019). The soil texture map of the study watershed was extracted from the Land System map. Fig. 3h illustrates an overview of the soil texture distribution in the Saddang Watershed, divided into four classes: loam, sandy loam, sandy clay loam, and clay.

Land use land cover (LULC)

LULC can be defined as the allocation and deployment of land for distinct purposes. It effects surface roughness, soil infiltration capacity, runoff generation, and the patterns of peak discharge within a watershed, providing essential consideration in MHP dam site selection (Abdulkareem *et al.,* 2019). LULC data were obtained by interpreting Landsat 8 OLI by using a supervised classification approach, i.e., the maximum likelihood method. Fig. 3i presents LULC distribution in the study area, indicating that forest and cropland encompass 66% of the study area. Bare land accounts only for 0.2%, while the combination of grassland and water bodies occupy 33.8% of the study area.

Analytical hierarchy process (AHP)

AHP is a widely adopted approach for Multi-Criteria Decision-Making (MCDM). The method is widely used in evaluating the suitability of sites for various purposes. This study created a 9x9 pairwise comparison matrix (Table 1), in which every criterion was subjected to ranking vis-à-vis the others, on the basis of Saaty's scale of 1-9 (Saaty, 2008) which was derived from the collective insights of an extensive review of relevant literature. A normalized matrix was then constructed through column-wise division

Table 1: Pairwise comparison matrix of AHP for MHP dam site suitability index mapping

Criteria	Stream order	SPI	Geology	Dd	Slope	TWI	SI	Soil texture	LULC	Normalized weight
Stream order	1.00	4.00	5.00	5.00	5.00	4.00	3.00	3.00	4.00	0.30
SPI	0.25	1.00	3.00	4.00	2.00	4.00	3.00	3.00	3.00	0.17
Geology	0.25	0.33	1.00	2.00	2.00	2.00	3.00	2.00	2.00	0.10
Dd	0.25	1.00	1.00	1.00	2.00	3.00	2.00	4.00	2.00	0.12
Slope	0.25	0.33	1.00	0.50	1.00	3.00	2.00	3.00	2.00	0.09
TWI	0.25	0.33	0.50	0.50	0.50	1.00	2.00	2.00	2.00	0.07
SI	0.25	0.25	0.50	0.33	0.50	0.50	1.00	2.00	2.00	0.06
Soil texture	0.25	0.25	0.50	0.50	0.33	0.50	0.50	1.00	1.00	0.04
LULC	0.25	0.25	0.50	0.50	0.50	0.50	0.50	1.00	1.00	0.05
Total	3.02	7.33	11.83	14.08	13.67	18.50	17.00	21.00	19.00	1.00
Consistency index										0.06
Random index										1.45
Consistency ratio										0.04

by the sum of the respective columns. The total scores of each criterion in the pairwise comparison were computed. Subsequently, the average of each row in the normalized matrix was calculated to obtain the criterion weight. An assessment was conducted to determine the consistency of criteria ratings throughout the paired comparison criteria and the obtained criterion weight. Such evaluation is essential for optimizing the priority scale and reducing subjectivity among the criteria used. Consistency Ratio (CR) was used in the evaluation by using Eqs. 4 and 5 (Saaty, 2008).

$$CI= \frac{\lambda_{max}-n}{n-1} \qquad (4)$$

$$CR= \frac{CI}{RCI} \qquad (5)$$

Where; CI is the consistency index, λ_{max} is the maximum eigenvalue, n is the number of criteria, CR is the consistency ratio, and RCI is the random consistency index (1.45 for nine criteria). On the basis of the evaluation, the obtained CR was 0.04 (<0.10), indicating that the weight of the criteria was within the rational degree of consistency (Saaty, 2008). Sub-criteria were subjected to rankings (0 to 9) aligned with various previous studies and professional judgment, as detailed in Table 2. High scores were assigned to sub-criteria with substantive influence, while sub-criteria exerting a minor influence obtained comparatively lower scores.

Overlay analysis for DSI map generation

DSI mapping used the overlay method in the GIS environment by combining the influences of criteria on the basis of criterion weight. All the criterion layers were transformed into a unified raster format, with their values being classified accordingly. The suitability index map was determined using Eq. 6 (Owolabi *et al.*, 2020).

$$DSI= \sum_{i=1}^{9} W_i(R_i) \qquad (6)$$

Where; DSI is the Dam Suitability Index representing the assessment of the potential for dam suitability, W_i is criterion weight for i criteria determining the importance of each criterion in the evaluation, R_i is the sub- criterion score indicating the relative significance of each sub-criterion, and i…9 represents the nine criteria used.

Validation of the DSI map

Validation was conducted by comparing the predicted dam suitability map against the existing MHP dam in the study area. The area under the curve (AUC) of the Receiver Operating Characteristic (ROC) was utilized as the metric to validate predictive performance (Rahmati *et al.*, 2019). The ROC curve is a widely used technique for evaluating the accuracy of models in predicting spatial phenomena. The construction involves utilizing pairs of two numbers, namely the genuine positive rate and the false negative rate (Mohammady *et al.,* 2019). AUC

Table 2: Classification of criteria for weighted overlay analysis

Criteria	Weight	Sub-criteria	Score
Stream order	0.30	First order	2
		Second order	4
		Third order	6
		Fourth order	7
		Fifth or more order	9
Standardized precipitation index (SPI)	0.17	<2.00	3
		-1.5 - -11.99	4
		-1.00 - -1.49	5
		-0.99 - 0.99	6
		1.00 - 1.49	7
		1.50 - 1.99	8
		>2.00	9
Geology	0.10	Igneous/basement complex	9
		Sedimentary rock	6
		Metamorphic/sandstones	4
Drainage density (Dd) (km/km^{-2})	0.12	<0.49	2
		0.49 - 2.67	5
		2.68 - 3.44	7
		3.45 - 4.75	8
		>475	9
Slope (%)	0.09	0-8	9
		8-15	7
		15-25	5
		25-40	3
		>40	2
Topographic wetness index (TWI)	0.07	<4.0	3
		4.01 - 8.0	5
		8.01-13.0	7
		13.01 - 17.0	8
		>17.01	9
Stream power index (SI)	0.06	<0.30	2
		0.301-0.50	4
		0.501-1.01	5
		1.01-5.1	7
		>5.1	9
Soil texture	0.04	Loam	1
		Sandy loam	4
		Sandy clay loam	6
		Clay	7
		Silt	9
Land use land cover (LULC)	0.05	Forest	1
		Cropland	1
		Grassland	2
		Waterbody/river	7
		Bare land	9

values range from 0 to 1, with superior predictive performance indicated by values close to 1, whereas those around 0.5 suggest predictions approaching randomness (Pham and Prakash, 2018).

Restriction for dam site selection

Identifying potential dam sites in the study area was contingent upon the incorporation of factors, including the suitability index and limitation condition related to socio-economic considerations, such as proximity from road, settlement, and forest conservation area (Ali *et al.,* 2023). MHP dams situated farther away from roads are subject to more significant infrastructure expenses and encounter increased energy loss (Stepanov *et al.,* 2016). Proximity to settlement results in substantial

cost reductions in the primary cable network infrastructure. The closeness of an MHP site to settlements can also have an effect on community engagement, land use conflicts, and environmental impacts, particularly for community-based MHP development. The existence of conservation forests also influences MHP dam selection because these areas are safeguarded by legislation. All potential dam locations in this study were considered to be outside conservation forest areas. These constraints were used to generate an unsuitable map for the MHP dam site. The Boolean technique was employed in this study (Table 3), in which 0 indicates unsuitable and 1 indicates permitted for MHP dam sites.

The Euclidean distance method was used to define proximity from road and settlement. The obtained proximity map was reclassified on the basis of restricted proximity and assigned the appropriate value. All restricted layers (Fig. 4) were subsequently incorporated and superimposed into the GIS environment, yielding binary values of 0 to denote unsuitable and 1 for suitable location of the MHP dam sites.

Identification of potential site for MHP dam

The potential site for MHP dam map was generated by combining the validated DSI, proximity to road and settlement, existence of conservation forest, and potential hydraulic head using overlay and query analysis within the GIS environment. The potential hydraulic head is the height differences between the dam and the powerhouse within a certain radius. In this study, the potential hydraulic head was calculated using a focal statistic tool in the GIS environment.

RESULTS AND DISCUSSION

This section is divided into several topics: DSI map for MHP, Validation of DSI map, Potential site for MHP dam, and Implication of the study result.

DSI map for MHP

A composite DSI layer was generated by incorporating all criteria and then categorising them into five distinct classes by utilizing the natural break method. Fig. 5 presents the spatial distribution of the suitability index for MHP dam sites. Various parts of

Table 3: Restriction factor for MHP dam site identification

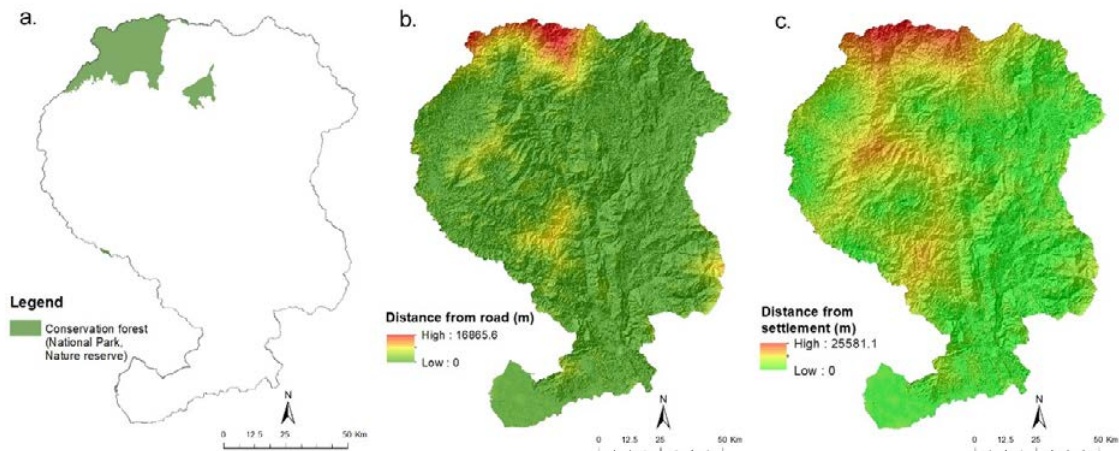| Parameter	Condition	Assigned value
Forest states	Conservation forest	0
Distance from settlement	≤ 4000	1
	> 4000	0
Distance from road	≤ 4000	1
	> 4000	0

Fig. 4: Restricted map for MHP dam site selection: conservation forest (a), distance from road (b), and distance from settlement (c)
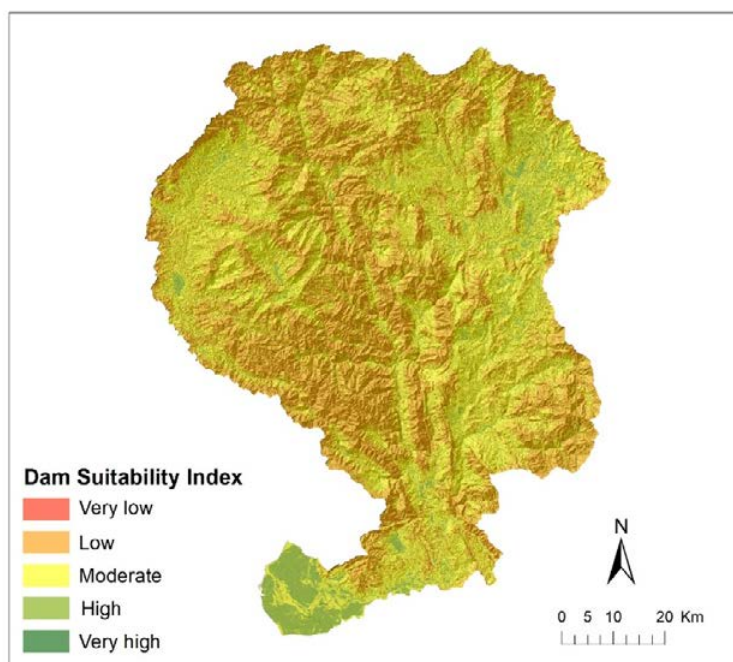
Fig. 5: Suitability index map for MHP dam site

a river may vary in their suitability for constructing MHP dams due to the diverse manifestations of the influencing elements being studied. The area classified with very high suitability is 41.4 km^2, representing 0.6% of the overall watershed. The most appropriate class is predominantly found in the stream channel in the central and downstream (southern) areas of the study watershed. The high suitability class (533.9 km^2 or 8.1%) is situated in the middle and southern areas of the watershed. The moderately suitable class covers an area of 1,675.5 km^2, representing 25.3% of the total. This class is evenly distributed across the entire watershed. The low and very low classes cover an area of 4,379.2 km^2 or 66.1% of the watershed. These classes are predominantly found in regions with extremely high elevations, specifically on hills ridges and peaks.

The factors that contribute to the presence class could be determined by comparing the DSI map with the different criterion layers. The areas classified as having very high and high suitability were characterized by high drainage density, high TWI and SI, second and higher stream order, low vegetation cover, moderate slope gradient, sandy clay loam soil texture, and normal temporal rainfall distribution in conjunction with igneous and sedimentary complex rock. These characteristics imply consistent and plentiful water flow for MHP operational continuity (Odiji *et al.,* 2021) and act as indicators of water availability, flow dynamics, runoff patterns, discharge characteristics, and potential energy generation (Korkovelos *et al.,* 2018). Higher TWI and SI values indicate higher flow accumulation and overland flow potential (Althuwaynee *et al.,* 2014). As the magnitude of the stream's order increases, a corresponding increase in discharge occurs while the gradient experiences a decrease (Sammartano *et al.,* 2019). High and very high suitability classes for MHP dam sites prioritize uninhabited or low vegetation cover areas due to minimal environmental effect associated with MHP projects in such areas, the cost-effectiveness of land obtaining, and the avoidance of significant effect on human activities (Ali *et al.,* 2023). A steeper slope results in increased runoff velocity and more water being generated, rendering the terrain more vulnerable to erosion and sediment transportation. Moderate to high slopes are particularly well-suited to the construction of MHP dam (Rahmati *et al.,* 2019). Regarding soil texture, fine to medium-textures are more suitable for MHP

dam structures due to their significantly higher potential for water retention (Ibrahim *et al.,* 2019). High and very high suitability classes residing in a normal category of SPI value (-0.99 to 0.99) (Anshuka *et al.,* 2019) would guarantee consistent rainfall supply within the watershed's hydrological system, facilitating continuous drainage of existing rivers throughout the year (Reyes *et al.,* 2022). The igneous rocks under dam construction have a better bearing capacity, especially concerning the foundation being built and the ability of a dam to hold water (Zewdie and Tesfa, 2023). The primary elements that influence the moderately suitable class are normal rainfall spatial distribution, a fairly steep slope, and moderate drainage density, TWI, and SI. Regions characterized by low precipitation, steep slope gradient, fragile geological composition, and limited drainage density exhibit low and very low suitability zones. The result of this study regarding the characteristics of suitability classes are in line with those of other previous studies. Al-Ruzouq *et al.* (2019), who used integrated GIS and machine learning in dam site selection in the United Arab Emirates (UAE), found that the very

high suitable zone for dams was characterized by adequate drainage and geological properties, such as relatively gentle slopes, geology dominated by sand, and high drainage density. Odiji *et al.* (2021), with their study conducted in Nigeria related to dam site suitability modeling, concluded that the area with high drainage density, high flow accumulation, gentle slope, moderate elevation, sufficient rainfall, basement complex rock, and low dense vegetation coverage exhibited high-level suitability. Othman *et al.* (2020), whose research theme was GIS-based modeling in the identification of check dam sites, defined the significant subfactors for check dam identification, consisting of hard rock for geology, clay loam soil texture, low vegetation coverage, moderate slope, and river with high potential flow.

Validation of the DSI map

The obtained DSI map was evaluated by comparing it with existing MHP dams in the study watershed, ensuring its accuracy. A total of 33 MHP dams exist in the study area for validation purposes (Fig. 6). The existing MHP dams are predominantly spread across
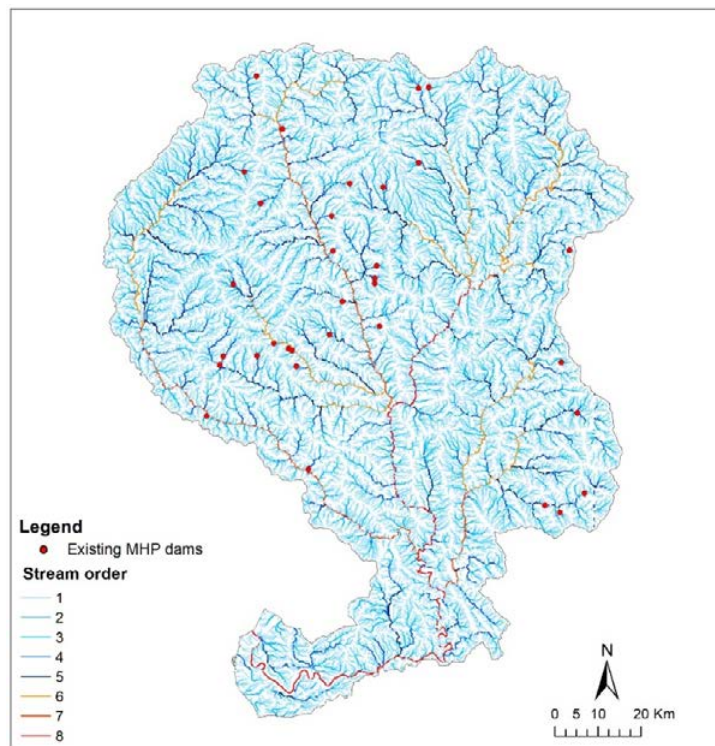

Fig. 6: Spatial distribution of existing MHP dams for validation

the central and upstream areas of the watershed, with a small proportion located in the eastern part. The model's performance in determining DSI was evaluated on the basis of the constructed ROC curve (Fig. 7). The prediction rate curve illustrates the model's capacity to make accurate predictions on the validation data. Based on Fig. 7, the AUC value was 0.919, indicating a satisfactory level of concurrence between the suitability index and the existing MHP dams. Several studies that showed good agreement between predicted and measured data were indicated by AUC values greater than 0.9, such as Yang *et al.* (2019) which studied landslide susceptibility mapping, Merghadi *et al.* (2020) which used machine learning application for landslide prediction, and Rahmati *et al.* (2019) which focused check dam site selection. Odiji *et al.* (2021), in their study of small hydropower dam site selection, obtained an AUC value of 0.8 in evaluating accuracy, indicating a strong correlation between the suitability map and existing dam data.

Characterization of existing MHP dams is also essential for defining potential MHP dam sites, particularly with respect to characteristics related to flow potential and socio-economic consideration (proximity from road and settlement). Fig. 8 presents the characteristic of existing MHP dams that are primarily situated in areas with high and very high suitability index classes, comprising 64% of the total dams, while 36% of existing MHP dams are in the moderate class. There are 52% of the dams located on the first and second stream orders, while 48% are on the third and fourth stream orders. The existing MHP dams are also primarily located within an area less than 4 km from road and settlement, accounting for 93% and 79%, respectively.

Potential site for MHP dam

The potential site for MHP dam was identified in accordance with several criteria: 1) potential flow and continuity; 2) the obtained DSI map; 3) the distance between two potential sites in the same stream; 4) the length of distinct MHP scheme; 5) potential hydraulic head; and 6) proximity from infrastructure and conservation forest. The approach used for identifying potential dam sites incorporated not only a hydrological point of view but also biophysical factors represented by DSI and socio-economic conditions. The preference of flow potential for potential MHP dam site was selected on the first and second order of stream. Nearly 50% of the existing MHP dams in the study area are located on the second order. This finding aligns with the study conducted by Sammartano *et al.* (2019) in South West England, which found that over 50% of the identified sites for MHP were situated in the first and second
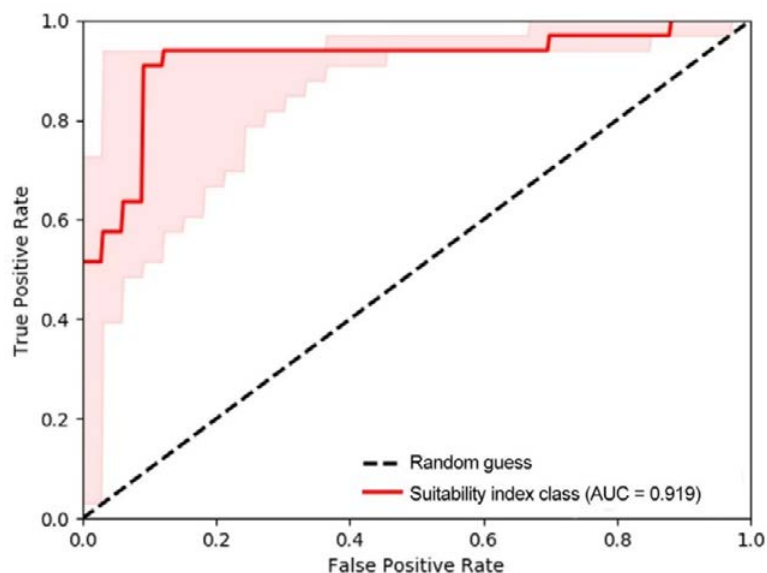

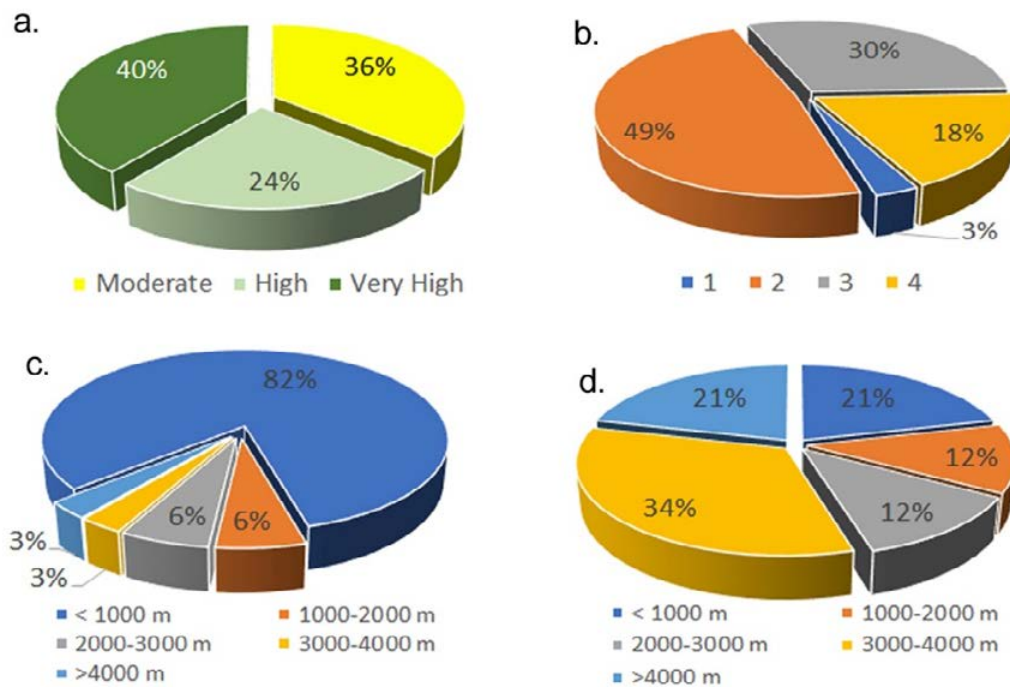Fig. 7: The ROC for accuracy evaluation of suitability index mapping

Fig. 8: Characteristic of existing MHP dams in the study area

stream order, with a subsequent drop in frequency as the stream order increased. High and very high suitability indices were considered for potential dam location selection. A distance of 500 m between two potential sites was the minimum spacing to prevent the interface of tailwater upstream and impoundment downstream (Moshe and Tegegne, 2022). A previous study suggested that the length of the distinct MHP scheme ranges from 500 m to 3,000 m (Pandey *et al.,* 2015). The current study used a 2,000 m radius of the single scheme MHP, assuming that it was sufficient for the MHP component, optimally regarding the cost of MHP development, and facilitating simple flow diversion. Several studies have proposed a hydraulic head threshold for MHP: 5 m (Mehari, 2020), 10 m (Rospriandana and Fujii, 2017), and 20 m (Pandey *et al.,* 2015). The current study defined the hydraulic head for MHP potential dam site as greater than 20 m. The potential dam location was also selected outside the conservation forest areas and less than 4,000 m from road and settlement. On the basis of all these conditions, overlay and query methods were used in the potential MHP dam selection. The identified

potential sites for MHP dam are presented in Fig. 9.

The query operation of all the criteria identified 635 points as potential sites for MHP dams. These potential sites were predominantly distributed in the eastern part of the watershed, characterized by dense infrastructure, including roads and settlements. The high potential hydraulic head (>20 m) of the obtained dam sites would play an essential role in achieving higher potential power generation with relatively small to moderate river flow. The identified potential sites are also likely to feature a narrow valley, commonly found in the first and second stream orders. A narrow valley, particularly the V-shape, provides advantages with regard to dam structure and flow diversion, potentially reducing construction and operational costs, and possible effects on the environment (Odiji *et al.,* 2021).

Implication of the study result

Potential sites for the MHP dam map have numerous critical applications and uses in the context of harnessing water energy and managing large watersheds. Some of the essential applications
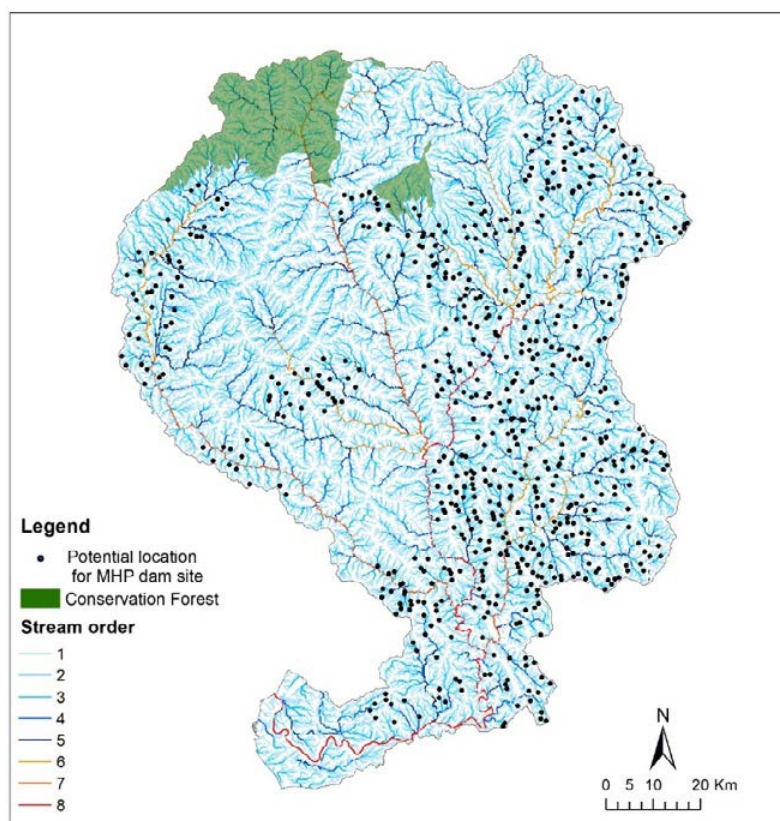
Fig. 9: Distribution of potential site for MHP dam in the study area

are as follows: 1) MHP dam site suitability mapping facilitates the identification of the most suitable locations for MHP dams based on biophysical, technical, and socio-economic factors, including water flow potential, geomorphometry, and proximity to existing infrastructure; 2) mapping assists in determining the potential energy that can be generated at each identified site to maximize the energy output while considering environmental and economic constraints; 3) dam site suitability mapping provides valuable insight into assessing the potential environmental impacts of constructing MHP dam, enabling the identification of sensitive areas that should be avoided or carefully managed, 4) understanding the suitability of sites within a watershed assists in the efficient management of water resources, and the allocation of water for energy production while ensuring other essential uses such as agriculture, drinking water supply, and ecological needs; 5) dam site suitability mapping results can inform policy decisions and planning processes related to renewable energy development, water resource management, and environmental protection; and 6) sharing dam suitability maps with local communities can promote transparency and facilitates communities' understanding of the potential benefits and drawbacks of MHP projects in their area, leading to better decision-making and collaboration. A more detailed investigation of potential sites is necessary to ensure the applicability of technical, biophysical, and socio-economical aspects. Various steps and consideration may be conducted by the government in implementing potential dam sites for MHP development. They include the following, 1) An environmental impact assessment will be carried out to evaluate potential effects on the ecosystem, wildlife, and local communities for formulating mitigation plans to minimize adverse effects; 2) Obtaining necessary permits and approvals from relevant authorities in

compliance with environmental regulations, land rights, and any other legal requirements; 3) Engaging with local communities to address concerns, gather feedback, and ensure that the project is aligned with the community's needs and interests; 4) Once a site is selected and approvals are in placed, infrastructure development begins, including constructing dams, powerhouse structures, turbines, and other necessary facilities; 5) The government will employ suitable technology and engineering expertise to design and build the hydroelectric units efficiently and safely; 6) Post-construction, ongoing monitoring and maintenance are critical to ensure that the units operate effectively and safely while minimizing environmental impacts; 7) Establishing connections to the power grid enables the electricity generated to be distributed and utilized across the region. The approach developed in this study is a valuable tool for assessing potential dam sites for MHP projects, but it also has limitations: 1) Differences in the scale and resolution data used that can affect the performance of the model and increase the uncertainty aspect; 2) Complexity of variables in MHP development influence the criteria selection that can be challenging and may oversimplify the real-world scenario; and 3) Environmental conditions that are subject to change over time due to climate variations, land use alterations, or natural events, may not adequately account in approach development, affecting the long-term reliability of the suitability predictions. Supplementing the result of GIS-based suitability modeling with detailed field surveys, local knowledge, and detailed on-site assessments is essential. The results of this study also indicate only potential sites without information on potential power that can be generated. The measurement of dependable discharge through direct measurement or a modeling approach is critical because of the consequences, especially for a more detailed scale of analysis and location. Investigation of detailed soil properties is also essential in implementing the potential dam site for MHP development, especially related to dam structure.

CONCLUSION

The lack of an up-to-date national or sub-national/regional inventory of potential dams' sites for MHP installation remains challenging in the midst of high dependency on fossil-based electricity and other global issues, such as climate change. This study has employed a comprehensive approach that utilized GIS-based suitability modeling to assess potential MHP dam sites in a large watershed. The integration of various geospatial data layers, including geomorphometry, geology, rainfall, soil texture, and LULC, allows for a robust analysis of DSI mapping. The potential sites for the MHP dams were obtained by incorporating the MHP DSI map with socio-economic factors (proximity distance from road and settlement), conservation forest areas, and potential hydraulic head. Using the Saddang watershed as the study location, the DSI map was obtained and divided into five suitability classes. High and very high categories of the suitability index constituted 8.7% of the study area. These areas were characterized by high TWI, drainage density, and SI, low vegetation cover, moderate slope, located on the second or higher stream orders, normal rainfall temporal distribution, sandy clay loam soil texture, and igneous and sedimentary complex rock. A total of 635 potential MHP dam sites were resulted from overlay and query processes on the basis of several criteria: high and very high DSI, first and second stream order, outside conservation forest areas, less than 4,000 m from road and settlement, and greater than 20 m of potential hydraulic head. The results of this study provide valuable insights for decision-makers, enabling them to make informed choices regarding MHP dam site selection for further detailed measurement of the targeted site. The methodology presented herein can serve as a valuable framework for future MHP project planning, not only in the studied watershed but also in similar regions worldwide in the context of large watersheds or at national/province level. The insights gleaned from this study are also expected to pave the way for more efficient and ecologically sound approaches to harness the immense potential of MHP resources. More detailed field surveys, local knowledge, and detailed on-site assessments are essential for supplementing GIS modeling in future work. Integrating GIS with other decision-making tools and involving stakeholders at various stages of site selection can help mitigate this study's limitations and produce more reliable and comprehensive results for MHP dam site suitability.

AUTHOR CONTRIBUTIONS

All Authors made equal contributions as the main

contributors. O. Setiawan conducted the research conceptualization, literature review, data collection, spatial data preparation, analysis and interpretation of results, and draft manuscript preparation. H.Y.S.H. Nugroho conducted the research conceptualization, the interpretation of results, and draft manuscript editing and review. N. Wahyuningrum conducted the interpretation of results, draft manuscript editing, and review. D. Auliyani prepared and analyzed spatial data, interpreted analysis results, and edited and reviewed the draft manuscript. K.S. Hardjo. analyzed the data and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
^{0}	Degree
'	Minute
"	Second
β	Slope gradient
λ_{max}	Maximum eigenvalue
σ	Standard deviation
A	Area
AHP	Analytical Hierarchy Process
AUC	Area under the curve
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
CI	Consistency index
CO_2	carbon dioxide
CR	Consistency Ratio
Dd	Drainage density
DEM	Digital elevation model
DSI	Dam suitability index
E	East
GW	Giga watt
GIS	Geographic information systems
ha	Hectare
km	Kilometer
km^2	Square kilometer
LULC	Land use land cover
m	Meter
MCDM	Multi-criteria decision-making
MHP	Micro hydropower plant
mm	Second
RCI	Random consistency index
ROC	Receiver operating characteristic
RS	Remote sensing
S	South
SI	Stream power index

SPI	Standardized precipitation index
TWI	Topographic wetness index
UAE	United Arab Emirates
WSM	Weighted sum method
xi	Monthly rainfall
$\overline{x}$	Average monthly rainfall

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AUTHOR (S) BIOSKETCHES

Setiawan, O., Ph.D., Senior Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *ogi.setiawan@brin.go.id*
- ORCID: 0000-000 2-8682-4849
- Web of Science ResearcherID: ABG-9899-2021
- Scopus Author ID: 57205433334
- Homepage: https://brin.go.id/page/civitas

Nugroho, H.Y.S.H., Ph.D., Principal Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *hung001@brin.go.id*
- ORCID: 0000-0001-9165-0305
- Web of Science ResearcherID: IQU-2612-2023
- Scopus Author ID: 57194607752
- Homepage: https://brin.go.id/page/civitas

Wahyuningrum, N., Ph.D., Senior Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *nini011@brin.go.id*
- ORCID: 0000-0003-1096-6645
- Web of Science ResearcherID: NA
- Scopus Author ID: 57216288607
- Homepage: https://brin.go.id/page/civitas

Auliyani, D., M.Sc., Junior Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *diah015@brin.go.id*
- ORCID: 0000-0001-7819-5838
- Web of Science ResearcherID: NA
- Scopus Author ID: 57219661069
- Homepage: https://brin.go.id/page/civitas

Hardjo, K.S., M.Sc., Assistant Professor, Department of Earth Technology, Geographic Information System, Vocational College, Universitas Gadjah Mada, Yogyakarta, Indonesia.
- Email: *karen.sh@ugm.ac.id*
- ORCID: 0009-0007-6477-8144
- Web of Science ResearcherID: NA
- Scopus Author ID: 57372375700
- Homepage: https://acadstaff.ugm.ac.id/MTk3NTExMDIyMDE0MDkxMDAx