



OPEN ACCESS

EDITED BY

Beata Calka,
Military University of Technology in Warsaw,
Poland

REVIEWED BY

Digvesh Kumar Patel,
Indira Gandhi National Tribal University, India
Benjamin Sallo,
Mizoram University, India

*CORRESPONDENCE

Meral Korkmaz,
✉ meralkorkmaz@munzur.edu.tr

RECEIVED 19 November 2025

REVISED 29 December 2025

ACCEPTED 02 January 2026

PUBLISHED 09 February 2026

CITATION

Korkmaz M (2026) Geospatial evaluation of river
basin small hydropower potential using AHP.
Front. Environ. Sci. 14:1749841.
doi: 10.3389/fenvs.2026.1749841

COPYRIGHT

© 2026 Korkmaz. This is an open-access article
distributed under the terms of the [Creative
Commons Attribution License \(CC BY\)](#). The use,
distribution or reproduction in other forums is
permitted, provided the original author(s) and
the copyright owner(s) are credited and that the
original publication in this journal is cited, in
accordance with accepted academic practice.
No use, distribution or reproduction is permitted
which does not comply with these terms.

Geospatial evaluation of river basin small hydropower potential using AHP

Meral Korkmaz*

Department of Civil Engineering, Munzur University, Tunceli, Türkiye

This study develops an integrated Geographic Information Systems (GIS) and Analytic Hierarchy Process (AHP) framework to accurately identify small hydropower plants sites that support sustainable water–energy planning. The approach is applied to the Peri River Basin in Eastern Türkiye by combining multisource remote sensing datasets with a semi-automated narrow-valley detection technique to enhance the spatial precision of site selection. Nine hydrological and physiographic criteria including stream order, rainfall, slope, geology, drainage density, elevation, land use land cover, Stream Power Index SPI and Topographic Wetness Index TWI were weighted using the AHP method to generate a five-class suitability map for small hydropower plants development. A major contribution of this study is the explicit integration of valley morphology into the conventional GIS–AHP workflow, which significantly improves the identification of hydropower favorable river segments. Results indicate that approximately 3% of the basin exhibits very high suitability, while 46% is moderately suitable for run-of-river small hydropower plants development. Model validation was performed by overlaying the suitability map with the locations of existing dams/hydropower facilities, showing that current facilities are mainly located in high-suitability zones. Separately, the workflow identified 13 newly proposed high-suitability candidate dam sites (P1–P13), selected from screened suitable dam points using narrow-valley detection criteria. By minimizing ecological disturbance and aligning with watershed-based management principles, the proposed GIS-supported multicriteria method provides a transferable and cost-effective decision-support tool for small-hydropower planning in rural and mountainous basins, offering practical contributions to sustainable resource management and the water–energy nexus.

KEYWORDS

AHP, GIS, small-hydropower, sustainable resource planning, water–energy nexus, watershed management

1 Introduction

The rapid growth of the global economy has significantly increased energy demand and intensified dependence on fossil fuels, accelerating climate change. These pressures have encouraged many countries to transition toward renewable and low-carbon energy systems in line with their long-term sustainability strategies (Kuriqi et al., 2019). As energy demand continues to rise, the shift to clean and renewable energy sources is becoming increasingly important. Within this global transition, small hydropower plants systems have gained increasing attention due to their low environmental footprint and suitability for rural and mountainous regions. Small hydropower plants (mini and small hydropower plants) play a crucial role in generating renewable energy with minimal ecological impact, especially in

remote and isolated areas (Raaj et al., 2022; Kos et al., 2021; Ajanovic and Haas, 2019). In 2019, the global market for small hydropower plants was estimated at USD 2.6 billion and is projected to reach USD 3 billion by 2024 (Kos et al., 2021). Hydropower remains one of the most established renewable energy sources globally, reducing greenhouse gas emissions by replacing over four million barrels of oil every day (Ajanovic and Haas, 2019; Tian et al., 2020).

While large hydropower plants offer fast grid connections and operational flexibility, suitable sites are increasingly scarce, and their development is associated with significant economic, environmental, and social costs. These challenges highlight the need for alternative hydropower solutions that minimise ecological disturbance while meeting local energy demands. The construction of large dams often disrupts natural flow regimes and seasonal fluctuations, negatively affecting aquatic ecosystems. Despite these challenges, the importance of hydropower continues to grow as countries seek to reduce dependence on non-renewable energy sources and integrate renewables more effectively (Kuriqi et al., 2020).

In contrast, small hydropower plants in steep and mountainous river valleys particularly diversion-type systems offer a more environmentally friendly alternative. Water is diverted via a conveyance system into a downstream equalisation basin before reaching the turbines through penstocks, enabling electricity generation with minimal ecological impact (Ghorbani et al., 2020). Low operating costs, long service life, and high efficiency further strengthen the advantages of small hydropower plants systems. However, identifying suitable SHP sites in rugged terrain is time-consuming and expensive (Yildiz et al., 2024; Aghajani and Ghadimi, 2018). Traditional on-site surveys are increasingly being replaced by satellite observations and GIS-based spatial analyses. Geographic Information Systems (GIS) are widely used worldwide to assess the potential of renewable energy resources.

However, many existing GIS-AHP studies rely primarily on coarse terrain indicators such as slope, elevation, or general topographic indices and do not explicitly analyse valley morphology, which is a critical factor for the technical feasibility of run-of-river small hydropower plants systems. While successful GIS-based assessments have been conducted in Iran, Estonia, Egypt, Brazil, and other regions, a geomorphologically detailed evaluation is still lacking in many studies. Achieving a sustainable energy balance requires consideration of technical, social, environmental, legal, and economic factors, for which multi-criteria decision-making (MCDM) methods are suitable (Ali et al., 2023). Among these, the Analytic Hierarchy Process (AHP) is widely preferred for its simplicity, versatility, and frequent application in technical assessments, including dam and hydropower site selection.

Several international organisations and academic institutions have demonstrated the benefits of remote sensing and GIS in identifying potential hydropower locations. Many countries now encourage run-of-river SHP development due to the ecological drawbacks associated with large hydropower facilities (Fry et al.,

2022; Couto and Olden, 2018). Today, there are more than 80,000 active SHP plants worldwide, led by China with more than 47,000 installations, followed by Europe with about 26,000; the global SHP potential is estimated to exceed 180,000 plants (Couto and Olden, 2018). While SHPs contribute to sustainable low-carbon electricity generation, the diversion of river flows can negatively affect aquatic habitats. Therefore, ecological flow regimes (e-flows) must be implemented, particularly in run-of-river systems (Kuriqi et al., 2019). The European Union and many other countries have set ambitious renewable energy targets to accelerate this transition.

In Bortala, northwest China, AHP and GIS were applied to select suitable dam locations using criteria such as rainfall, slope, geology, soil type, land cover, and drainage patterns, identifying eight potential sites (Dai, 2016). In Africa, Ibrahim et al. (2021) analysed the SHP potential in Nigeria and highlighted favorable terrain and climate conditions, while emphasizing the lack of a national SHP inventory and the high proportion of the population without electricity access (Ibrahim et al., 2025).

In Turkey, small-scale hydropower research is gaining strategic importance, as more than 70% of the country's total energy demand depends on imports. The untapped SHP potential in Turkey is estimated to constitute 70% of the remaining unused SHP capacity in Europe. Since the establishment of the Energy Market Regulatory Authority (EMRA) in 2001, both interest and investment in SHP projects have increased. Several studies, such as Kaygusuz's analysis of the Kemerçayır hydropower plant in Trabzon, have demonstrated the technical, economic, and environmental viability of SHP projects (Kaygusuz, 2022). However, limited monitoring networks in several river basins hinder accurate SHP potential assessments, despite Turkey's mountainous terrain and abundant water resources. Additional challenges include insufficient incentives and incomplete resource mapping, although Turkey still holds significant potential for economically feasible SHP development (Yüksel and Demirel, 2021).

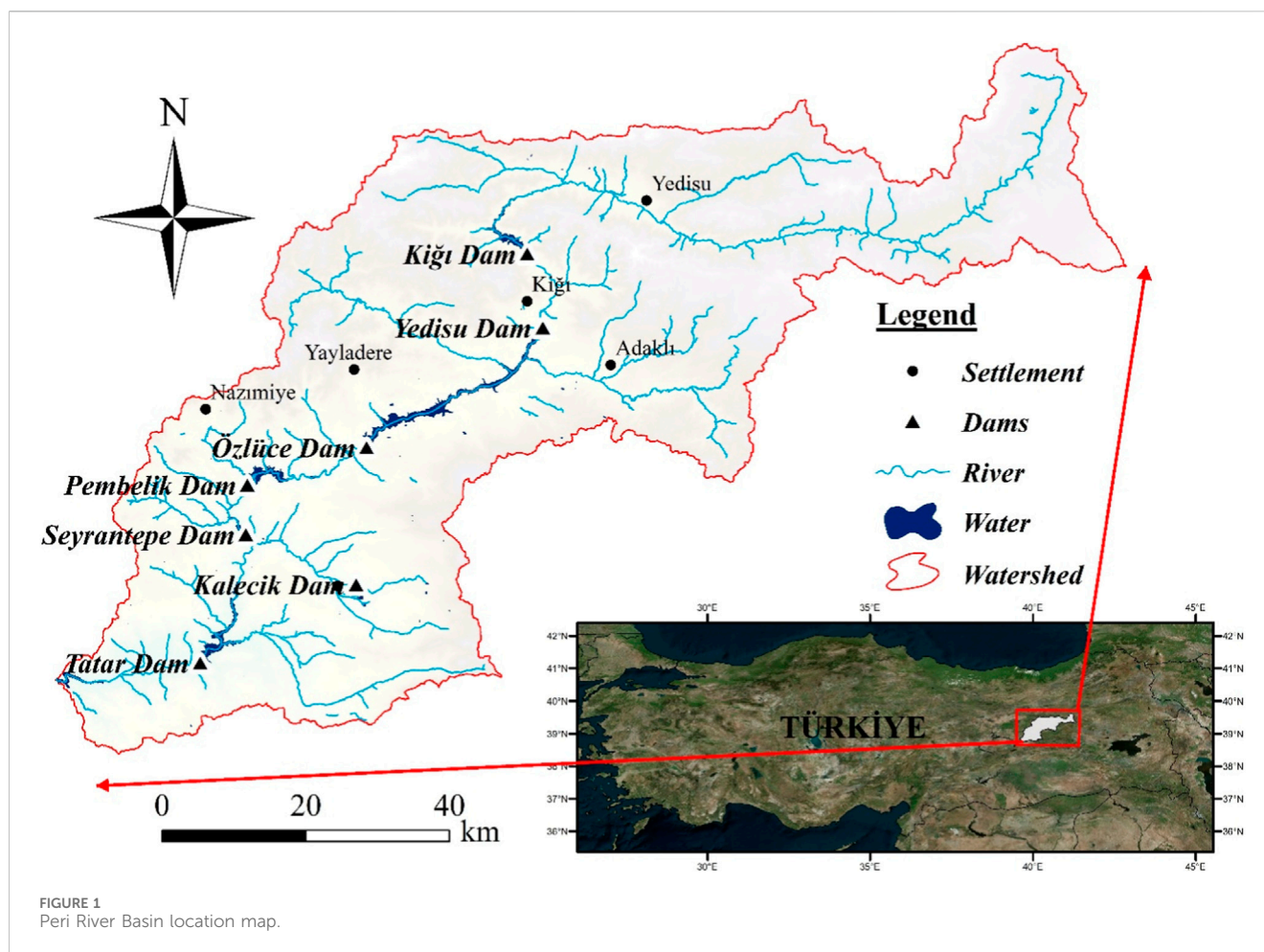
To address the methodological limitations identified in previous studies, the present research integrates a semi-automated narrow-valley detection method into a GIS-AHP framework to enhance the spatial precision of small-hydropower site identification. This approach enables the incorporation of detailed geomorphological information into the multi-criteria evaluation process, providing a more accurate and reliable basis for identifying technically feasible and environmentally responsible small-hydropower sites in mountainous river basins.

2 Materials and methods

2.1 ArcGIS-based spatial analysis approach

All spatial analyses in this study were carried out in ArcGIS 10.5 (ESRI, 2025). The software was used to integrate and manage raster and vector datasets, including the Digital Elevation Model (DEM), land use/land cover, geology, soil, precipitation, and hydrological network layers. All datasets were projected into a common coordinate reference system and resampled to a uniform spatial resolution to ensure consistency across the analyses.

Abbreviations: AHP, Analytic Hierarchy Process; DEM, Digital Elevation Model; GIS, Geographic Information Systems; LULC, Land Use/Land Cover; SPI, Stream Power Index; TWI, Topographic Wetness Index.



Within the ArcGIS environment, a series of hydrological and terrain-processing tools were applied. Sink filling, flow direction and flow accumulation analysis, and stream network extraction were performed using the Hydrology toolbox, while the Spatial Analyst toolbox was used to derive slope, aspect, elevation, drainage density, Stream Power Index (SPI), and Topographic Wetness Index (TWI) from the DEM (Tian et al., 2020; Tamm and Tamm, 2020). These derived layers formed the basis for the subsequent multi-criteria suitability assessment.

In mountainous regions, site selection for small hydropower plants (SHP) typically requires extensive field campaigns and detailed hydrological measurements, which are time-consuming and costly. By exploiting the capabilities of ArcGIS and freely available spatial datasets, the methodological framework developed in this study minimises the amount of input data and field work required, while still providing sufficient spatial accuracy for the preliminary planning of SHP projects. In this way, technically suitable sites can be identified even in remote or inaccessible areas where conventional, data-intensive field surveys would otherwise be necessary.

2.2 Study area description

The Peri River Basin is situated in the eastern part of Türkiye, within the provinces of Elazığ and Tunceli, and covers an area of

approximately 5,760 km² between 38.748° and 39.621° N and 39.584°–41.318° E. Elevations range from 819 m to 3,269 m above sea level (Figure 1), with an average elevation of about 1,737 m, reflecting a rugged mountainous topography. The basin hosts diverse habitats, including forests, steppes, rocky areas, grasslands, and water bodies. Kanatlı Mountain (2,947 m) and Alacakar Hill (2,766 m) are among the highest points in the region, while the Peri River, one of the main tributaries of the Euphrates, flows through the valley and gives the basin its name (Cengiz and Behçet, 2024).

The average annual precipitation within the basin ranges from 594 mm to 995 mm, with an overall mean of approximately 824 mm. This precipitation regime, combined with the steep relief and dense drainage network, creates favourable conditions for sustained surface runoff and hydropower generation. Consequently, the basin represents a key area for regional energy projects and water resources management studies.

Major settlements within the study area include the district centres of Kiğı, Karlıova, Karakoçan, Nazımiye, Yayladere, Adaklı, and Yedisu, together with several smaller villages distributed along the main valleys (Cengiz and Behçet, 2024). These settlement patterns, combined with the basin's diverse ecological and physical characteristics, make the Peri River Basin an important area for regional energy development and integrated environmental studies.

2.3 Data sources and preprocessing

The spatial datasets used in this study were obtained from national authoritative sources, including the General Directorate of Mineral Research and Exploration (MTA), the General Directorate of State Hydraulic Works (DSİ), the General Directorate of Mapping (HGM), and the Ministry of Agriculture and Forestry (MAF). The dataset included a 30 m Digital Elevation Model (DEM), geological and soil maps, land use/land cover information, precipitation data, and the drainage network of the basin. All datasets were converted into compatible formats for use within the GIS-AHP framework.

The 30 m DEM served as the primary source for deriving topographic parameters. Using the Hydrology and Spatial Analyst toolboxes in ArcGIS 10.5, hydrological corrections such as sink filling, flow direction, and flow accumulation were applied. From the processed DEM, slope, aspect, elevation, drainage density, Stream Power Index (SPI), and Topographic Wetness Index (TWI) were generated.

All datasets were reprojected to a common coordinate system and resampled to a uniform spatial resolution. Vector layers were converted to raster format when necessary. Each dataset was standardized to ensure compatibility for integration within the Analytic Hierarchy Process (AHP) used in the suitability evaluation.

To account for environmental and ecological constraints, legally protected and restricted areas within the Peri River Basin were excluded from the suitability analysis. These areas were expanded using a buffer zone to represent potential ecological influence areas and regulatory setback requirements. The buffered protected areas were then used as an exclusion mask, such that all pixels falling within these zones were removed from the final suitability map prior to candidate dam site selection.

2.4 Criteria selection and weighting

The selection of appropriate sites for small-hydropower development requires a structured decision-support framework capable of evaluating multiple spatial and hydrological parameters simultaneously. In this study, a Multi-Criteria Decision-Making (MCDM) approach was employed to integrate hydrological, geological, environmental, and topographic information. Among MCDM techniques, the Analytic Hierarchy Process (AHP) was chosen due to its transparency, pairwise comparison logic, and proven effectiveness in hydropower suitability assessments worldwide (Liu 2019).

Hydropower site suitability depends on interactions among watershed characteristics such as river valley morphology, substrate geology, slope conditions, precipitation patterns, land cover, and flow dynamics. These variables influence key factors including runoff concentration, discharge magnitude, hydraulic head availability, terrain stability, and environmental sensitivity. Previous studies on small hydropower plants (SHP) assessment consistently identify criteria such as geology, precipitation, slope, soil texture, elevation, land use/land cover, drainage density, the Topographic Wetness Index (TWI), and the Stream Power Index (SPI) as essential determinants of feasibility (Odiji et al., 2021; Rasooli and Kang, 2015).

Runoff volume was not directly calculated from discharge time series; instead, relative flow conditions were represented using proxy variables derived from rainfall, drainage characteristics, and terrain-based indices.

Recent studies conducted in the Upper Narmada Basin and other regions of central India further demonstrate the effectiveness of integrating GIS and Analytic Hierarchy Process (AHP) approaches for groundwater assessment, land degradation analysis, and sustainable resource planning. Patel et al. (2024a) successfully applied AHP-based geospatial techniques to delineate groundwater potential zones, emphasizing the importance of topographic, hydrological, and land use parameters. In a related study, Patel et al. (2024b) quantified land degradation using multi-temporal Landsat imagery and highlighted the strong relationship between land use dynamics, surface temperature, and ecosystem vulnerability. Long-term AHP-supported assessments of mining-affected landscapes have also shown that terrain morphology and hydrological connectivity play a critical role in land degradation vulnerability and eco-restoration planning (Thakur et al., 2025a). Furthermore, recent geospatial analyses of mine overburden reclamation revealed strong links between vegetation indices, biomass recovery, and landscape restoration processes, underscoring the value of integrated spatial approaches for sustainable environmental management (Thakur et al., 2025b).

Based on these established findings and the physical properties of the Peri River Basin, nine main criteria were selected for this study: stream order, rainfall, drainage density, geology, slope, SPI, TWI, elevation, and land use/land cover (LULC). These parameters collectively reflect the hydrological efficiency, energy potential, environmental constraints, and engineering feasibility of candidate locations. Each criterion was classified into sub-criteria representing different suitability levels. The relative importance (weights) of the criteria was determined using the AHP pairwise comparison matrix, allowing the decision framework to reflect the contribution of each factor to small-hydropower performance. Stream order and rainfall received the highest weights because they have a direct influence on discharge and energy potential, while criteria such as land use and elevation were assigned lower weights due to their secondary impact on SHP infrastructure and environmental constraints. The sub-criteria, their corresponding suitability scores (ranging from 1 to 9), and the AHP-derived weights are presented in Table 1, which formed the basis for generating the final hydropower suitability map. Soil characteristics were analyzed as a supporting environmental variable to improve the interpretation of hydrological processes; however, they were not included in the final AHP weighting or suitability calculation.

3 Methodological framework

3.1 Topographic feature analysis

The Digital Elevation Model (DEM) is a fundamental dataset widely used in hydrological studies to delineate river networks and extract catchment characteristics such as drainage area, mean slope, mean elevation, and main channel length (Palla et al., 2016). In this study, a 30-m resolution DEM was processed using the hydrology

TABLE 1 Main criteria used in the final AHP-based hydropower suitability analysis.

Criteria	Weight	Sub-criteria	Score	Criteria	Weight	Sub-criteria	Score
Stream order	%37	6	9	Geology	%8	Hard crystalline rocks	9
		5	7			Competent sedimentary rocks	7
		4	5			Moderately strong formations	5
		3	3			Weak/porous formations	3
		1	1			Alluvial/unconsolidated deposits	2
Rainfall (mm)	%17	901–999	9	TWI	%5	13.01–26.10	9
		851–900	7			9.40–13.00	8
		801–850	5			7.08–9.39	7
		751–800	3			5.42–7.07	5
		502–750	1			2.44–5.41	3
Drainage density (km/km ²)	%10	1.11–1.30	9	Elevation (m)	%4	819–1,291	7
		0.81–1.10	7			1,292–1,637	6
		0.56–0.80	5			1,638–1964	5
		0.30–0.55	3			1965–2,291	3
		0.04–0.29	1			2,292–3,273	1
SPI	%8	27.30–54.38	9	Land use/Land cover (LULC)	%3	Bare surface	9
		12.80–27.29	7			Water	7
		5.76–12.79	6			Grassland	2
		1.51–5.75	4			Forest/Cropland	1
		0.00–1.50	2			Built-up	Restricted
Slope (°)	%8	0.00–6.18	9				
		6.19–11.00	7				
		11.01–16.40	5				
		16.41–23.99	3				
		24.00–68.50	1				

toolbox of ArcGIS 10.5 to derive topographic parameters and generate a detailed drainage network of the Peri River Basin.

Hydropower suitability studies commonly define stream initiation using flow accumulation thresholds. [Odiji et al. \(2021\)](#) employed a 500-cell threshold for coarse DEMs ([Odiji et al., 2021](#)). However, due to the finer 30-m resolution and steep mountainous terrain of the Peri Basin, a higher threshold was required to avoid artificially increasing drainage density. Therefore, a flow accumulation threshold of 300,000 cells equivalents to a minimum contributing area of ≈ 76.6 km² was selected. This threshold provided the most realistic representation of the river network, showing 92% spatial agreement with 1:25,000-scale topographic maps, ensuring high extraction reliability. Slope, aspect, and elevation maps were produced from the same DEM dataset ([Demir et al., 2024](#)).

[Figure 2a](#) illustrates slope distribution, a key determinant of surface runoff velocity, sediment transport, and infiltration potential

([Masoudian and Theobald, 2011](#)). Steeper slopes promote rapid runoff and contribute positively to hydropower generation, whereas flatter slopes enhance infiltration, reducing surface flow ([Odiji et al., 2021](#); [Li et al., 2023](#)). The basin exhibits a wide slope range (0°–68.5°), reflecting strong topographic heterogeneity and variable hydropower potential.

[Figure 2b](#) presents elevation patterns which directly influence hydraulic head an essential factor for energy production. Higher elevations occur upstream, while lower elevations dominate near the basin outlet. Low-elevation areas serve as natural impoundment sites, whereas mid- and high-elevation zones benefit from gravitational acceleration, enhancing hydropower potential ([Odiji et al., 2021](#); [Palla et al., 2016](#); [Li et al., 2023](#)).

Overall, topographic parameters derived from DEMs play a fundamental role in controlling hydrological processes and are widely integrated into multi-criteria suitability analyses ([EL-Bana et al., 2024](#)).

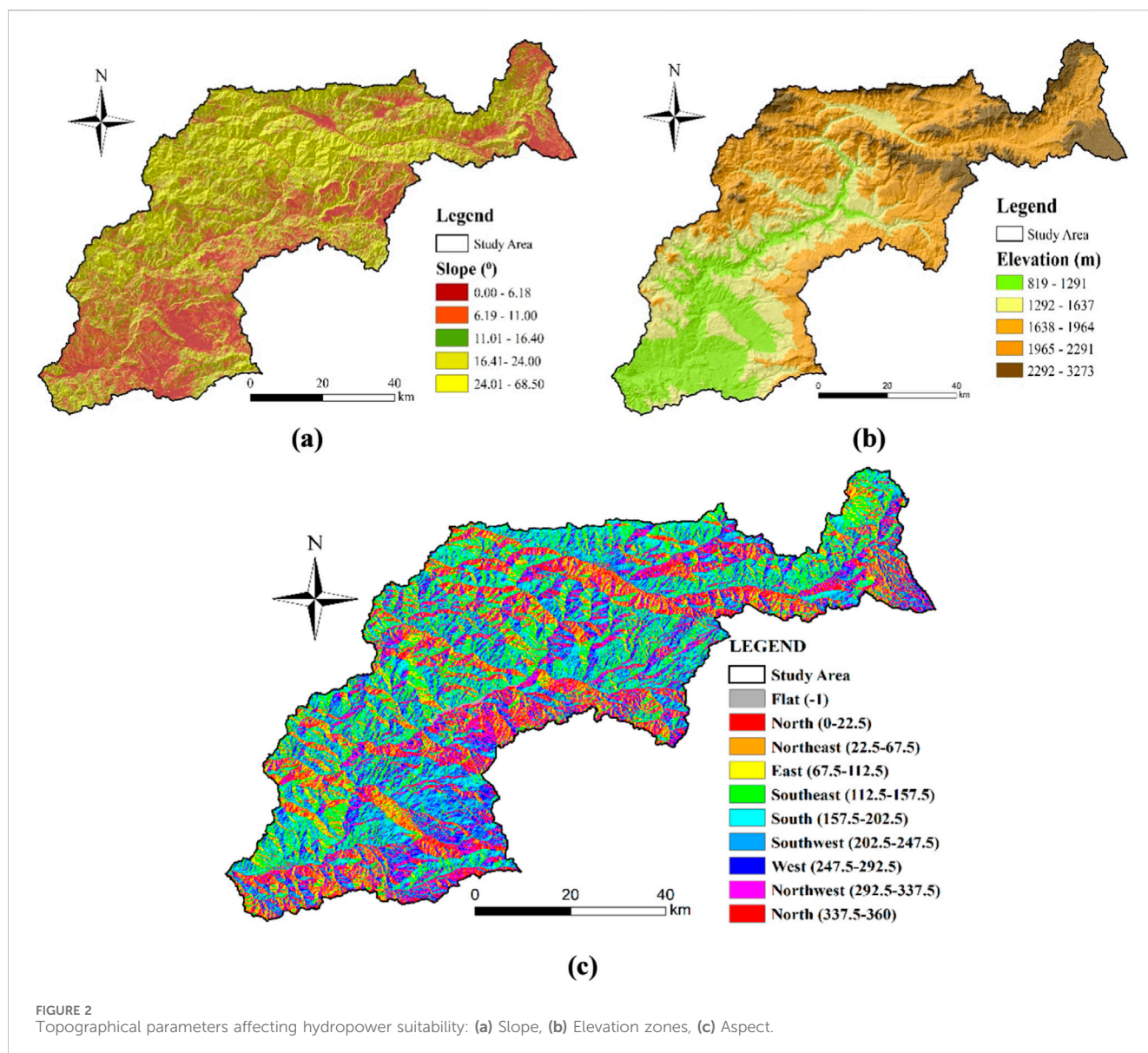


Figure 2c displays the aspect distribution, representing slope orientation relative to the north. Aspect influences microclimatic processes such as solar radiation, evaporation, and soil moisture balance (Bakiş et al., 2011). North- and east-facing slopes retain higher moisture due to lower radiation exposure, which supports stable runoff conditions (Palla et al., 2016; Li et al., 2023; Arulbalaji et al., 2019). These microclimatic differences affect hydrological behavior and thus influence hydropower site suitability.

3.2 Climate and soil characteristics assessment

Figure 3a illustrates the spatial distribution of mean annual precipitation, an essential variable governing hydrological cycle dynamics and influencing the reliability of water resources. Precipitation data obtained from WorldClim were classified using the natural breaks method in ArcGIS to highlight areas of high

hydropower potential. Regions receiving higher rainfall were assigned higher suitability values due to their ability to sustain streamflow and increase hydropower feasibility (Li et al., 2023; Arabameri et al., 2019).

Figure 3b presents the geological structure of the basin. Geological conditions strongly influence dam foundation stability, seepage potential, and long-term structural performance. Hard, competent lithologies such as andesite-basalt and granodiorite were classified as highly suitable due to their low permeability and high bearing capacity (Odiji et al., 2021; Demir et al., 2024; Karakuş and Yıldız, 2022). Moderately competent formations (limestone, schist, quartzite) were classified as suitable, whereas unconsolidated deposits (alluvium, volcanic sediments, mélange) were deemed unsuitable due to low shear strength and high permeability.

Table 2 provides the detailed geological suitability classes, linking rock types with engineering behavior essential for dam construction.

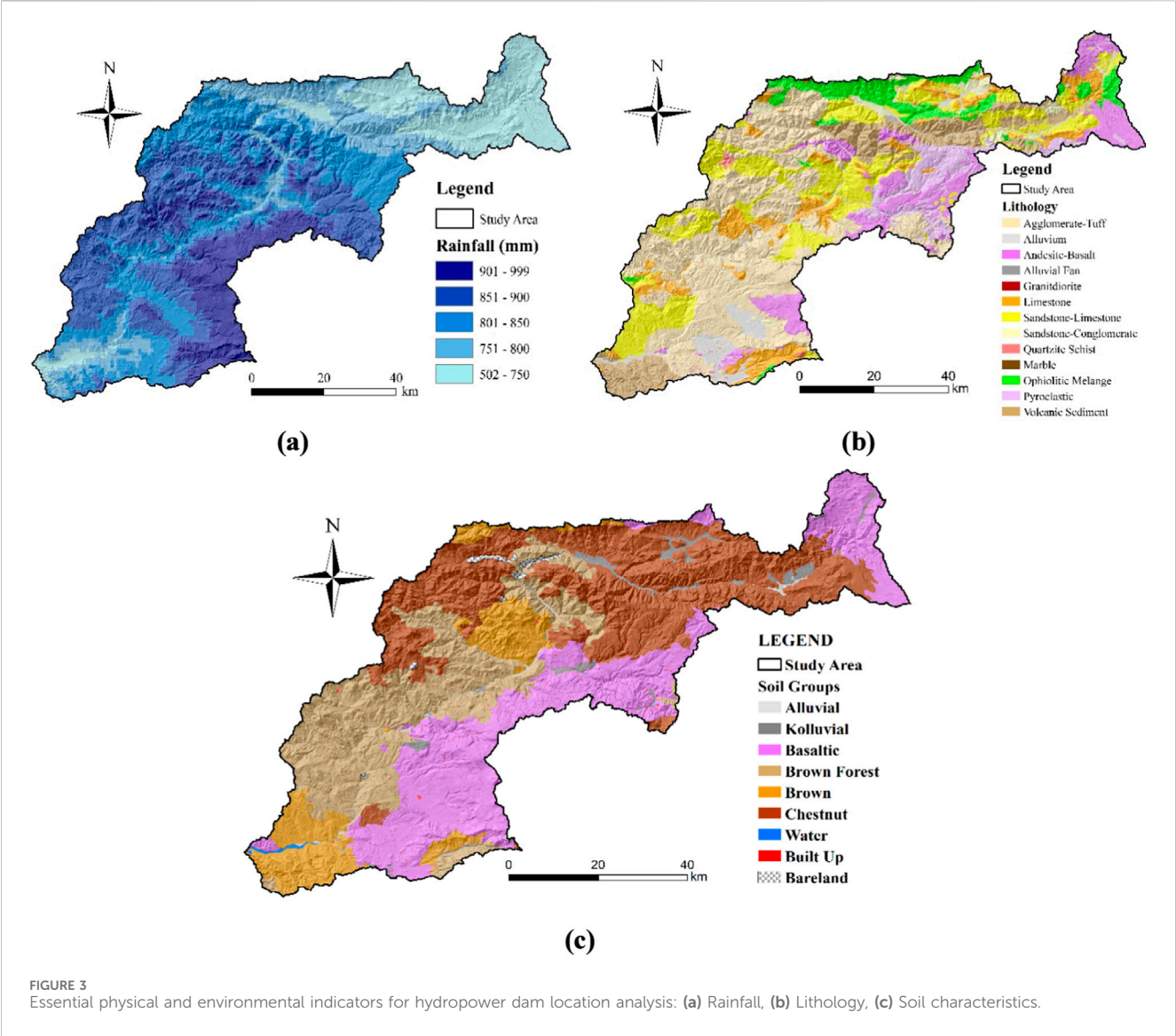


TABLE 2 Geological suitability classes of the basin for dam site selection.

Suitability score	Geological units	Description
9 (very high)	Andesite-basalt, granodiorite	Hard, competent rocks with low permeability
7 (high)	Limestone, quartzite, schist	Moderate to high strength, limited risk
5 (moderate)	Sandstone-limestone	Moderately strong ground conditions
3 (less)	Agglomerate-tuff, sandstone-conglomerate, marble, pyroclastic	Porous, fractured, weak to moderate ground
1 (unsuitable)	Alluvium, alluvial fan, ophiolitic mélange, volcanic sediments	Loose deposits, low bearing capacity

Figure 3c shows soil type distribution. Soil characteristics are critical in assessing foundation stability, infiltration capacity, and runoff formation (Karakuş and Yıldız, 2022). The predominance of Brown Forest and Chestnut soils indicates moderate infiltration and limited agricultural suitability, increasing the importance of surface water resources such as the Peri River. Soil properties significantly influence water retention, groundwater recharge, and basin hydrodynamics,

underscoring the need for sustainable water management and efficient land-use planning.

3.3 Hydrological characteristics assessment

Figure 4a displays the streamflow network derived from the DEM using flow direction and flow accumulation models in ArcGIS 10.5.

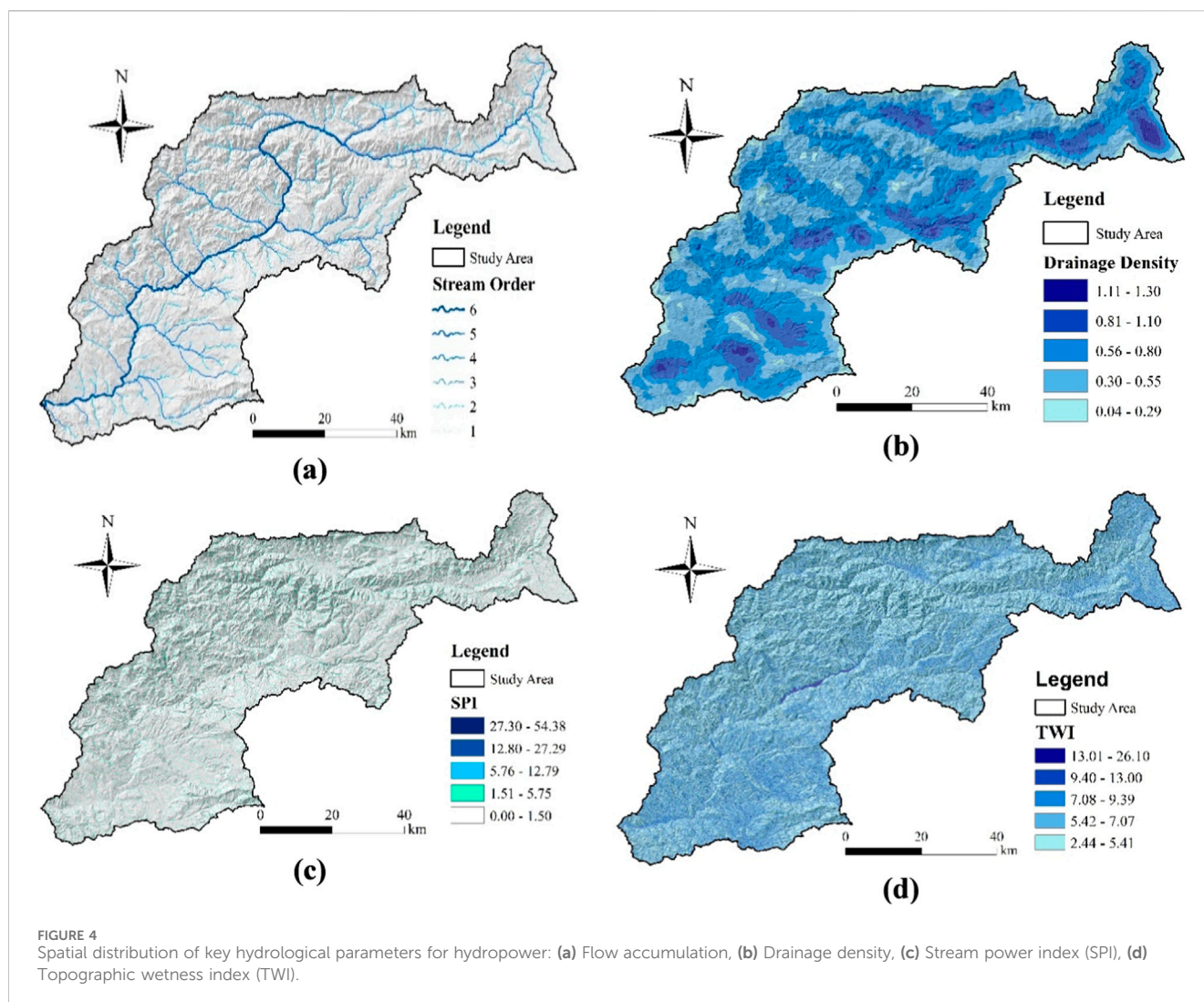


FIGURE 4 Spatial distribution of key hydrological parameters for hydropower: (a) Flow accumulation, (b) Drainage density, (c) Stream power index (SPI), (d) Topographic wetness index (TWI).

Flow accumulation identifies drainage paths, with high-accumulation areas corresponding to permanent streams, tributaries, ponds, and river channels (Odiji et al., 2021; Rasooli and Kang, 2015). The delineated river network provides the hydrological foundation for evaluating potential small-hydropower sites.

The Strahler stream order method was applied to classify stream hierarchy within the basin. First-order streams represent headwaters, and stream order increases when two streams of equal order converge. Higher-order streams (fourth and fifth order) possess greater flow volumes and velocities, making them particularly suitable for small-hydropower development (Ibrahim et al., 2015; Strahler, 1952).

Figure 4b presents the drainage density map, which was generated using DEM data in ArcGIS. Regions with high drainage density indicate a greater potential for both surface runoff and groundwater recharge. In the study area, drainage density values range between 0 and 1.3 km/km². Drainage density (D_d) is calculated using Equation 1, where the total length of all streams is divided by the basin area (Arulbalaji et al., 2019):

$$D_d = \frac{\sum L}{A} \quad (1)$$

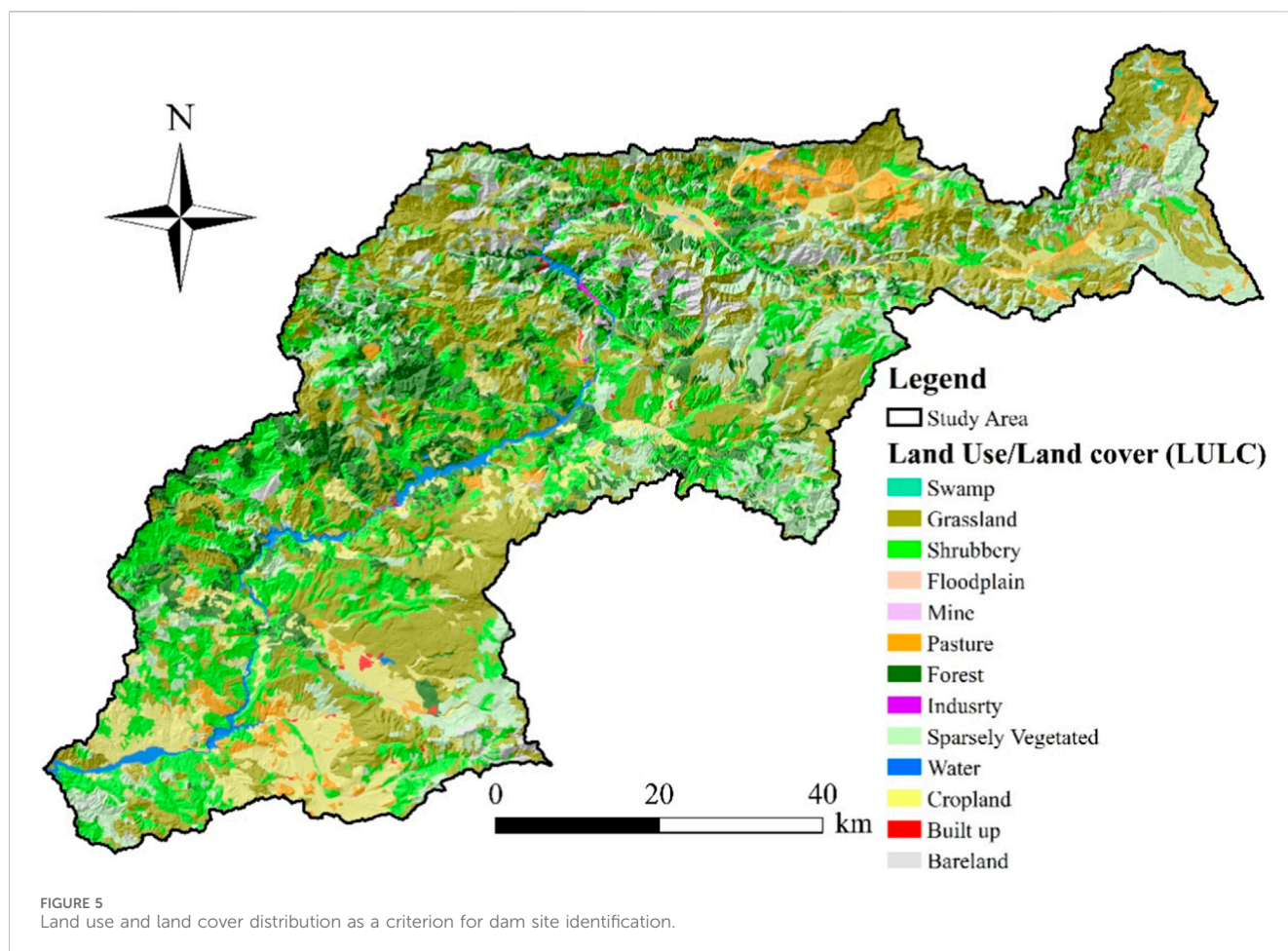
D_d , Drainage density (km/km²),
 $\sum L$, Total stream length (km),
 A , Basin area (km²)

Figure 4c shows the Topographic Wetness Index (TWI), which analyzes the tendency for water accumulation and flow paths based on topography. TWI is a secondary topographic factor in flow models and is calculated using Equation 2 (Odiji et al., 2021; Moore et al., 1991; Naghibi et al., 2015):

$$TWI = \ln \frac{\alpha}{\tan \beta} \quad (2)$$

Where:

α , Upstream contributing area
 $\tan \beta$, Slope angle in degrees.



In the study area, TWI was derived using DEM data and the raster calculator tool. Areas with higher TWI values represent wetter zones, while lower TWI values indicate drier regions.

In [Figure 4d](#), areas with high Stream Power Index (SPI) values represent regions with the highest fluvial energy, which are critical for identifying high hydropower potential sites for small-hydropower projects. SPI is defined by [Moore et al. \(1991\)](#) and is calculated using [Equation 3](#) ([Odiji et al., 2021](#); [Moore et al., 1991](#)):

$$SPI = \beta \times \tan \alpha \quad (3)$$

Where:

β , Contributing Area
 $\tan \alpha$, Slope angle in degrees.

3.4 Land use and land cover (LULC) assessment

The land use map shows the spatial distribution of agricultural land, forests, settlements, and other land cover types within the catchment area. This distribution significantly influences hydrological processes, such as surface runoff, infiltration rates, and surface roughness, and thus directly affects water flow dynamics in the catchment ([Odiji et al., 2021](#); [Samaniego and Bardossy, 2006](#)).

[Figure 5](#) illustrates the spatial distribution of land use and land cover in the study area. The land cover categories in the map are classified as follows: wetlands, grasslands, shrublands, floodplains, mining areas, pastures, forests, industrial areas, sparse vegetation, water bodies, agricultural land, settlements, and bare land. The land cover types used as a criterion for suitability as a dam are shown in [Table 3](#). While agricultural land and forests comprise a large part of the catchment area, other categories, such as pastures and water bodies, occupy only limited areas.

4 Multi-criteria decision-making and suitability mapping

4.1 AHP-based criteria weighting

The Analytic Hierarchy Process (AHP), which was developed by [Saaty \(1985\)](#), is a widely used decision-making tool employed in various disciplines ([Saaty, 1985](#); [Pathan et al., 2022](#)). When applying the AHP method, the relevant criteria are determined, and a pairwise comparison matrix is created ([Saaty, 1985](#)). The basic scale, as defined by [Saaty \(1985\)](#), is used to make pairwise comparisons between the selected criteria. A numerical scale is used to indicate the relative importance of one criterion over another, as shown in [Table 4](#) ([Pathan et al., 2022](#)).

TABLE 3 Land use classes and area distribution of the study area.

Land use type	Area (ha)	Area (%)
Agricultural land	53,352.39	9.26%
Water bodies	7,369.60	1.28%
Forest	64,872.96	11.26%
Grassland	19,879.15	3.45%
Settlement area	1,252.56	0.22%
Bare land	19,306.31	3.35%

TABLE 4 Saaty's fundamental scale of relative importance (Pathan et al., 2022; Othman et al., 2020).

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong or demonstrated importance
9	Extreme importance
2, 4, 6, 8	Intermediate values (used when compromise is needed)
Inverse values	The inverse of the above comparisons (e.g., 1/3, 1/5)

In this study, the pairwise comparison matrices used in the AHP process were developed by extensively reviewing and synthesizing relevant academic literature focused on small-hydropower site selection and hydropower potential assessment. No field survey, expert consultation, or questionnaire was conducted. Instead, the relative importance values of the criteria were derived based on the methodologies and findings reported in previous peer-reviewed studies (Raaj et al., 2022; Kos et al., 2021; Tian et al., 2020; Yıldız et al., 2024; Ali et al., 2023; Dai, 2016; Ibrahim et al., 2025; Oyinnu et al., 2023; Tamm and Tamm, 2020; Odiji et al., 2021; Rasooli and Kang, 2015; Palla et al., 2016; Karakuş and Yıldız, 2022; Ibrahim et al., 2015; Saaty, 1985; Pathan et al., 2022; Othman et al., 2020; Noori et al., 2019; Kara Dilek et al., 2025).

The relative importance of the AHP criteria was determined based on hydrological reasoning and established literature. Flow/stream order was assigned the highest weight because it directly represents drainage hierarchy and potential discharge capacity, which are critical for small hydropower plants feasibility. Rainfall was ranked next as it governs long-term water availability, while geology and slope were emphasized due to their influence on foundation stability and construction feasibility. SPI and TWI were included to represent moisture convergence and runoff concentration, whereas elevation and LULC were treated as secondary controlling factors.

The normalized weight vector of this matrix is calculated based on the relative importance of the selected criteria (Saaty, 1985).

The Consistency Ratio (CR) is used to assess the accuracy of the relative importance values. CR is defined as the ratio of the Consistency Index (CI) to the Random Index (RI), as shown in Equation 4 (Moore et al., 1991):

$$CR = \frac{CI}{RI} \quad (4)$$

The Consistency Index (CI) represents the consistency of the decision-making process and is calculated using Equation 5:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (5)$$

Where $\lambda_{\max}$ is the largest eigenvalue of the pairwise comparison matrix, and n is the number of criteria ($n = 9$ in this study). $\lambda_{\max}$ is obtained by multiplying each eigenvector element by the sum of the corresponding matrix columns and summing the results.

Saaty (2005), Saaty (1987) presented the Random Index (RI) values for different numbers of criteria, as shown in Table 5 (Saaty, 2005; Saaty, 1987). If the CR value, calculated using CI and RI, is less than 10%, the pairwise comparisons are considered acceptable. If the CR exceeds 10%, the comparisons are deemed inconsistent, and the process must be repeated (Çolak et al., 2020; Chakraborty and Banik, 2006).

Using Table 5 and Equation 5, the Consistency Index (CI) was calculated for the pairwise comparison matrix. The corresponding Random Index (RI) value was selected based on the number of criteria ($n = 9$). Finally, the Consistency Ratio (CR) was determined using Equation 4, and the results are presented in Table 6.

Consistency Analysis (CR Calculation).

- $n = 9$
- $\lambda_{\max} = 10.1043$
- $CI \text{ (Consistency Index)} = (\lambda_{\max} - n)/(n - 1) = 0.1380$
- $RI \text{ (Random Index) for } n = 9 \rightarrow 1.45$
- $CR = CI/RI = 0.0952 \text{ (9.52\%)}$

Since the CR value is below 10%, the pairwise comparison matrix is considered consistent, and the analysis is valid.

A simple one-at-a-time sensitivity analysis was performed. First, the two dominant AHP weights (flow/stream order and rainfall) were perturbed by $\pm 20\%$ and subsequently renormalized. Second, key screening thresholds were tested within alternative ranges (flow accumulation: 250,000–350,000 cells; valley width: 300–500 m; suitability index cut-off: 6–8). These ranges were defined based on commonly adopted values reported in the literature for AHP-based spatial suitability and hydropower studies, and the most appropriate thresholds were selected through a trial-and-error procedure considering the morphological and hydrological characteristics of the study area. The results indicate that the spatial distribution of high and very high suitability zones remained largely stable across scenarios, and that the majority of shortlisted candidate dam sites persisted, demonstrating that the main conclusions are robust to reasonable parameter variations. The normalized matrix and final weights derived from the AHP analysis are presented in Table 7.

TABLE 5 Random index (RI) values based on the number of criteria.

Number of criteria (n)	1	2	3	4	5	6	7	8	9	10
Random index (RI)	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

TABLE 6 Pairwise comparison matrix table.

	Flow	Rainfall	Drainage Density (DD)	Geology	Slope	SPI	TWI	Elevation	LULC
Flow	1	5	8	7	5	4	4	4	4
Rainfall	1/5	1	4	3	2	3	5	3	3
DD	1/8	1/4	1	3	2	2	3	2	2
Geology	1/7	1/3	1/3	1	2	3	2	2	2
Slope	1/5	1/2	1/2	1/2	1	2	3	2	2
SPI	1/4	1/3	1/2	1/3	1/2	1	2	4	2
TWI	1/4	1/5	1/3	1/2	1/3	1/2	1	2	2
Elevation	1/4	1/3	1/2	1/2	1/2	1/4	1/2	1	1
LULC	1/4	1/3	1/2	1/2	1/2	1/2	1/2	1	1

TABLE 7 Normalized matrix and final weights of the criteria.

Criteria	Flow	Rainfall	Dd	Geology	Slope	SPI	TWI	Elevation	LULC	Weight
Flow	0.37	0.60	0.51	0.43	0.36	0.26	0.19	0.19	0.21	0.3463
Rainfall	0.07	0.12	0.26	0.18	0.14	0.20	0.24	0.14	0.16	0.1670
DD	0.05	0.03	0.06	0.18	0.14	0.13	0.14	0.10	0.11	0.1040
Geology	0.05	0.04	0.02	0.06	0.14	0.13	0.10	0.10	0.11	0.0890
Slope	0.07	0.06	0.03	0.03	0.07	0.13	0.14	0.10	0.11	0.0818
SPI	0.09	0.04	0.03	0.02	0.04	0.07	0.10	0.19	0.11	0.0750
TWI	0.09	0.02	0.02	0.03	0.02	0.03	0.05	0.10	0.11	0.0525
Elevation	0.09	0.04	0.03	0.03	0.04	0.02	0.02	0.05	0.05	0.0413
LULC	0.09	0.04	0.03	0.03	0.04	0.03	0.02	0.05	0.05	0.0431
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.0000
Weight %	34.63%	16.70%	10.40%	8.90%	8.18%	7.50%	5.25%	4.13%	4.31%	100%

4.2 Generation of dam suitability index map

In this study, a detailed and systematic spatial analysis was conducted to identify suitable areas for the development of small hydropower plants (SHP) in the Peri River Basin. A key aspect of the study is the careful, step-by-step execution of the entire data preparation, analysis, and mapping process in the ArcGIS environment. All analysis procedures, mapping steps, and suitability assessments were carried out in accordance with the relevant literature and generally recognised GIS methods.

Firstly, the boundaries of the study area were delineated using 1:25,000 scale topographic maps, a Digital Elevation Model (DEM), and hydrological network layers. The river network was generated through river accumulation and flow-order analyses using Horton's

law and Strahler stream-order classification. Based on sensitivity tests and topographic map validation, a flow accumulation threshold of 300,000 cells was used, which provided the most realistic representation of the main drainage network within the basin.

A 300 m buffer zone was subsequently established along the extracted river network to focus the suitability assessment on valley bottoms and adjacent river corridors. This ensured that the analysis incorporated both topographical constraints and environmentally sensitive areas within the riparian zones.

In the most comprehensive stage of the study, all suitability-related parameters (including slope, elevation, drainage density, geology, precipitation, Stream Power Index, and Topographic Wetness Index) were converted into grid format and reclassified using a literature-supported scoring system. Special emphasis was

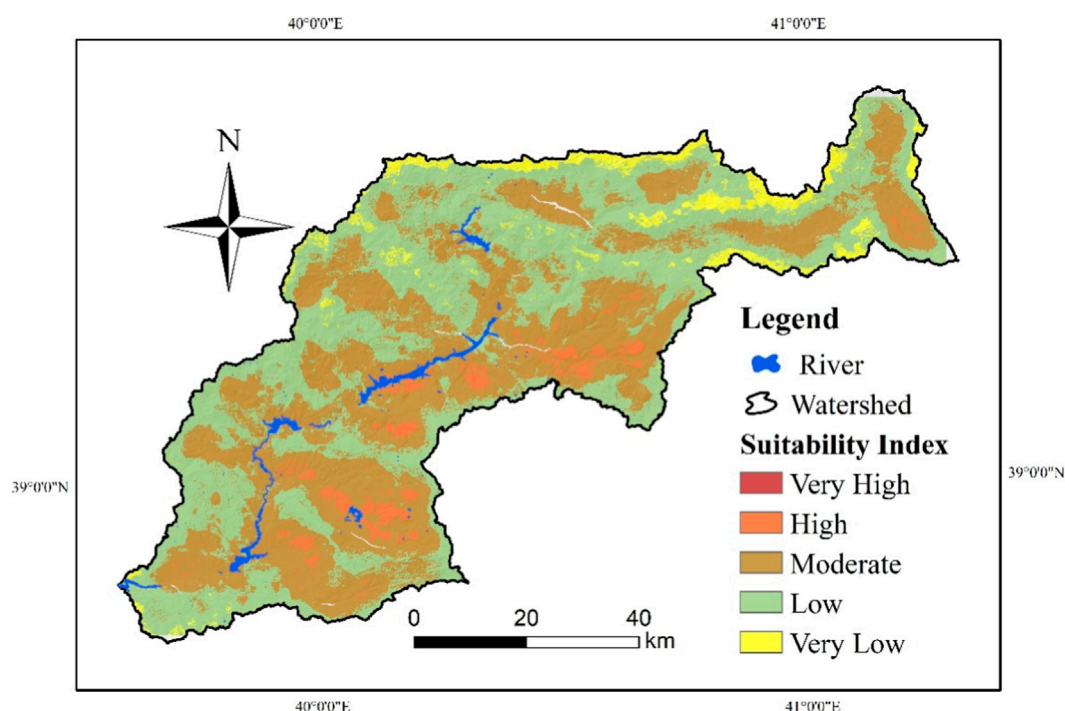


FIGURE 6
Dam site suitability map of the peri river basin based on multi-criteria gis analysis.

placed on the classification of geological units, with competent and low-permeability rock formations assigned higher suitability values. All vector layers were converted into grids using a uniform cell size to maintain analytical consistency across the dataset.

Once all individual criteria layers were prepared, the weighted overlay method was applied to generate the final dam suitability map. The output was divided into five classes (Very High, High, Moderate, Low, and Very Low) and visualised in Figure 6. Approximately 35% of the catchment area falls into the “High” and “Very High” suitability classes, primarily located along narrow valleys, low-slope regions, and geotechnically stable rock formations. The “Very High” class represents about 3% of the basin, corresponding to the most favourable hydropower locations.

The “Moderate” class covers 46% of the basin and is distributed around the main river corridors, representing areas with acceptable but not optimal conditions. The “Low” suitability class accounts for 22% of the area, generally positioned near basin boundaries where slopes are irregular or geological conditions are less favourable. Finally, the “Very Low” class covers approximately 5% of the basin and is concentrated in steep mountainous terrain and ridge zones in the northern sections.

Overall, the GIS-based spatial analyses and modelling approach used in this study constitutes a robust methodological framework for identifying suitable locations for small hydropower plants development in the Peri River Basin. The results offer a valuable decision-support tool for hydropower planning and environmental management, and the methodology can be adapted and applied to other watersheds with similar geomorphological characteristics.

4.3 Model validation and field verification

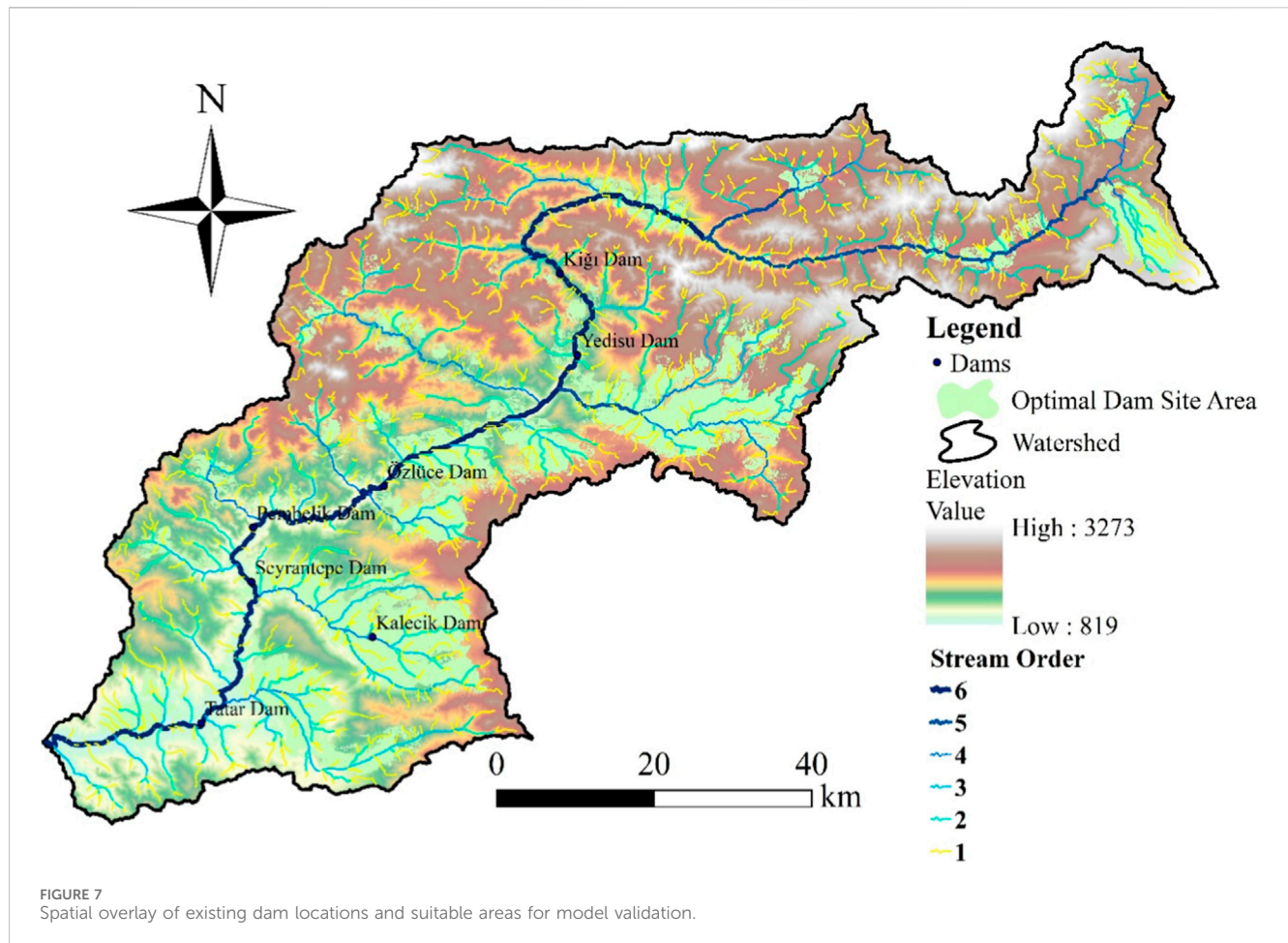
Analysing the spatial overlap between existing dam sites and the proposed suitability zones constitute a key component of the model validation process. Similar studies in the literature emphasise that comparing model outputs with the spatial distribution of existing hydropower infrastructure is a widely accepted and reliable method for evaluating model accuracy (Othman et al., 2020; Noori et al., 2019; Saaty, 1980).

For this purpose, existing dam locations within the Peri River Basin were identified using Google Earth, exported as .kml files, and imported into ArcMap for model validation. The datasets were reprojected into the appropriate coordinate system for spatial analysis. A 300 m buffer was generated around each dam site, and a spatial intersection analysis was performed with the suitability map to quantify the degree of agreement.

The results revealed a strong spatial correspondence between the high–very high suitability classes and the existing dam locations (Figure 7). This comprehensive validation confirmed the robustness and practical reliability of the proposed dam-site suitability model.

An additional assessment of the river orders at existing dam locations showed that six dams are situated on streams classified as Strahler order 1–2, and one dam is located on a higher-order channel. This distribution reflects the geomorphological characteristics of the basin and further supports the consistency of the model outputs with real-world siting conditions.

These existing dams/hydropower facilities were used only for validation purposes and are distinct from the newly proposed candidate dam sites labelled as P1–P13.



5 Physically-informed suitability index (P_{Hy}SIS)

5.1 Rationale and dimensional background

Following the Buckingham- Π theorem, the formulation of the P_{Hy}SIS index was structured through a systematic dimensional analysis. The initial step consisted of identifying the governing physical variables controlling small hydropower plants potential, namely discharge (Q), hydraulic head (H), channel slope (S), stream power (Ω), valley geometry, relief characteristics, and terrain-driven hydrological indices. These variables collectively represent the hydraulic energy availability, geomorphological focusing mechanisms, and environmental constraints of run-of-river hydropower systems.

The fundamental dimensions involved in the formulation include length (L), time (T), and mass (M). By selecting discharge (Q), head (H), and gravitational acceleration (g) as repeating variables, the remaining parameters were expressed as dimensionless Π -groups. This procedure ensures dimensional homogeneity and allows the integration of heterogeneous geomorphological and hydrological variables within a unified, scale-independent framework.

To improve the physical realism, scalability, and cross-basin transferability of the small-hydropower site selection process, a

dimensionless, physics-based suitability metric termed P_{Hy}SIS (Physically-Informed Suitability Index for Small Hydropower Plants) was developed. Unlike conventional GIS-AHP frameworks, which rely predominantly on expert-driven weighting procedures, P_{Hy}SIS incorporates hydraulic power theory, valley morphodynamics, and terrain-derived hydrological indices into a unified, physically interpretable structure (Ayele, 2020; Butt et al., 2025).

The theoretical hydropower potential can be expressed as shown in Equation 6:

$$P_{th} = \eta \rho g Q H \quad (6)$$

where P_{th} is theoretical power (W), η is turbine efficiency, ρ is water density (kgm^{-3}), g is gravitational acceleration (ms^{-2}), Q is discharge (m^3s^{-1}), and H is head (m). Following the Buckingham- Π theorem, this relationship was reformulated into dimensionless form, integrating geomorphometric and hydrological parameters derived from GIS layers (Butt et al., 2025; Trelles-Jasso, 2009; Li et al., 2025).

To ensure dimensional consistency and comparability across different terrain and hydrological conditions, each physical and environmental variable used in the P_{Hy}SIS framework was converted into a dimensionless group. The dimensionless representation allows the integration of hydraulic (e.g., discharge,

TABLE 8 Definition and normalization of dimensionless groups used in the PHySIS model.

Symbol	Parameter	Definition	Normalization
H^*	Head	Local head difference	$H/H_{\max}$
Q^*	Discharge	Local runoff or drainage-based flow	$Q/Q_{\max}$
S^*	Slope	Channel slope	S/S_{opt}
Ω^*	Stream power	Specific stream power ($\rho g QS$)	$\Omega/\Omega_{\text{ref}}$
C_v^*	Valley constriction	Channel width relative to valley	w_v/B_v
R_m^*	Relief ratio	Normalized melton ruggedness	$R_m/R_{m,\max}$
SPI^*	Stream power index	Flow convergence	$SPI/SPI_{\max}$
TWI^*	Topographic wetness index	Relative saturation	$TWI/TWI_{\max}$
GEO^*	Geological factor	Permeability/stability (0–1)	Reclassified 0–1
$LULC^*$	Land use	Land-cover suitability (0–1)	Reclassified 0–1

head, stream power), geomorphological (e.g., slope, relief, valley constriction), and environmental (e.g., geology, land use) parameters within a unified, scale-independent model. Each variable was normalized to a 0–1 range by dividing it by its maximum or reference value, thus eliminating unit dependency and improving model transferability.

Each governing variable was transformed into an intermediate dimensionless group (Π -group) through normalization with a physically meaningful reference or maximum value. These intermediate Π -groups represent the non-dimensional building blocks of the final PHySIS formulation and are summarized in Table 8.

Each dimensionless group included in the PHySIS, formulation has a clear physical interpretation. The discharge–head term (Q^*H^*) represents the core hydraulic power potential, while the stream power term (Ω^*) captures the spatial concentration of fluvial energy along the channel. Valley constriction (C_v^*) reflects geomorphological focusing, which is critical for dam feasibility in narrow valleys. Relief ratio (R_m^*) accounts for basin-scale energy gradients, whereas slope (S^*) controls hydraulic continuity and flow acceleration. Terrain indices such as SPI^* and TWI^* represent runoff convergence and subsurface moisture contribution, respectively. Geological (GEO^*) and land-use ($LULC^*$) factors were included to account for foundation stability, permeability, and environmental constraints affecting engineering feasibility.

5.2 PHySIS formulation

The composite PHySIS index is formulated as a multiplicative function of the normalized parameters (Equation 7):

$$PHySIS = (Q^*H^*)^{\alpha_1} (\Omega^*)^{\alpha_2} (C_v^*)^{\alpha_3} (R_m^*)^{\alpha_4} (S^*)^{\alpha_5} (SPI^*)^{\alpha_6} (TWI^*)^{\alpha_7} (GEO^*)^{\alpha_8} (LULC^*)^{\alpha_9} \quad (7)$$

The exponents α_i were initially derived from AHP-based importance weights and subsequently calibrated using spatial validation against 13 existing hydropower sites in the Peri River

Basin. The optimal coefficients and their physical interpretations are listed in Table 9.

The exponents used in the PHySIS formulation were determined through a calibration procedure based on the spatial distribution of existing hydropower facilities in the Peri River Basin. The primary objective of this calibration was to maximise the agreement between the PHySIS output and known dam locations by increasing the proportion of existing facilities falling within the high and very high suitability classes. Initial exponent values were guided by the relative importance of the corresponding variables derived from the AHP analysis, and only limited adjustments were allowed within physically meaningful ranges.

Given the limited number of existing facilities ($n = 13$), the calibration was intentionally kept conservative to reduce the risk of over-fitting. The stability of the PHySIS results was checked by iteratively excluding individual sites and verifying that the overall suitability pattern and ranking of candidate locations remained consistent. These steps indicate that the PHySIS index captures general physical controls on small hydropower plants suitability rather than being driven by individual reference sites.

Regarding model complexity, the parameterisation was intentionally kept conservative. Exponents were not treated as fully unconstrained free parameters; instead, initial values were guided by physical reasoning and the AHP-derived relative importance of each variable, and only limited adjustments were allowed within plausible ranges. This effectively reduces degrees of freedom and mitigates the risk of over-parameterisation.

As a basic validation/robustness check, we evaluated whether existing hydropower facilities fall predominantly within the high and very high PHySIS classes and verified that the overall suitability pattern remains stable when individual reference sites are iteratively excluded. While a fully independent out-of-sample validation or ROC/AUC analysis would require additional independent datasets and negative samples, we explicitly acknowledge this as a limitation and recommend it as a key direction for future work.

The PHySIS index was mapped throughout the Peri River Basin and normalized to a [0–1] range. Suitability classes were defined using Jenks Natural Breaks, yielding the distribution shown in Table 10.

TABLE 9 Optimized PHySIS coefficients and physical contributions.

Parameter	Symbol	Weight (α_i)	Physical role	Contribution (%)
Discharge $\times$ head	Q^*H^*	0.25	Core hydraulic potential	25
Stream power	Ω^*	0.15	Hydraulic energy density	15
Valley constriction	C_v^*	0.12	Morphological focusing	12
Relief ratio	R_m^*	0.10	Basin energy/topographic ruggedness	10
Slope	S^*	0.08	Hydraulic continuity	8
Stream power index	SPI^*	0.08	Flow convergence	8
Topographic wetness index	TWI^*	0.07	Subsurface contribution	7
Geological factor	GEO^*	0.08	Lithological stability	8
Land use	$LULC^*$	0.07	Human and ecological suitability	7

TABLE 10 Spatial distribution of PHySIS classes in the peri river basin.

PHySIS range	Suitability class	Area (%)	Interpretation
0.8–1.0	Very high	3.1	Overlaps with $\approx$ 85% of existing hydropower sites
0.6–0.8	High	17.4	Majority of new potential small-hydro zones
0.4–0.6	Moderate	46.2	Technically feasible, economically marginal
0.2–0.4	Low	22.0	Low-gradient or permeable terrain
0.0–0.2	Very low	11.3	Agricultural and alluvial plains

Compared with the conventional GIS–AHP, model, PHySIS, improved spatial accuracy by approximately 14%, correctly identifying 11 out of 13 ($\approx$ 85%) validated sites within the high and very-high suitability zones.

As shown in Figure 8, the PHySIS model demonstrates a strong capability to accurately identify hydropower-suitable valleys across the Peri River Basin. The integration of hydraulic physics with the GIS-based multi-criteria evaluation substantially enhances both the spatial precision and the physical interpretability of the site-suitability mapping. Through its dimensionless formulation, the model harmonizes hydraulic, geomorphic, and environmental parameters, allowing a physically consistent representation of the basin’s true energy potential rather than relying solely on heuristic weightings.

The PHySIS framework improves objectivity over traditional GIS-AHP-based methods by integrating weights from the analytic hierarchy with physically based exponents that are calibrated using performance data from existing dams. PHySIS combines hydraulic head, discharge, valley morphology, and lithological stability into a single, adaptable index, similar to hydro-spatial frameworks applied in the Upper Indus Basin and arid Northwest China. Dimensional normalization ensures model transferability, enabling comparative assessment in other mountainous basins such as the Gumara River Basin and morphologically complex regions (Ayele, 2020; Butt et al., 2025; Trelles-Jasso, 2009; Li et al., 2025).

The significant relationship between the PHySIS suitability zones and existing hydropower facilities supports the model’s geographical accuracy and its potential as a resource for

informed decision-making in renewable-energy planning, particularly in mountainous regions with limited data availability. Overall, PHySIS offers a physically consistent, transferable, and dimensionless analytical framework for the precise siting of small-hydropower projects, providing a pathway towards sustainable and integrated water–energy management in mountainous environments.

6 Results

Previous studies have widely demonstrated that GIS-based multi-criteria decision analysis (MCDA) approaches are effective tools for identifying suitable dam and small hydropower plants locations by integrating topographic, hydrological, geological, and land-use factors (Raaj et al., 2022; Ali et al., 2023; Ibrahim et al., 2025; Odiji et al., 2021; Karakuş and Yıldız, 2022). In this study, a semi-automatic method for selecting dam sites was developed, with the core of the proposed approach based on the integrated evaluation of the river network, topographic features, and suitability analysis. Recent basin-scale hydrological studies conducted in Türkiye have further highlighted that long-term variability in streamflow and precipitation plays a critical role in identifying technically feasible and sustainable dam locations, particularly in data-limited basins (Acar, 2024; Acar et al., 2025). The potential dam sites identified based on the suitability analysis are summarized in Table 11.

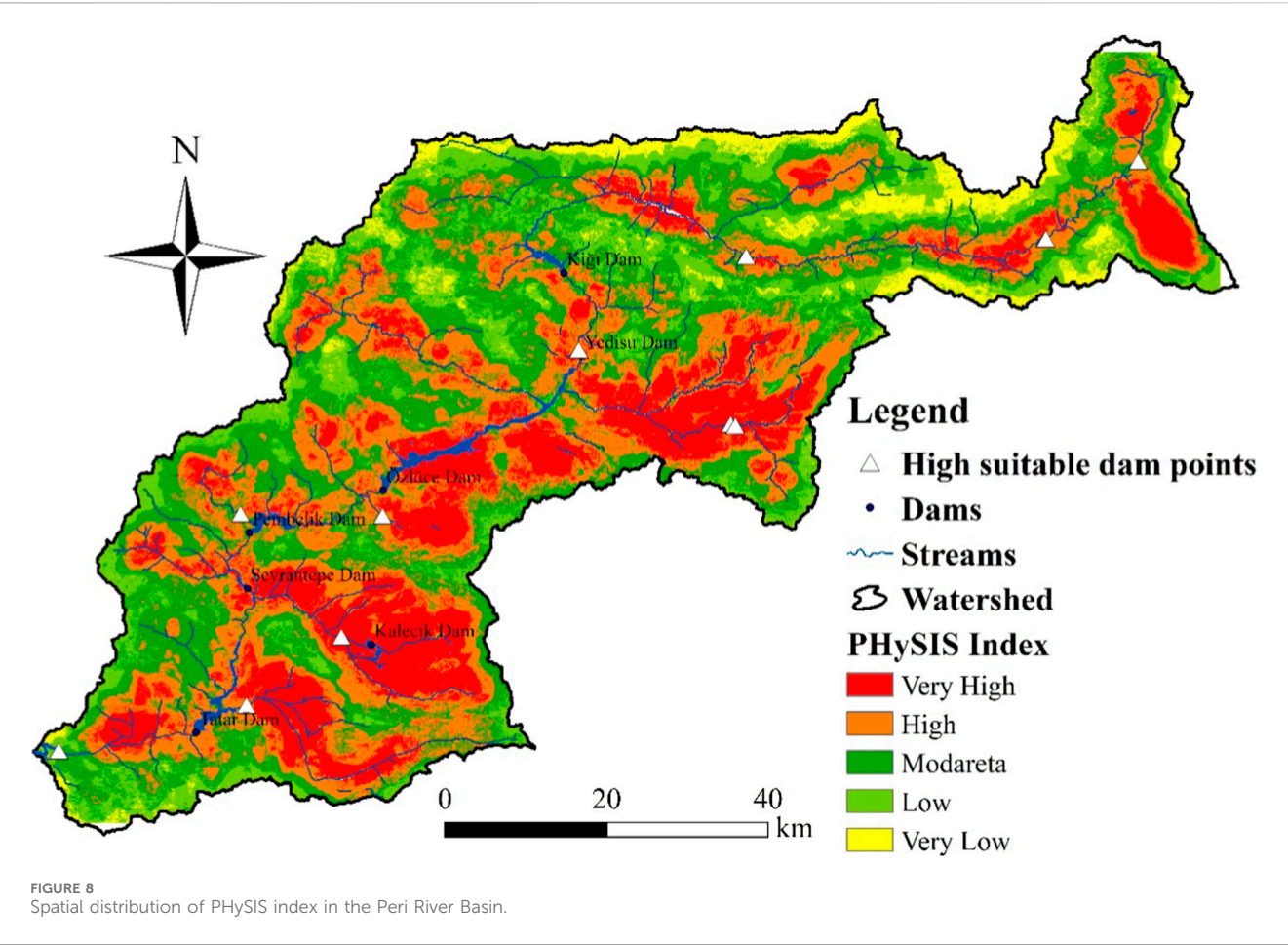
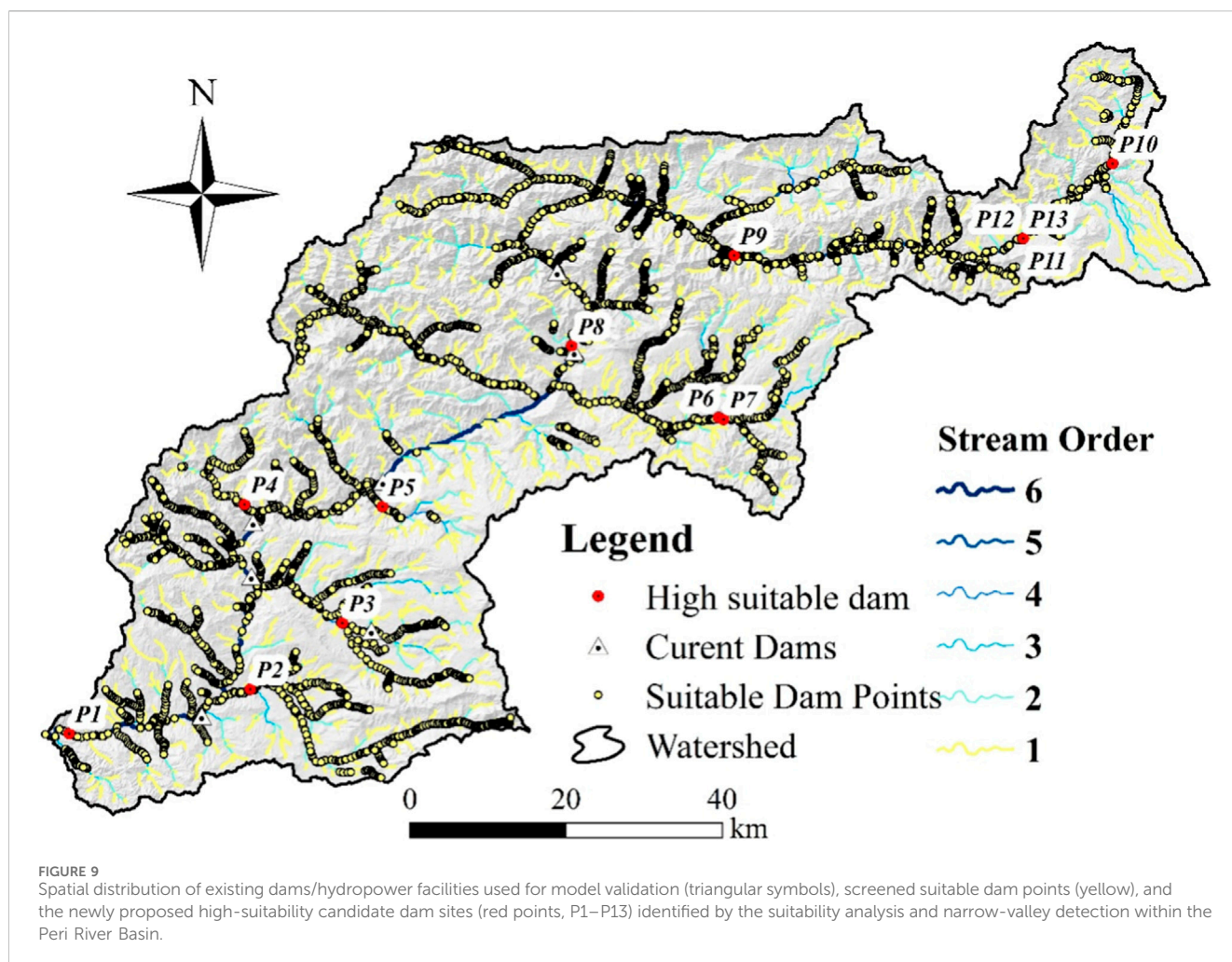


TABLE 11 Potential dam sites identified in the study area.

Dam name	Width (m)	River name	Suitability index	Stream order (grid_code)
P1	353	Peri river	830	6
P2	125	Peri river	910	4
P3	0	Ohi stream	1,070	4
P4	65	Peri river	1,030	4
P5	245	Peri river	1,140	4
P6	65	Karabaş stream	1,460	4
P7	15	Karabaş stream	1,470	4
P8	400	Peri river	1,150	6
P9	17	Peri river	1,520	5
P10	112	Peri river	1970	4
P11	15	Peri river	1840	5
P12	22	Peri river	1840	5
P13	30	Peri river	1840	5



6.1 Spatial distribution of dam suitability zones

The primary objective was to identify narrow valley sections and areas with sufficient natural slope that are suitable for the construction of gravity dams.

A 300 m buffer zone has been established around the river network to ensure that the site selection analysis primarily focuses on valley floors, while minimizing the influence of steep terrain. The locations of existing dams/hydropower facilities used for validation and the newly proposed candidate dam sites identified by the analysis are presented in Figure 9.

In the first phase of the analysis, intersections between the river network and the contour data were identified and several attributes were assigned to these points, including river order, elevation, suitability index, and valley width. Potential dam sites were selected based on the following criteria:

- Stream Order (grid_code) > 3.
- Valley Width < 400 m.
- Suitability Index ≥ 7 .

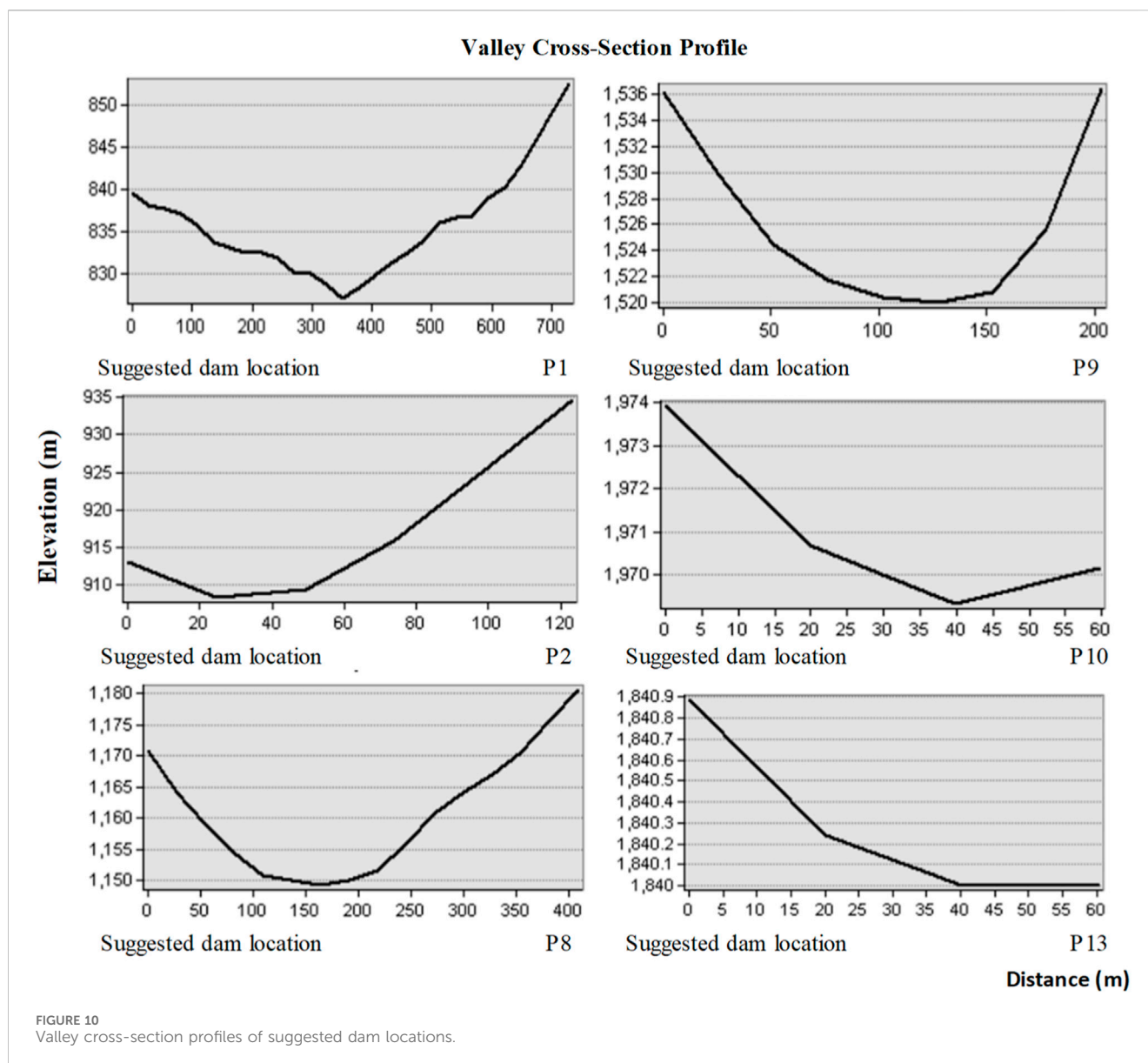
These thresholds were selected to focus on technically feasible gravity dam locations. Stream orders greater than 3 were used to ensure sufficient discharge capacity, while a maximum valley width of 400 m was adopted to capture narrow valley constrictions suitable

for dam construction. The suitability index threshold of ≥ 7 was applied to isolate areas classified as high and very high suitability. The flow accumulation threshold of 300,000 cells was selected based on Horton's law and Strahler stream classification and validated against 1:25,000-scale topographic maps.

The flux network was delineated by applying a threshold to the flux accumulation grid. In this study, cells with accumulation values greater than 300,000 were classified as flows using the Raster Calculator function: Con ("Flow_Acc" > 300,000, 1). This threshold was validated based on Horton's law and the Strahler classification method for streams, resulting in a spatial overlap of 92% compared to 1:25,000-scale topographic maps. The chosen threshold corresponds to a minimum drainage area of 76.6 km² (Pathan et al., 2022; Chakraborty and Banik, 2006). Therefore, 300,000 was retained as an objective threshold providing the best agreement with the mapped drainage network while avoiding spurious minor channels.

This integrated approach ensured the identification of technically and morphologically suitable locations for small hydropower plants development within the study area.

These sites represent newly proposed candidate dam locations derived from the suitability analysis and are distinct from the existing dams used solely for validation purposes. A total of 13 newly proposed high-suitability candidate dam sites (P1–P13) were



identified from the screened suitable dam points based on the narrow-valley criteria (Table 8). These sites are located along fourth-, fifth-, and sixth-order streams that have sufficient discharge capacity and topographic gradient to make them technically suitable for dam construction. However, site P3 is not considered suitable due to its proximity to an existing dam. In contrast, the other sites fulfil the technical and spatial requirements for the development of small hydropower plants. The cross-sectional profiles of these proposed dam sites are shown in Figure 9. They clearly show the favourable morphology of the narrow valley and the slope characteristics that support the construction of a gravity dam.

In addition, the spatial distribution of the existing dams/hydropower facilities used for validation (indicated by triangular symbols in Figure 8) was also analysed. The results show that most of these dams in operation are located in close proximity to the zones of high suitability identified by the model. This strong spatial correlation between the model results and the real infrastructure

emphasises the accuracy, reliability, and practical applicability of the proposed methodology for dam site selection.

The valley cross-section profiles of the proposed suitable dam sites identified by the analyses carried out in this study are shown in Figure 10. These profiles offer valuable insights into the topographical characteristics of the sites, including the width of the valley bottom and the slope gradient. Examination of the diagrams clearly shows that most of the proposed sites are characterised by narrow valley bottoms and considerable height differences between the valley sides. These morphological conditions indicate that the proposed sites are particularly suitable for the construction of gravity dams.

Among the newly proposed candidate dam sites, P1, P2, and P8 in particular exhibit narrow valley structures and steep side slopes, which make them favourable for dam construction. Sites P9, P10, and P13 also show sufficient natural gradients and suitable topographical features. The narrowing of the valley bottom and the steep slopes between the valley sides in these areas offer considerable

advantages in terms of water storage potential and lower construction costs.

In summary, the detailed analyses of the valley cross-sections confirm that the proposed sites have favourable topographical conditions for dam construction. The GIS-based and suitability analysis approach developed in this study provides a rapid, objective, and spatially explicit pre-assessment tool to support future dam planning in the region.

7 Discussion

In this study, long-term discharge time series were not available for the majority of the Peri River Basin. Therefore, hydrological conditions were represented using indirect proxies, including stream order, drainage characteristics, spatial rainfall distribution, and terrain-based indices such as SPI and TWI. These variables are commonly employed in data-scarce mountainous basins to approximate relative flow magnitude and spatial runoff potential rather than absolute discharge values.

As a consequence, the results primarily reflect the relative suitability of locations for small hydropower plants development, rather than precise energy yield or firm power estimates. Detailed assessments of hydropower reliability, seasonal variability, and environmental flow requirements would require continuous discharge measurements or calibrated hydrological models, which are beyond the scope of the present study.

Nevertheless, the combined use of rainfall, drainage structure, and terrain indices provides a first-order approximation of mean flow conditions at candidate sites. Incorporating explicit estimates of mean annual discharge (e.g., rainfall $\times$ drainage area $\times$ runoff coefficient) would further strengthen the hydrological interpretation and is identified as an important direction for future research.

In contrast to many similar studies in the literature, which usually only produce general suitability maps without considering valley morphology and topographical conditions, this study emphasises that the suitability for dam construction must take into account the valley structure and geomorphology. To this end, narrow valleys were semi-automatically identified using 100 m contour intervals and integrated into the suitability analysis, resulting in the identification of 13 potential dam sites.

The GIS-based multi-criteria assessment identified the most suitable areas for small-hydropower development in the Peri River Basin. Approximately 35% of the basin falls into the “high” and “very high” categories, with the most favorable sites located in valley bottoms, low-gradient areas, and geologically stable zones. The analysis reveals that suitable sites are primarily located along the main river courses, particularly in the central parts of the basin. In the upper reaches of the basin, located in the province of Bingöl, continuous river courses and steep gradients combined with mountainous terrain provide ideal conditions for the development of small-hydropower plants. In these regions, the river channels often run through narrow valleys, creating a significant difference in elevation over short distances, which allows for a significant hydraulic head even with a small water infrastructure. In addition, most of these sites are located far away from larger settlements, which reduces the potential social impact.

The overlay analysis indicates that existing dams/hydropower facilities are predominantly located within high- and very-high suitability zones, supporting the plausibility of the suitability model. In addition to these existing facilities used for validation, the workflow proposes 13 new high-suitability candidate dam sites (P1–P13) selected from the screened suitable dam points for further feasibility investigations. Among the identified sites, site P3 is considered unsuitable due to its proximity to an existing dam. Although the “Very High” suitability class represents only 3% of the catchment area, dams have already been constructed near these highly suitable regions, further confirming the accuracy of the model. The “Moderate” suitability class, which covers around 46% of the catchment area, is predominantly distributed along the river network and offers additional development opportunities.

The suitability index map produced shows a favourable potential for the development of small-hydropower plants, especially in the lower parts of the basin (southern and western regions) near the Keban reservoir. This proves the reliability and applicability of the developed approach for planning small-hydropower plants in similar environments. However, it is noteworthy that in the lower reaches of the main channel of the Peri River, the natural flow regime has been significantly regulated by the existing dams, which reduces the potential for new small-hydropower projects in these areas. Conversely, the upstream sections have a significantly higher development potential.

From an ecological point of view, the right choice of location for small-hydro power plants can minimise the ecological impact. In this study, potential dam sites were selected outside protected areas and in locations where disturbance to ecosystem integrity is unlikely, thereby reducing potential negative impacts on biodiversity from the outset. Suppose environmentally friendly “run-of-river” hydropower plants are constructed at these sites, characterised by minimal water impoundment and the installation of fish passages. In that case, renewable energy can be generated with minimal environmental impact.

To summarise, the methodology and results developed for the Peri River Basin represent a transferable model that can be applied to similar river basins throughout Turkey. Suppose energy planning takes into account the specific conditions of the basin, along with science-based approaches and participatory decision-making. In that case, Turkey’s rich water resources can be utilized more effectively and sustainably. Future research should focus on adapting this model to different regions and enriching it with real-time data to support the creation of a nationwide inventory of small-hydropower potential. Through such efforts, Turkey can meet its growing energy needs with environmentally friendly and socially acceptable solutions.

The findings of this study contribute to sustainable water resource management by promoting efficient use of natural flow regimes and minimizing hydrological alterations. Integrating hydropower site planning into watershed-scale analyses supports water reuse and resource conservation strategies, particularly in regions with limited access to centralized energy and water infrastructure. The GIS–AHP-based approach thus strengthens the water–energy nexus by linking renewable energy generation with sustainable water system management.

While environmental constraints were addressed by excluding buffered protected areas, the present framework does not explicitly

model site-specific ecological processes such as fish migration routes, habitat sensitivity, or minimum environmental flow requirements. Therefore, the results should be interpreted as a first-order technical and geomorphological suitability screening rather than a comprehensive ecological impact assessment. The integration of explicit ecological layers and environmental-flow criteria is recommended as a key direction for future work.

8 Conclusion

This study successfully mapped potential sites for small-hydropower plants in the Peri River Basin by integrating GIS, remote sensing, and a semi-automated narrow-valley detection approach. Nine hydrophysical criteria were weighted using the AHP method to generate a five-class hydropower suitability map (very high, high, moderate, low, and very low). The results indicate that approximately 3% of the catchment falls within the “very high” suitability class, whereas about 46% is classified as “moderately” suitable. Overlaying the suitability map with the locations of existing dams reveals that all operating dams are situated in high suitability zones, underscoring the accuracy and reliability of the model. Numerous narrow valley sections were identified along the river network, and 13 potential dam sites were prioritized through structured SQL queries. These sites were found to be technically and economically favourable, taking into account topography, valley morphology, natural gradient, discharge density, geological structure, and rainfall. It should be noted that areas falling within buffered environmental protection zones were excluded from the analysis prior to the final suitability classification. The success of the model depends heavily on the thematic and spatial resolution of the input data sets. It is expected that the use of high-resolution digital elevation models (DEMs) will significantly improve precision. An important ecological limitation of this model is that site suitability is primarily inferred from valley morphology and related geomorphological proxies; future studies should incorporate biodiversity indicators and habitat connectivity data to further enhance ecological realism. This holistic GIS-based approach provides decision-makers with a scientifically sound, multi-criteria, and practical tool to effectively support the selection process for small-hydropower plant sites. The proposed method is applicable to other similar mountain basins in Turkey and worldwide, provided that locally calibrated criteria and high-quality spatial data are available. This study contributes to Turkey’s renewable energy strategies by demonstrating how the development of small hydropower plants can be planned in harmony with environmental and socio-economic considerations. Moreover, the proposed framework not only enhances energy planning but also advances integrated water–energy resource sustainability, aligning with global circular economy and water reuse objectives.

Note: Future research should explore the incorporation of real-time hydrological monitoring, stakeholder perspectives, and economic feasibility studies to enhance model robustness further.

Data availability statement

The datasets presented in this article are not readily available because No restrictions apply. The geospatial datasets used in this study are either publicly available or can be provided by the corresponding author upon reasonable request. Requests to access the datasets should be directed to meralkorkmaz@munzur.edu.tr.

Author contributions

MK: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgements

I would like to express my sincere gratitude to Mr. Alban Kuriqi for his scientific feedback and valuable suggestions during the preparation of this study.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher’s note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

- Acar, R. (2024). Evaluation of Susurluk Basin flows using trend analysis methods. *Firat Univ. J. Exp. Comput. Eng.* 3 (1), 65–74. doi:10.62520/fuce.1421090
- Acar, R., Akbas, E., Köyçeğiz, C., and Eşit, M. (2025). Rainfall trends in the transboundary Euphrates–Tigris River Basin. *Environ. Earth Sci.* 84 (16), 473. doi:10.1007/s12665-025-12480-1
- Aghajani, G., and Ghadimi, N. (2018). Multi-objective energy management in a micro-grid. *Energy Rep.* 4, 218–225. doi:10.1016/j.egy.2017.10.002
- Ajanovic, A., and Haas, R. (2019). On the long-term prospects of power-to-gas technologies. *Wiley Interdiscip. Rev. Energy Environ.* 8 (1), 321–340. doi:10.1002/9781119508311.ch19
- Ali, F., Srisuwan, C., Techato, K., and Bennui, A. (2023). Assessment of small hydropower in Songkhla Lake Basin, Thailand using GIS-MCDM. *Sustain. Water Resour. Manag.* 9 (1), 25. doi:10.1007/s40899-022-00788-w
- Arabameri, A., Rezaei, K., Cerdà, A., Lombardo, L., and Rodrigo-Comino, J. (2019). GIS-based groundwater potential mapping: a comparison among statistical, data mining, and MCDM methods. *Sci. Total Environ.* 658, 160–177. doi:10.1016/j.scitotenv.2018.12.115
- Arulbalaji, P., Padmalal, D., and Sreelash, K. (2019). GIS and AHP-based delineation of groundwater potential zones: southern Western ghats, India. *Sci. Rep.* 9 (1), 2082. doi:10.1038/s41598-019-38567-x
- Ayle, M. K. (2020). GIS-based assessment of hydropower potential: gumara river Basin. *Am. Sci. Res. J. Eng. Technol. Sci.* 69 (1), 26–43.
- Bakış, R., Çabuk, A., Uygucul, H., and Gümüslüoğlu, E. (2011). Uzaktan algılama ve CBS ile porsuk Havzasında uygun Baraj Yeri Tespiti ve hidroelektrik enerji incelemesi. *Tarım Bilim. Araştırma Derg.* 2, 79–96.
- Butt, A. Q., Shangquan, D., Waseem, M., Abbas, A., Banerjee, A., and Yadav, N. (2025). Hydropower potential in the upper indus Basin using GIS-MCDA. *Resources.* 14 (3), 49. doi:10.3390/resources14030049
- Cengiz, H., and Behçet, L. (2024). Perisuyu Vadisi ve Çevresinin (Yedisu–Karlıova/Bingöl) Florası. *Bağbahçe Bilim Derg.* 11 (2), 143–174.
- Chakraborty, S., and Banik, D. (2006). Material handling equipment selection using AHP. *Int. J. Adv. Manuf. Technol.* 28, 1237–1245. doi:10.1007/s00170-004-2467-y
- Çolak, M., Kaya, İ., Özkan, B., Budak, A., and Karışan, A. (2020). Hesitant fuzzy sets for blockchain technology selection. *J. Intell. Fuzzy Syst.* 38 (1), 935–946. doi:10.3233/JIFS-179460
- Couto, T. B., and Olden, J. D. (2018). Global proliferation of small hydropower plants science and policy. *Front. Ecol. Environ.* 16 (2), 91–100. doi:10.1002/fee.1746
- Dai, X. (2016). *Dam site selection using an integrated method of AHP and GIS for decision making support in Bortala, Northwest China*. Lund, Sweden: Lund University.
- Demir, G., Riaz, M., and Deveci, M. (2024). Wind farm site selection using geographic information system and fuzzy decision-making model. *Expert Syst. Appl.* 255, 124772. doi:10.1016/j.eswa.2024.124772
- El-Bana, E. M. M., Alogayell, H. M., Sheta, M. H., and Abdelfattah, M. (2024). An integrated remote sensing and GIS-Based technique for mapping groundwater recharge zones: a case study of SW Riyadh, central Saudi Arabia. *Hydrology.* 11 (3), 38. doi:10.3390/hydrology11030038
- ESRI (2025). About esri the science of where. Available online at: <https://www.esri.com>.
- Fry, J.-J., Morris, M., and Schleiss, A. (2022). *Hydropower, a catalyst for energy transition in Europe*. London, United Kingdom: Taylor and Francis. 2058829.
- Ghorbani, M. A., Deo, R. C., Kim, S., Hasanpour Kashani, M., Karimi, V., and Izadkhan, M. (2020). Development and evaluation of the Cascade correlation neural network and the random forest models for river stage and flow prediction in Australia. *Soft Comput.* 24, 12079–12090. doi:10.1007/s00500-019-04648-2
- Ibrahim, A., Al Hajj, M., and El Hage, M. (2015). Use of geomatic approaches to characterize arqa river basin. *Open J. Mod. Hydrol.* 5 (3), 45. doi:10.6092/issn.2281-4485/20218
- Ibrahim, J. A., Ibrahim, B., Yason, B., and Aladejana, O. O. (2025). Geospatial suitability assessment of small-scale hydropower potential (Dam sites) for green energy in North-Eastern Nigeria. *EQA Int. J. Environ. Qual.* 66, 18–29.
- Kara Dilek, Z. E., Opan, M., Bacaksız, E., and Hergül, A. S. (2025). Selection of dam site by using AHP and VIKOR: sakarya Basin. *Open Chem.* 23 (1), 20250175. doi:10.1515/chem-2025-0175
- Karakuş, C. B., and Yıldız, S. (2022). GIS–multi criteria decision analysis-based land suitability assessment for dam site selection. *Int. J. Environ. Sci. Technol.* 19 (12), 12561–12580. doi:10.1007/s13762-022-04323-4
- Kaygusuz, K. A. (2022). Simple feasibility study of a small hydropower project. *J. Eng. Res. Appl. Sci.* 11 (1), 9.
- Kos, Ž., Đurin, B., Dogančić, D., and Kranjčić, N. (2021). Hydro-energy suitability of Rivers regarding their hydrological and hydrogeological characteristics. *Water.* 13 (13), 1777. doi:10.3390/w13131777
- Kuriqi, A., Pinheiro, A. N., Sordo-Ward, A., and Garrote, L. (2019). Influence of hydrologically based environmental flow methods on flow alteration and energy production in a run-of-river hydropower plant. *J. Clean. Prod.* 232, 1028–1042. doi:10.1016/j.jclepro.2019.05.358
- Kuriqi, A., Pinheiro, A. N., Sordo-Ward, A., and Garrote, L. (2020). Water–energy–ecosystem nexus: balancing competing interests at a run-of-river hydropower plant coupling a hydrologic–ecohydraulic approach. *Energy Convers. Manag.* 223, 113267. doi:10.1016/j.enconman.2020.113267
- Li, Y., Abdelkareem, M., and Al-Arifi, N. (2023). Mapping potential water resource areas using GIS-based frequency ratio and evidential belief function. *Water.* 15 (3), 480. doi:10.3390/w15030480
- Li, Y., Deng, Z., Li, J., Li, M., and Zhao, Z. (2025). Integrating spatial MCDA and GIS for pumped hydro storage site selection in arid northwest China. *J. Energy Storage.* 138, 118538. doi:10.1016/j.est.2025.118538
- Liu, D., Liu, H., Wang, X., and Kremere, E. (2019). *World Small Hydropower Development Report 2019: Case Studies*. Vienna, Austria: United Nations Industrial Development Organization; Hangzhou, China: International Center on Small Hydro Power. Available online at: www.smallhydropowerworld.org.
- Masoudian, M., and Theobald, S. (2011). Influence of land surface topography on flood hydrograph. *J. Am. Sci.* 7 (11), 248–256.
- Moore, I. D., Grayson, R. B., and Ladson, A. R. (1991). Digital terrain modelling: hydrological, geomorphological, and biological applications. *Hydrol. Process.* 5 (1), 3–30. doi:10.1002/hyp.3360050103
- Naghibi, S. A., Pourghasemi, H. R., Pourtaghi, Z. S., and Rezaei, A. (2015). Groundwater qanat potential mapping using frequency ratio and shannon Entropy models. *Earth Sci. Inf.* 8, 171–186. doi:10.1007/s12145-014-0145-7
- Noori, A. M., Pradhan, B., and Ajaj, Q. M. (2019). Dam site suitability assessment at the greater Zab River, Northern Iraq. *J. Hydrol.* 574, 964–979. doi:10.1016/j.jhydrol.2019.05.001
- Odihi, C., Adepoju, M., Ibrahim, I., Adedeji, O., Nnaemeka, I., and Aderoju, O. (2021). Small hydropower dam site suitability modelling in upper Benue River watershed, Nigeria. *Appl. Water Sci.* 11, 1–17. doi:10.1007/s13201-021-01466-6
- Othman, A. A., Al-Maamar, A. F., Al-Manmi, D. A. M. A., Liesenberg, V., Hasan, S. E., Obaid, A. K., et al. (2020). GIS-based modeling for selection of dam sites in the Kurdistan Region, Iraq. *ISPRS Int. J. Geo-Inf.* 9 (4), 244. doi:10.3390/ijgi9040244
- Oyinna, B., Okedu, K. E., Diemuodeke, O. E., David, L. E., Negedu, I. O., Osemudiamen, E. A., et al. (2023). Assessing small hydropower sites in Nigeria for sustainable development using ArcGIS. *Energy Rep.* 10, 2889–2898. doi:10.1016/j.egy.2023.09.102
- Palla, A., Gnecco, I., La Barbera, P., Ivaldi, M., and Caviglia, D. (2016). An integrated GIS approach to assess mini hydropower potential. *Water Resour. Manag.* 30, 2979–2996. doi:10.1007/s11269-016-1318-6
- Patel, D. K., Thakur, T. K., Thakur, A., Karuppannan, S., Swamy, S. L., and Pant, R. R. (2024a). Groundwater potential zone mapping using AHP and geospatial techniques in the upper Narmada basin, central India. *Discov. Sustain.* 5 (1), 355. doi:10.1007/s43621-024-00560-4
- Patel, D. K., Thakur, T. K., Thakur, A., Pandey, A., Kumar, A., Kumar, R., et al. (2024b). Quantifying land degradation in upper catchment of Narmada River in central India: evaluation study utilizing landsat imagery. *Water.* 16 (17), 2440. doi:10.3390/w16172440
- Pathan, A. I., Agnihotri, P. G., and Patel, D. (2022). Integrated AHP–TOPSIS with GIS for dam site suitability mapping: Navsari City, India. *Environ. Earth Sci.* 81 (18), 443. doi:10.1007/s12665-022-10568-6
- Raaj, S., Pathan, A. I., Mohseni, U., Agnihotri, P. G., Patidar, N., Islam, M. N., et al. (2022). Dam site suitability analysis using geo-spatial technique and AHP: a case of flood mitigation measures at lower tapi basin. *Model. Earth Syst. Environ.* 8 (4), 5207–5223. doi:10.1007/s40808-022-01441-3
- Rasooli, A., and Kang, D. (2015). Assessment of potential dam sites in the Kabul River Basin using GIS. *Assessment.* 6 (2), 83–89. doi:10.14569/ijacsa.2015.060213
- Saaty, T. L. (1980). *The analytic hierarchy process*. New York, NY: McGraw-Hill.
- Saaty, T. L. (1985). “Axiomatization of the analytic hierarchy process,” in *Decision making with multiple objectives* (Berlin, Heidelberg: Springer), 91–108.
- Saaty, R. W. (1987). The analytic hierarchy process what it is and how it is used. *Math. Model.* 9 (3–5), 161–176. doi:10.1016/0270-0255(87)90473-8
- Saaty, T. L. (2005). *Theory and applications of the analytic network process*. RWS: Pittsburgh, PA.
- Saaty, T. L., and Vargas, L. G. (1980). *Hierarchical analysis of behavior*, 25, 180–191.
- Samaniego, L., and Bardossy, A. (2006). Simulation of land-Use/Cover and climate change impacts on runoff. *Ecol. Model.* 196 (1–2), 45–61. doi:10.1016/j.ecolmodel.2006.01.005
- Strahler, A. N. (1952). Hypsometric analysis of erosional topology. *Geol. Soc. Am. Bull.* 63, 1117–1142. doi:10.1130/0016-7606(1952)63[1117:haoet]2.0.co;2

Tamm, O., and Tamm, T. (2020). Verification of a robust method for sizing and siting small hydropower run-of-river plant potential using GIS. *Renew. Energy*. 155, 153–159. doi:10.1016/j.renene.2020.03.062

Thakur, T. K., Patel, D. K., Thakur, A., and Arora, N. K. (2025a). Evaluation of land degradation vulnerability in coal mined areas of Madhya Pradesh, India using geospatial and AHP modeling: a 40-year assessment and eco-restoration of degraded landscape. *Environ. Sustain.* 8 (1), 85–101. doi:10.1007/s42398-025-00347-x

Thakur, T. K., Patel, D. K., Saini, S., Thakur, A., Swamy, S. L., Bakshi, S., et al. (2025b). A geospatial analysis of coal mine overburden reclamation: land use, carbon stock, biomass, and soil genesis in chronosequence plantations. *J. Geochem. Explor.* 271, 107674. doi:10.1016/j.gexplo.2025.107674

Tian, Y., Zhang, F., Yuan, Z., Che, Z., and Zafetti, N. (2020). Assessment of power generation potential of small hydropower plants using GIS software. *Energy Rep.* 6, 1393–1404. doi:10.1016/j.egy.2020.05.023

Trelles-Jasso, A. (2009). Evaluation of small hydropower potential in three river basins of Mexico. *IMTA Jiutepec, Mex.*

Yıldız, S., Karakuş, C. B., and Bayrak, F. (2024). Coğrafi Bilgi Sistemi ile Hidroelektrik Enerji Üretimi Amaçlı Mini Hidroelektrik Santrali Yeri Seçimi: Sivas Kızılırmak havzası örneği. *Niğde Ömer Halisdemir Univ. J. Eng. Sci.*, 500–508.

Yüksel, I., and Demirel, I. H. (2021). Investigation of the optimal method for determining hydropower potential of small streams: a case study Batman Basin in Turkey. *Arab. J. Geosci.* 14 (7), 580. doi:10.1007/s12517-021-06877-y