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Developing a fuzzy analytic network process (ANP) and fuzzy analytic hierarchy process (AHP) model to evaluate small hydropower plant potential

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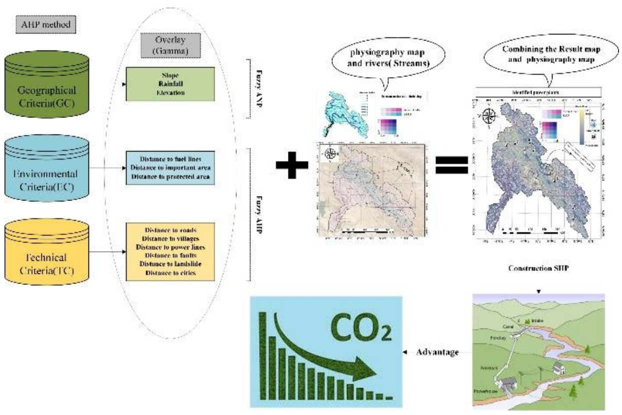
Abstract

Despite the fact that the energy sector has contributed to the destruction of the environment through its emissions of greenhouse gases, human societies have paid more attention to renewable energy sources such as small hydropower plants in response to this issue. For the purpose of determining zoning, 12 layers of environmental, technical, and geographical criteria have been used. In order to achieve the results of this study, we combined multi-criteria decision-making (MCDM) with fuzzy algorithms. Basically, the fuzzy-AHP method of weighting is used as a method for evaluating the technical and environmental criteria that do not have an internal relationship with one another. Using the fuzzy-ANP method, we are able to weight geographical criteria that are related to one another and are evaluated in terms of their relative importance. In order to identify the zoning map, layers have been overlaid by using the gamma operator 0.9 in order to identify the zoning map. In order to produce the final zoning map, the zoning and the physiographic maps are combined using the Sum operator. Therefore, 13 suitable sites were selected for the construction of power plants, resulting in 22084.69 megawatts of energy being generated per year and 5.8 tons of greenhouse gases being prevented from being released into the atmosphere. During the course of this study, a watershed located in Iran, known as the Karoun watershed, was studied. Furthermore, the methods applied in this research could be performed in other watersheds and evaluated the potential of other power plants such as solar and wind power plants.

Keywords: SHP (Small Hydropower Plants), AHP, ANP, GHG emissions



Graphical Abstract

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1-Introduction

Since a large part of human and economic activities today are dependent on energy consumption, the energy sector plays an essential role in the economic development of a nation. It is estimated that the energy sector emits a significant amount of greenhouse gases that cause environmental damage. Moreover, electricity and heat producers contribute approximately 40% of global CO_2 emissions [1]. As of May 2022, CO_2 concentrations in the atmosphere have reached 421 parts per million (ppm), up from 280 parts per million (ppm) pre-industrially [2, 3]. The reduction of global carbon dioxide (CO_2) emissions is thus urgently needed by 2030, with a significant portion of this reduction taking place within the energy sector [4]. In 1971 energy supply was 230 EJ. There has been an increase in energy demand due to population growth, industrialization, and urbanization [5, 6], Accordingly, the International Energy Agency (IEA) estimates that energy demand will increase annually at a rate of 1.3% between 2020 and 2030, reaching 670 EJ by 2030 [7]. This is one of the sectors that produces the greatest amount of carbon dioxide emissions. To combat climate change, increasing energy supply must be met with renewable energy sources [8].

A hydropower plant as a renewable energy source installed capacity is classified according to its producer and country. The International Union of Electricity Producers and Distributors considers capacities up to 10 megawatts to be the standard for SHPs [9]. In terms of renewable energy, water represents 71% of the world's total. In addition, 16% of the world's electricity is produced by hydropower [10]. Renewable energy sources, particularly solar and wind power, can provide countries with certain economic benefits and may help reduce the burden of fossil fuels [11]. In addition, they are capable of meeting the demands and needs of population growth, as well as of combating climate change [12, 13]. It is undeniable that energy is a vital factor in developing countries all over the world. It is believed that economic and environmental factors impede the access of the global community to renewable energy, particularly in rural areas. Thus, governments and other organizations are attempting to bring electricity to communities or to provide commercial energy to them [14].

SHP site evaluation requires extensive experience and knowledge. This section has relatively higher costs than the entire project. A preliminary analysis of a project can be performed by developers using a variety of methods before investing in the project. In order to obtain valid and accurate results, it is necessary to conduct an "on ground" survey of potential locations for the generation of electricity. Researchers are able to use this information to make better decisions using decision-making methods. In combination with GIS, these methods could be used to evaluate the potential sites for SHPs and determine whether they are viable from an environmental and technical standpoint [15]. Hydrological modeling has also benefited from GIS techniques because they are easy to use, inexpensive, and time-effective [16].

AHP and ANP, combined with logic fuzzy, were used in this research to evaluate the potential of the SHP site. AHP and ANP are both multiple-criteria decision-making (MCDM) techniques. The concept of multi-criteria decision-making, also known as MCDM, encompasses a number of principles, approaches, and tools developed to help decision-makers navigate intricate decision-making process systematically and methodically. A MCDM problem can be divided into two types: one where the data is considered continuously and modeling and optimization are performed accordingly, and the second where continuous data is transformed into discrete data and modeling and optimization are implemented accordingly. In order to solve first category problems, there are a number of different approaches, including MAUT, AHP, ANP, and TOPSIS. Studies conducted indicate that none of the methods are ideal and that their use depends on the circumstances in which they are used. [17].

The purpose of this study is to use an AHP/ANP-based decision analysis methodology for a number of reasons. By using a systematic approach, it enables decision-makers to handle complex decision-making challenges by subdividing the primary problem into more manageable and feasible subproblems. Furthermore, when there are interdependencies between distinct elements, such as criteria and alternatives, the application of ANP is crucial.

A variety of methods and tools have been used by researchers to estimate a river's hydropower potential using GIS and RS. In 2020 a study was conducted using GIS and RS to identify suitable dam sites in Kurdistan Iraq. This study overlays 14 layers which consist of tectonic zones, distance to active faults, lithology, distance to lineaments, soil type, land cover, distance to towns and cities, hypsometry, slop gradient, average precipitation, stream width, curve number grid and distance to major roads, and distance to villages with the help of AHP and Weighted sum method WSM to define eleven suitable locations for dam construction [18]. In another study, GIS and AHP techniques were used to analyze spatial data, including slop, precipitation, geology, soil type, drainage, and land use [19]. Another study conducted in 2020 evaluated potential dam sites in Imo state using the fussy logic approach. The approach considers rainfall, soils, runoff, geology, stream order, and land use [20]. So far, there has been no explanation of how to identify and select potential dam locations. Instead, they have developed a Dam site suitability map (DSSM) [21].

The maximum potential hydropower production in the La Plata basin has been assessed using a GIS-based methodology. A study is being conducted to determine whether (and when) hydropower shortages will occur in the La Plata basin over the next decade. Population dynamics, rapid economic development, and changes in the hydrological regime are three factors that may affect the utilization of natural resources in the La Plata Basin. During the research process, demographic processes and economic development were considered in relation to energy demand and supply in the La Plata basin. As part of the second phase of this research, changes in the hydrological regime and land use are being examined in relation to hydropower exploitation in the La Plata Basin. Next, by using a newly developed GIS-based tool (VAPIDRO-ASTE), the maximum hydropower potential in the La Plata Basin was assessed. The study identified potential vulnerabilities in the basin by comparing maximum theoretical hydropower with current production and future energy demand trends [22]. Also, in another study, an assessment and ranking of potential small hydropower sites using GIS-fuzzy logic multicriteria scoring of existing irrigation dams is provided. Dam characteristics are evaluated (normal reservoir level, reservoir capacity, dam purpose, and dam ageing) as well as grid connection spatial characteristics. A Site Suitability Index (SSI) measures the suitability of each criterion separately and then aggregates them. Data from the daily continuous monitoring of the most suitable dam including flow and head during the irrigation season used in this research. Additionally, the best grid connection route from the dam to its nearest substation was determined using optimal path methodology to minimize land expropriation [23]. Also, research conducted using geospatial assessment tolls and rainfall-runoff hydrological model to evaluate the SHP potentials of OSB in the BENIN-QWENA river basin catchment. A spatial approach, which combined Arc-Hydro, Remote Sensing (RS), and GIS, was used to characterize the Osse Sub-basin (OSB) and calculate the peak discharge Qp using the Natural Resources Conservation Service - Curve Number (NRCS-CN) hydrological model. By analyzing the catchment parameters obtained along the drainage network in a run-of-river project, this method can be used to identify potential locations for Small Hydropower (SHP) projects that satisfy the requirement of building hydropower plants [24].

Other studies have been done using fuzzy multi-criteria decision-making methods for locating other types of power plants other than hydroelectric power plants. One of the studies focuses on the GIS-based site selection and technical potential evaluation of PV solar farms using Fuzzy-Boolean logic and AHP multi-criteria decision-making approach. The study aims to determine locations in Khuzestan province with excellent, good, and moderate suitability for installing photovoltaic power plants and investigates the potential of electricity generation using two dominant PV panel technologies, namely single-crystalline and poly-crystalline silicon. The study considers a significant number of restrictions and uses Fuzzy-Boolean logic and AHP to achieve higher accuracy and reliability of results than other similar studies[25]. Another study discusses the optimal planning of rural hybrid systems for clean electricity supply, incorporating various alternatives and sustainability considerations. It introduces an integrated decision-making approach for designing PV-WT-HydT-BioGen-BES systems, taking into account on/off-grid hybridizations. The primary goal is to ensure sustainable and reliable electricity for 27,808 residents in Ghulam Shah township, Pakistan, by assessing the potential of local resources including solar irradiance, wind speed, ambient temperature, biomass supply, and water stream flow[26].

This study aims to measure the potential of small hydropower plants in rural areas based on technical, environmental, and geographical criteria to harness this energy efficiently with the least amount of damage. In order to identify these places, AHP methods are combined with ANP methods to measure and decide on criteria that are related, and fuzzy logic is used to unify the range of criteria values. The hydrological factors are combined with the model to identify the points of maximum energy extraction. The research aims to accomplish three general goals: 1. Using GIS along with AHP and ANP and fuzzy logic to determine the most suitable location for a a large watershed with impassable access in some areas. 2. Modeling and identification of canals and rivers using digital elevation models (DEMs) 3. Consolidation of the above points to identify the locations of dikes and power plants as well as the energy production based on the distance between the dikes and the power plants in order to propose the location for the development and construction of the power plant. In general, in this study, using environmental, technical, and geographical criteria, places for the construction of hydroelectric power plants in large watersheds with impassable areas have been proposed in order to minimize construction costs and prevent destruction of important agricultural lands.

2-Study area

In this study, Karoun has been selected as a case study for the evaluation of the potential of small hydropower plants using GIS and AHP-ANP/Fussy methods. It is the longest and largest river in Iran with a length of 950 kilometers. There are eight provinces in Iran that are part of the Karoun catchment area. These provinces include Isfahan, Chaharmahal Bakhtiari, Khouzestan, Kohgilye va Boierahmad, Lorestan, Markazi, Fars, and Hamedan. There are also over 66680 km2 of Karoun catchments that consist of 25% plains and 75% mountains with an average elevation of 2200 meters above sea level. In the study area, the annual minimum temperature was 8^{0}c and the maximum temperature was 27 ^{0}c. Furthermore, the longitude ranges from 48^{0}12' to 52^{0}00'N, while the latitude ranges from 29^{0}55' to 34^{0}10'E. The Karoun watershed is characterized by higher altitudes from the eastern north to the eastern south, with the most rainfall occurring in the central area of this region. The location of the Karoun watershed in Iran is shown in Figure 1.

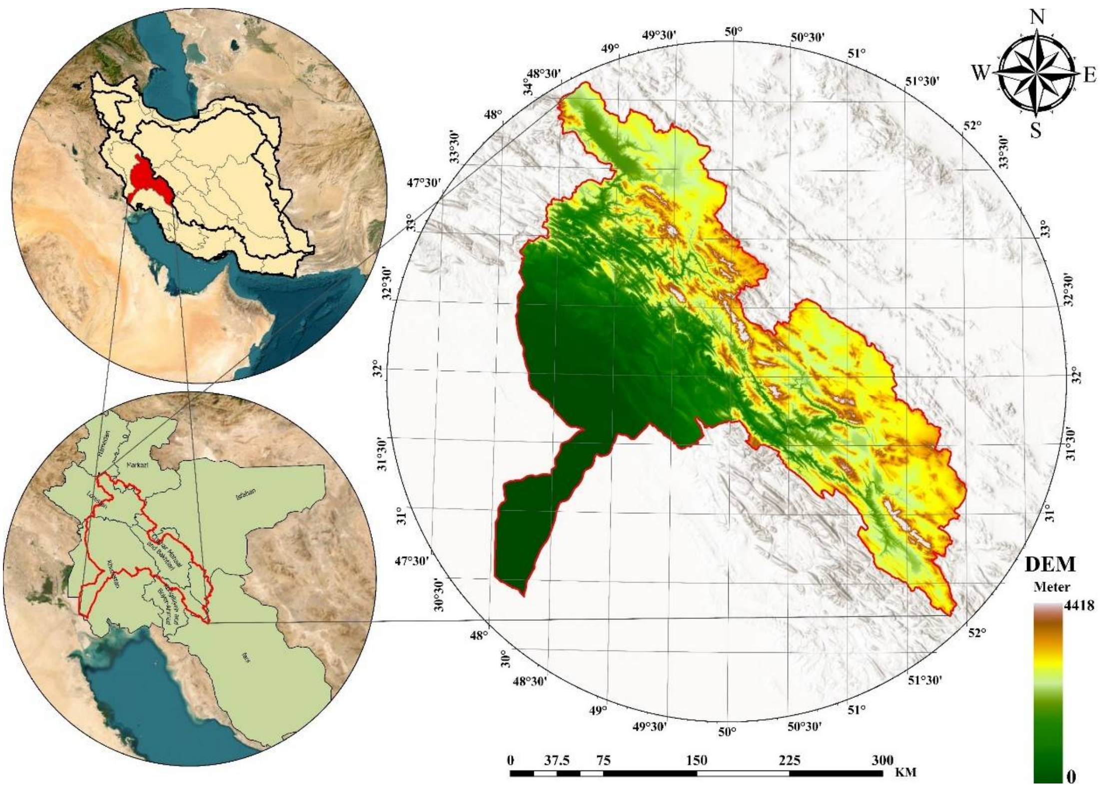


Figure 1. Location of the Karoun watershed

3-Methods

In this study, small hydropower plants are evaluated in three phases, including finding suitable sites for SHPs, identifying hydrological maps and rivers, and calculating the energy generated by SHPs. An overview of the study is depicted in Figure 2 the form of a flowchart.

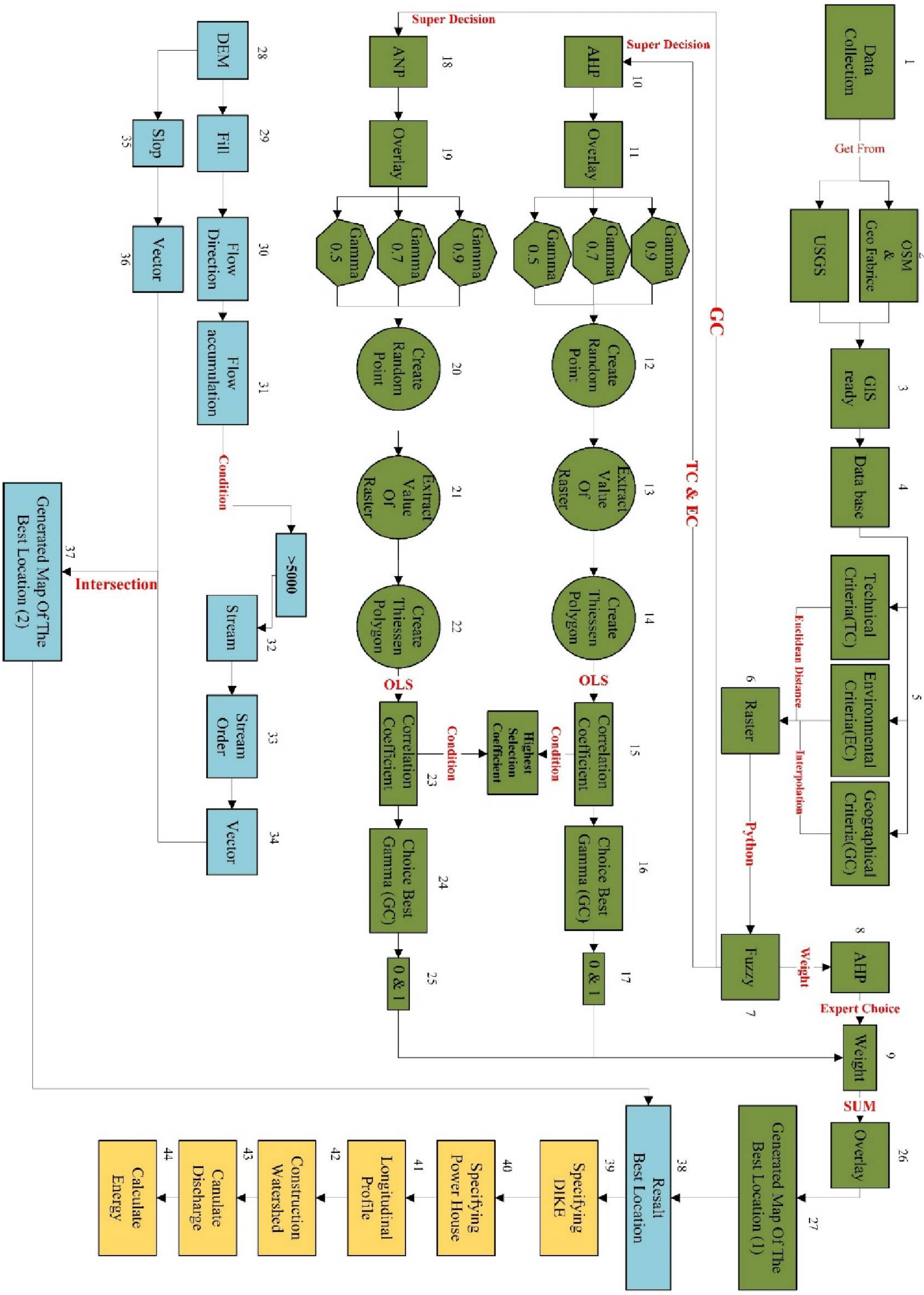


Figure 2. Flowchart of methods used in research

3-1-Locating suitable sites for the construction of hydropower plants

An assessment of potential hydropower plant sites was conducted using GIS using methods such as ANP-AHP/Fussy. Taking into account the complications of the region, data is collected and categorized into three main criteria and twelve sub-criteria (Table 4). Using GIS, information is prepared as rasters and stored in the database (Figure3). Fuzzyification is performed in the Python environment in order to unify the data and prevent large amounts of data. In fuzzy logic methods, values of variables are described by linguistic expressions that are consistent with expert judgments.

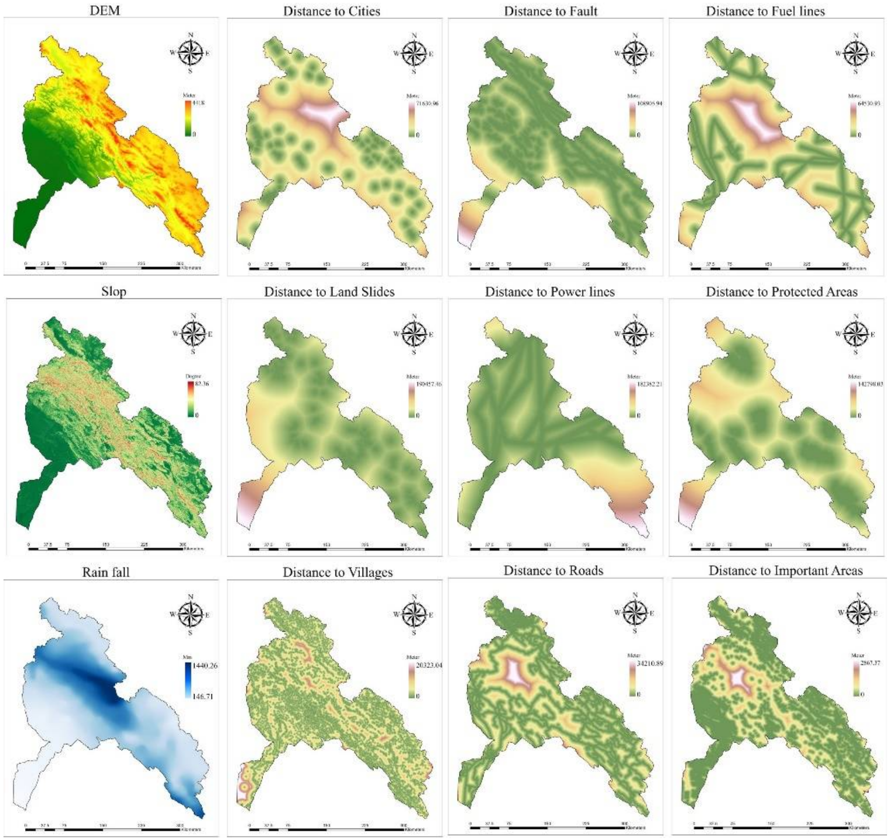


Figure 3. Raster map applied for fuzzification

Furthermore, this methodology is capable of mimicking human reasoning and thought [23]. Hence, it is capable of capturing dynamic system behaviors as well as uncertainties. As a fuzzy set, A can be described as:

$$A = \{(x_1, \mu_1); (x_2, \mu_2); (x_3, \mu_4) \ldots.\} \quad (1)$$

x is the numerical range of the membership function, which ranges from 0 to 1. To determine the numerical limits, the previous models in the same area were calibrated using the to see from the study area. Several points have been suggested by the Iranian Ministry of Energy in several studies, most of which are located at an inappropriate distance from the region's tolls. Different criteria can be defined by a fuzzy set as follows:

$$DEM\ (m) = \{((0,2000), 1); ((2000,3000), 0 < \mu < 1)\}$$

$$Slope\ (degree) = \{((0,5), 0); ((5,30), 0 < \mu < 1); ((30,40), 1); ((40,50), 0 < \mu < 1)\}$$

$$Rainfall\ (mm) = \{((0,300), 0); ((300,600), 0 < \mu < 1); ((x > 600), 1)\}$$

$$Distance\ to\ cities\ (km) = \{((0,2), 0); ((2,5), 0 < \mu < 1); ((5,10), 1); ((10,20), 0 < \mu < 1)\}$$

$$Distance\ to\ landslides\ (km) = \{((0,2), 0); ((2,4), 0 < \mu < 1); ((x > 4), 1)\}$$

$$Distance\ to\ vilages\ (km) = \{((0,0.5), 0); ((0.5,1), 0 < \mu < 1); ((1,5), 1); ((5,10), 0 < \mu < 1)\}$$

$$Distance\ to\ faults\ (km) = \{((0,2), 0); ((2,4), 0 < \mu < 1); ((x > 4), 1)\}$$

$$Distance\ to\ power\ lines\ (km) = \{((0,5), 1); ((5,10), 0 < \mu < 1)\}$$

$$Distance\ to\ roads\ (km) = \{((0,0.2), 0); ((0.2,4), 0 < \mu < 1); ((4,5), 1); ((5,10), 0 < \mu < 1)\}$$

$$Distance\ to\ fuel\ lines\ (km) = \{((0,0.5),0);((0.5,1),0<\mu<1);((x>1),1)\}$$

$$Distance\ to\ protected\ areas\ (km) = \{((0,1),0);((1,3),0<\mu<1);((x>3),1)\}$$

$$Distance\ to\ important\ areas\ (km) = \{((0,0.5),0);((0.5,1),0<\mu<1);((x>1),1)\}$$

The raster calculator tool in ArcGIS Pro can be used to generate fuzzy maps through the membership function in raster data. Fuzzy maps are shown in Figure 4.

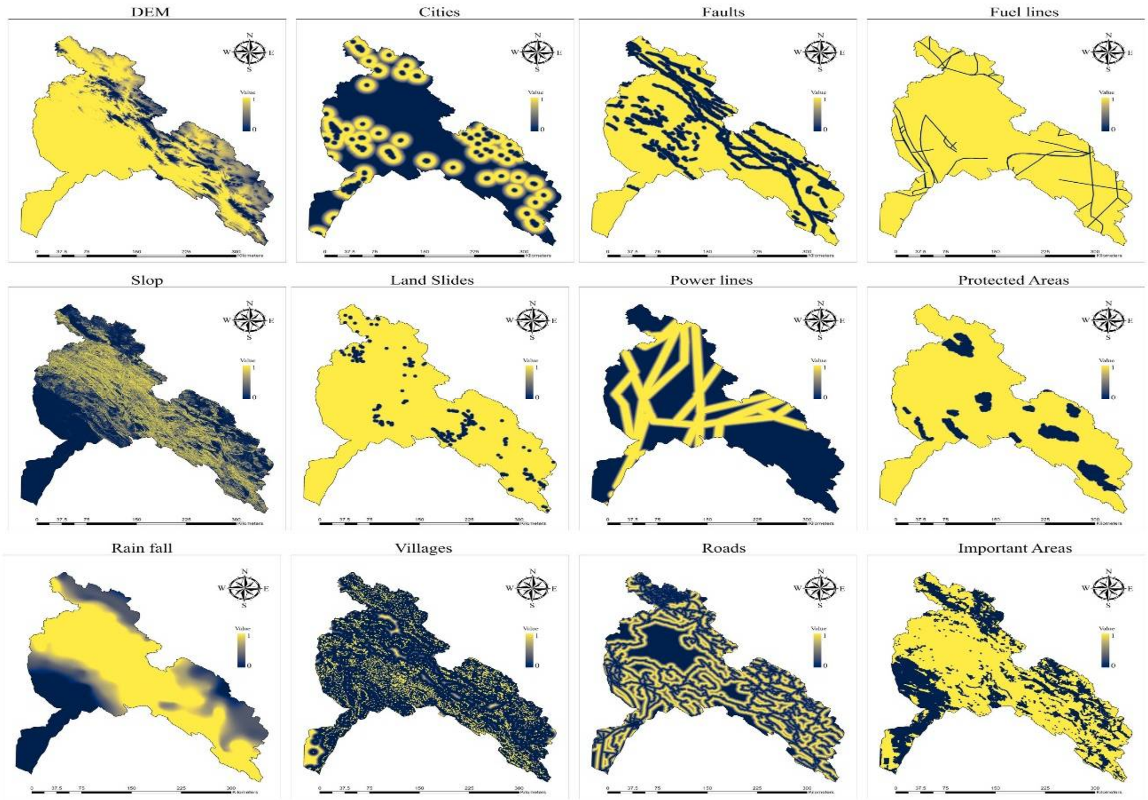


Figure 4. Fuzzy maps obtained

As soon as the data is ready, an AHP/ANP weighting process is performed. An AHP is applied to three main criteria and AHP-ANP is applied to 12 sub-criteria. Despite the simplicity of the calculations of the AHP method, the ANP matrix also calculates the internal relationships between the sub-criteria. Generally, the weight matrix of sub-criteria that have no special relationship to one another, such as sub-criteria related to the main technical and environmental criteria, is calculated utilizing the AHP method. Using the ANP method, sub-criteria related to the main geographic criteria is determined by considering their internal relationships. In addition, the weight matrix derived from the previous step (AHP for the three main criteria) is multiplied in the fuzzy layers before the data is entered into the GIS system. The AHP-ANP methods for the main criteria and sub-criteria are shown in Figure5.

3-2-AHP method

Intangible criteria are measured using AHPs and ANPs proposed by Saaty[27-30]. In Saaty's Fundamental Scale, a ratio scale is used to rate the preferences of decision-makers (Table 1) [28].

To determine the weightening for the three stages of the main criteria and sub-criteria, the fundamental scale is shown in Table 2.

1. complex decision-making problems can be broken down into subproblems (criteria, alternatives, etc.) within the hierarchy. A hierarchy structure starts with the objective at the top, then defines alternatives, and finally decides between them.

2. The relative significance of all alternatives at all levels can be determined by decomposing the problem into layers and

comparing them pairwise. This process is done as follows:

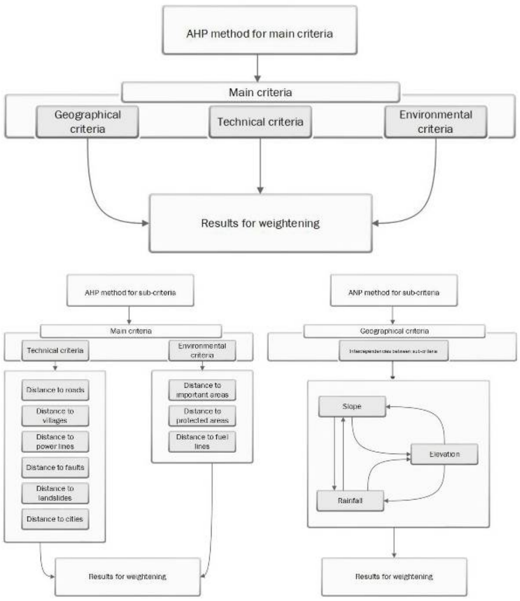


Figure 5. AHP-ANP methods for weighting main criteria and sub-criteria

2.1. By distinguishing the attributes of the measured material, relative weights can be calculated in AHP.

With c=cj (where j=1,2,...,n) as the set criteria, the pair-wise assessment's effect on n criteria can be summarized in (n × n) valuation matrix A. As a function of aij (where i,j=1,2,...,n), j indicates the significance of aspect i.

$$A = \begin{bmatrix} 1 & a_{12} & - & a_{1n} \\ a_{21} & 1 & - & a_{2n} \\ - & - & - & - \\ a_{n1} & a_{n2} & - & 1 \end{bmatrix}, a_{ji} = \frac{1}{a_{ij}}, \quad i,j = 1, \dots, n \tag{2}$$

Table1. Satay's Fundamental Scale

Intensity importance	definition
1	equal importance/preference
2	weak
3	moderate importance/preference
4	moderate plus
5	strong importance/preference
6	strong plus
7	very strong or demonstrated
8	very, very strong
9	extreme importance/preference

Table 2. Fundamental scale for all criteria

Fundamental Scale for Main Criteria (GC/TC/EC) -------> AHP																				
Environmental criteria	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	Geographical criteria
Environmental criteria	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	Technical criteria
Geographical criteria	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	Technical criteria
Fundamental Scale for sub-Criteria (TC/EC) -------> AHP																				
Distance to cities	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	Distance to land slides
Distance to cities	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	Distance to powerlines
Distance to cities	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	Distance to villages
Distance to cities	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	Distance to faults
Distance to cities	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	Distance to roads
Distance to land slides	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	>=9.5	Distance to powerlines
Distance to land slides	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	>=9.5	Distance to villages
Distance to land slides	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	Distance to faults
Distance to land slides	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	>=9.5	Distance to roads
Distance to powerlines	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	Distance to vilages
Distance to powerlines	>=9.5	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	>=9.5	Distance to faults
Distance to powerlines	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	Distance to roads
Distance to villages	>=9.5	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	Distance to faults
Distance to villages	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	Distance to roads
Distance to faults	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	>=9.5	Distance to roads
Distance to Fuel lines	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	Distance to important Areas
Distance to Fuel lines	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	Distance to protected Areas
Distance to important Areas	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	Distance to protected Areas
Fundamental Scale for sub-Criteria (GC) -------> ANP																				
Elevation	>=9.5	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	>=9.5	Rainfall
Elevation	>=9.5	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	>=9.5	Slop
Rainfall	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	>=9.5	Slop

2.2. Each element is normalized relative weighted using the geometric mean in the comparison matrix.

$$GM = \{a_{i1} * a_{i2} * a_{i3} * \dots * a_{ij}\}^{\frac{1}{n}} \tag{3}$$

2.3. A matrix X denotes a column vector with n dimensions. $X = A * W$, where:

$$W = [W_1, W_2, W_3, \dots, W_N]^T \tag{4}$$

$$X = A * W = \begin{bmatrix} 1 & a_{12} & - & a_{1n} \\ a_{21} & 1 & - & a_{2n} \\ - & - & - & - \\ a_{n1} & a_{n2} & - & 1 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ - \\ W_n \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} \tag{5}$$

$$CV_i = \frac{c_i}{W_i} \quad (6)$$

2.4. A consistency value (CV) is calculated on the basis of a vector representing a group of alternatives.

2.5. Finding the biggest eigenvalue λ_{max}.

2.6. Determine the consistency index (CI), as follows.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (7)$$

The smaller the CI value, the smaller the deviation from consistency. There is a direct correlation between the excellence of the results and the consistency of the AHP judgments.

Table 3 shows the random index (RI) used in decision-making.

Table 3. Random index (RI) values

Attributes	RI
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.4
9	1.45
10	1.49

2.7. There is a consistency ratio (CR) indicated as follows:

$$CR = \frac{CI}{RI} \quad (8)$$

A CR value less than 0.1 is accepted, and if it increases, the process is repeated. The tool is used to evaluate the consistency and hierarchy of decision-makers.

3. To convince, it must be shown that the pair-wise comparison to satisfy each attribute has been completed more effectively.

3-3-ANP method

The general framework provided by ANP allows the theory to be applied to decision-making without assumptions regarding the independence of higher-level elements from lower-level elements[31, 32]. ANP is a general form of analytical hierarchy process, which has been used to select projects, plan products, make strategic decisions, and optimize schedules to release the limitations of hierarchical structure [33]. Unlike AHP, which represents a framework with a hierarchical, unidirectional relationship, ANP is capable of allowing complex relationships among decision levels and attributes [34].

Generally, ANP comprises four major steps:

1. Construction of models and problem structuring: Hierarchical structures are established. Models consist of goals, criteria, attributes, and alternatives, such as AHP.

2. Comparisons of pairwise elements using matrices and priority vectors: As with AHP, pairwise comparisons of elements are conducted within a matrix framework, and a local priority vector can be derived in order to estimate the relative importance of the elements under comparison.

3. Super matrix formation: A network replaces the hierarchy if the criteria are interrelated.

Alternative selection: At the conclusion of the study, the alternative with the highest overall priority should be chosen.

Weight values for different criteria and sub-criteria are shown in Table 4: After the weighting process, through gamma operators, environmental, technical, and geographical sub-criteria are overlayed. The gamma operator is used because it modifies fuzzy sum and fuzzy product. Environmental and technical sub-criteria show a map and geographical sub-criteria also show a different map. The best gamma operator was selected based on the correlation between the data using ordinary least squares (OLS) analysis. This study analyzed three different gamma 0.9, gamma 0.7, and gamma 0.5 operators.

The two output maps obtained from the gamma operators are converted into mathematical intervals 0 and 1 to apply initial weighting (Figure 6).

$$Value_2 = \frac{(value_1 - min_1) * (max_2 - min_2)}{(max_1 - min_1) + min_2} \quad (9)$$

$Value_2$ is displayed for variables within the selected range. $value_1$ Represents the variable's value in its initial range. Initial interval minimums and maximums are min_1 and max_1 respectively, while the chosen interval minimums and maximums, min_2 and max_2.Interval selection was conducted once for a map derived from AHP environmental and technical criteria, and once for a map derived from ANP geographical criteria.

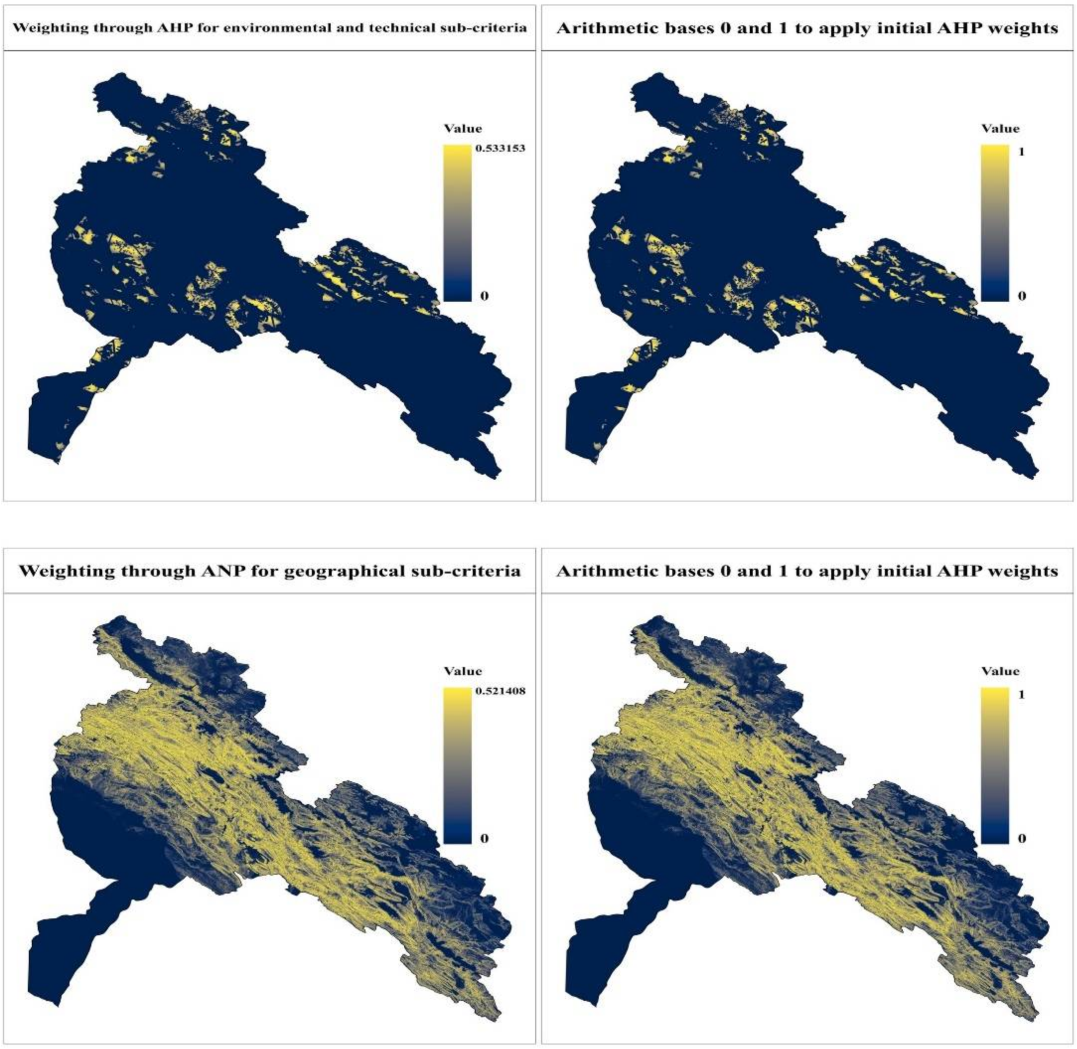


Figure 6. AHP method for TC/EC sub-criteria and ANP methods for GC sub-criteria

Table 4. Different criteria and sub-criteria and calculated weight based on different methods and data-derived sources

Main Criteria	Weight (based on AHP)	Sub-criteria	Weight (based on ANP)	Weight (based on AHP)	Source
Geographical Criteria	0.57	Slop	0.59	–	–
		Rainfall	0.13	–	Meteorological Organization
		Elevation	0.28	–	USGS
Technical Criteria	0.29	Distance to roads	–	0.19	OSM
		Distance to villages	–	0.19	OSM
		Distance to power lines	–	0.17	Ministry Of Energy
		Distance to faults	–	0.03	OSM
		Distance to landslide	–	0.03	OSM
		Distance to cities	–	0.05	OSM
Environmental Criteria	0.14	Distance to fuel lines	–	0.04	Ministry Of Energy
		Distance to important area	–	0.15	OSM
		Distance to protected area	–	0.15	OSM

As a result, they are multiplied by the weighting corresponding to the main criteria taken from the AHP method (Figure 7).

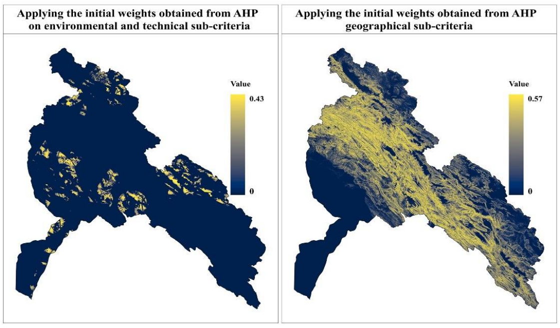


Figure 7- Applying the initial weights obtained from AHP on TC/EC sub-criteria and GC sub-criteria

The SUM operator is then used to combine the two maps obtained. A map resulting from this process shows suitable areas for hydropower plant construction. To obtain the exact points, the physiographical and river maps must be combined with the final map (Figure 8).

3-4-Identifying physiography map and rivers (Streams)

Physiography maps and rivers are derived from Digital Elevation Models (DEM). Throughout nature, water accumulates in the lowest cells of an area as it is produced by rainfall and flows over different surfaces.

Naturally, these cells represent the most promising prospects for the construction of futuristic hydroelectric power plants.

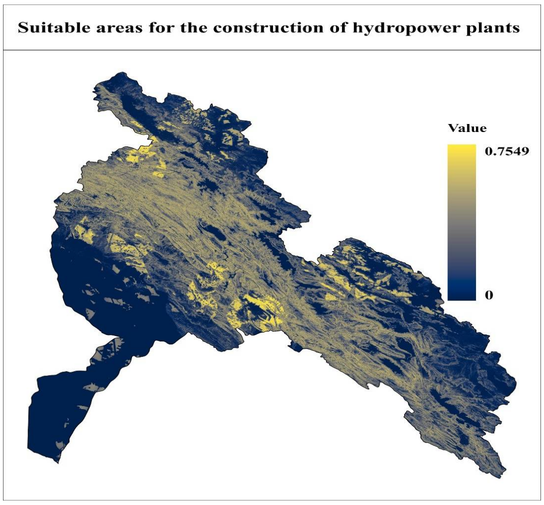


Figure 8. Result map using SUM operator

As soon as the digital height model has been rebuilt using the fill command, the Raster Calculator command is used to extract cumulative flows above 5000. The smaller the number entered for the Raster Calculator command, the more the head of the river will result (The current accumulation of the sum of discharged cells is obtained using the Flow Accumulation command). Flow hydrology is also affected by the level of rivers. Based on the stealer method and the cumulative flows obtained, rivers are graded. In addition, to determine the slop of the river, both the slop of the area and the grade of the river are crossed with each other after converting to vector mode. This method produces a map showing the slop of each river based on its level change (Figure 9). Eventually, by combining the map derived from the first part with the river (stream) map, the most appropriate location for the power plants can be determined (Figure 10).

Based on the equation below, we can calculate the amount of energy produced by SHPs:

$$P(W) = \eta . \rho . H_{net} . Q . g \quad (10)$$

In this equation, $\boldsymbol{Q}$ represents the flow rate at the dike's exit point (m^3/s), $\boldsymbol{\rho}$ represents water density, **g** represents the earth's gravity (m/s^2), $\boldsymbol{H_{net}}$ represents the height difference between the dike and the power plant (m), and $\boldsymbol{\eta}$ represents turbine efficiency.

The discharge at the dike's exit section can be calculated using Equation 11 by identifying the hydrometric stations closest to the exit points.

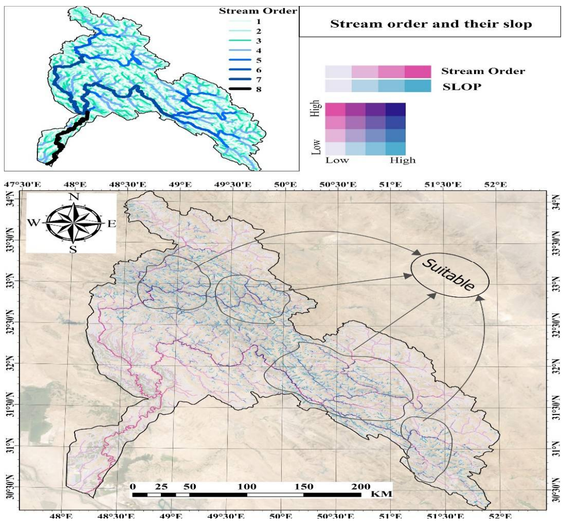


Figure 9. Intersection StreamOrder and Slop

Discharges and areas of hydrometric stations are derived from the Ministry of Energy's database.

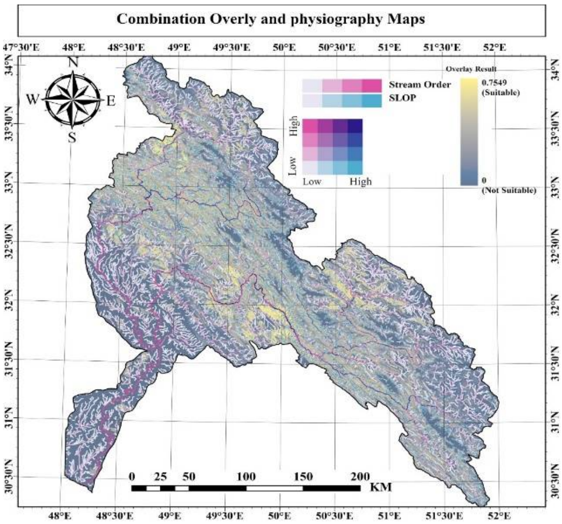


Figure 10. Combining the Result map (figure 8) and physiography map (figure 9)

Initially, the cumulative flow and direction of the flow are used to calculate the catchment area of the dike points. As a result, the discharge of the dike can be determined.

$$Q_{Dike}\left(\frac{m^3}{s}\right) = \frac{Q_{Base\ hydrometric\ station}\left(\frac{m^3}{s}\right) * A_{Dike's\ Watershed}\,(km^2)}{A_{Watershed}\,(km^2)} \quad (11)$$

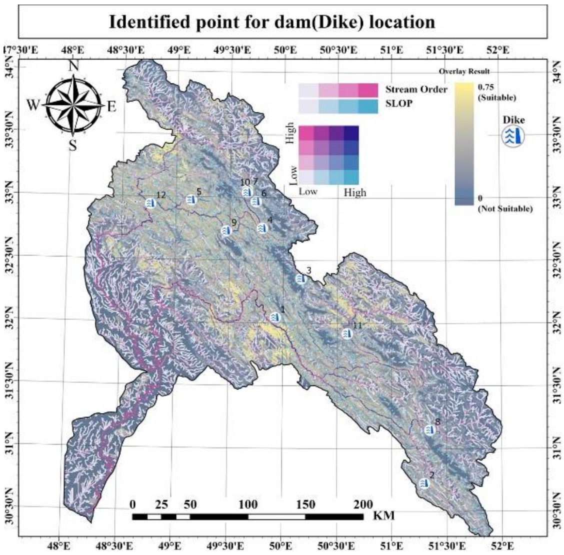
Considering the head loss in the pipe and operational considerations, H_{net} is slightly lower than H, therefore it is considered 0.9H.

According to research, a typical turbine efficiency in power plants is 0.75 of energy output. The evaporation rate also affects discharge and ultimately generator output. For cold and hot months, differences in discharge are calculated using 0.9 and 0.7 coefficients, respectively. A certain amount of river flow is considered environmental flow during both the hot and cold months of the year, according to the Montana method [35]. Producing energy and developing agriculture are incompatible. Upstream consumption and irrigation water requirements directly affect surface water requirements for energy production. Consequently, the Optimal allocation of water for hydropower generation and agriculture (more energy and food production) results in sustainable and resilient water, food, and energy systems. According to a study for optimal water allocation, domestic water demand, environmental flow requirement, industrial demand, agricultural demand, and hydropower generation were the priorities for the distribution of water, from higher to lower. To determine the energy generated in hydropower plants a coefficients of 0.9 and 0.7 have been applied for the cold and hot months, respectively [36, 37]. An electrical power plant consists of a dike that collects water during certain hours of the day and transfers it through pipes to turbines to generate electricity. Energy production in this study is calculated based on 12 hours of working time per day.

4-Results

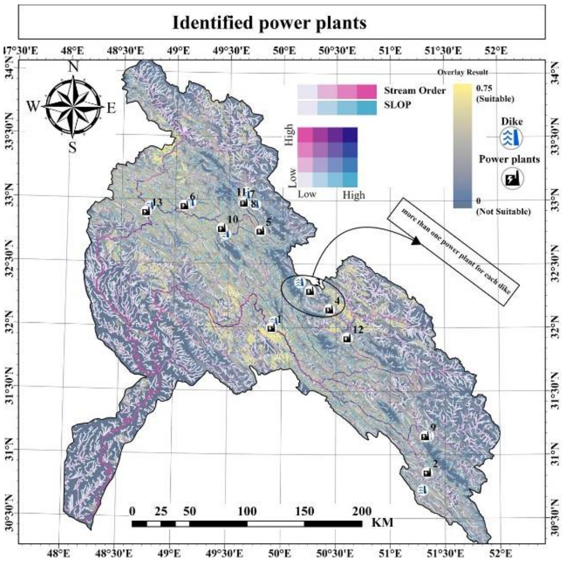
Ideally, the sites should be located on rivers with high slops and high elevations in the direction of low slops and high elevations. The low-order streams have a high slop, but a low water flow. In contrast, high-order streams have a low slop and a high water flow which should be considered when choosing streams. The optimum point for the dike should be determined by ensuring that the river level is neither too low-order nor too high-order. In this research, points with a distance of 5 km are created in all the ranked rivers and based on these points, the value of checkered cells in the first part (Suitable areas for the construction of hydropower plants map) of the study as well as the slop and height of the points are extracted (Extract Multi Values to Point). From these points, inappropriate values are removed from zoning, as well as points with significant height and slop are extracted. Consequently, 12 points (Dike) were identified (Figure 11).

Also, the points of the power plant are manually entered so that the beginning of the line is known as the dike section, and the end of the line is known as the location of the power plant. A location for the power plant should be selected along the same route as the dike but at a lower height. A dike and power plant should be located in such a way that while obtaining the desired height difference, the route selected should not be too long in light of the high construction costs. To evaluate the selected path, it is necessary to use longitudinal profiles. It is possible that there will be more than one power plant for each dike point due to the high desire for height and slop in some areas. Consequently, 13 points (Power) were identified (Figure 12). Also, the height between the dike point and the power plant can be determined in this part of the study.



ID	XUTM	YUTM	Height	Slope	Utility (overlay result)
1	398942	3545834	866	22.51	0.48
2	528362	3399086	1721	35.42	0.57
3	421493	3580198	2324	26.24	0.48
4	387771	3624727	1626	21.8	0.47
5	326153	3649966	930	23.62	0.49
6	382457	3648363	1886	29.49	0.56
7	374930	3658849	1845	26.68	0.53
8	533185	3446261	1789	42.57	0.45
9	356569	3622598	1076	43.15	0.47
10	374879	3656409	1845	30.02	0.57
11	461479	3531488	1484	27.21	0.54
12	290865	3646900	617	36.94	0.57

Figure 11. Location of identified points for dam (Dike)



Type	XUTM	YUTM	Height	Head	Slope	Utility
Dike	398942	3545834	866		22.51	0.48
Power	396421	3540521	588	278	10.79	0.32
Dike	528362	3399086	1721		35.42	0.57
Power	532268	3414237	1557	164	7.04	0.23
Dike	421493	3580198	2324		26.24	0.48
Power	430127	3572598	2217	107	12	0.3
Power	446940	3556494	1782	542	5.67	0.22
Dike	387771	3624727	1626		21.8	0.47
Power	386991	3625208	1532	94	26.41	0.53
Dike	326153	3649966	930		23.62	0.49
Power	320814	3647602	830	100	6.25	0.24
Dike	382457	3648363	1886		29.49	0.56
Power	372620	3649651	1754	132	21.38	0.46
Dike	374930	3658849	1845		26.68	0.53
Power	372147	3651004	1774	71	17.61	0.41
Dike	533185	3446261	1789		42.57	0.45
Power	530411	3445975	1675	114	32.6	0.54
Dike	356569	3622598	1076		43.15	0.47
Power	353416	3627583	964	112	15.18	0.38
Dike	374879	3656409	1845		30.02	0.57
Power	372620	3649690	1754	91	26.5	0.5
Dike	461479	3531488	1484		27.21	0.54
Power	462466	3531353	1452	32	10.83	0.32
Dike	290865	3646900	617		36.94	0.57
Power	287489	3642439	530	87	17.44	0.42

Figure 12. Location of identified points for power

Table 5. Calculated discharge for the dike points

ID	Area waterShed (Dike)	Base hydrometry area	Base hydrometry discharge	Discharge dike (m3/s)
1	54.29	25036	242.67	0.53
2	490.28	885	16.37	9.07
3	340.73	340.73	2.89	2.89
4	650.13	1210	13.03	7
5	371.75	6437	131.13	7.57
6	803.23	743	3.72	4.02
7	420.11	414	9.47	9.61
8	3485.62	3995	34.07	29.73
9	4370.77	1210	13.03	47.07
10	1106.79	1210	13.03	11.92
11	5698.48	3825	18.22	27.14
12	6412.04	6437	131.13	130.62

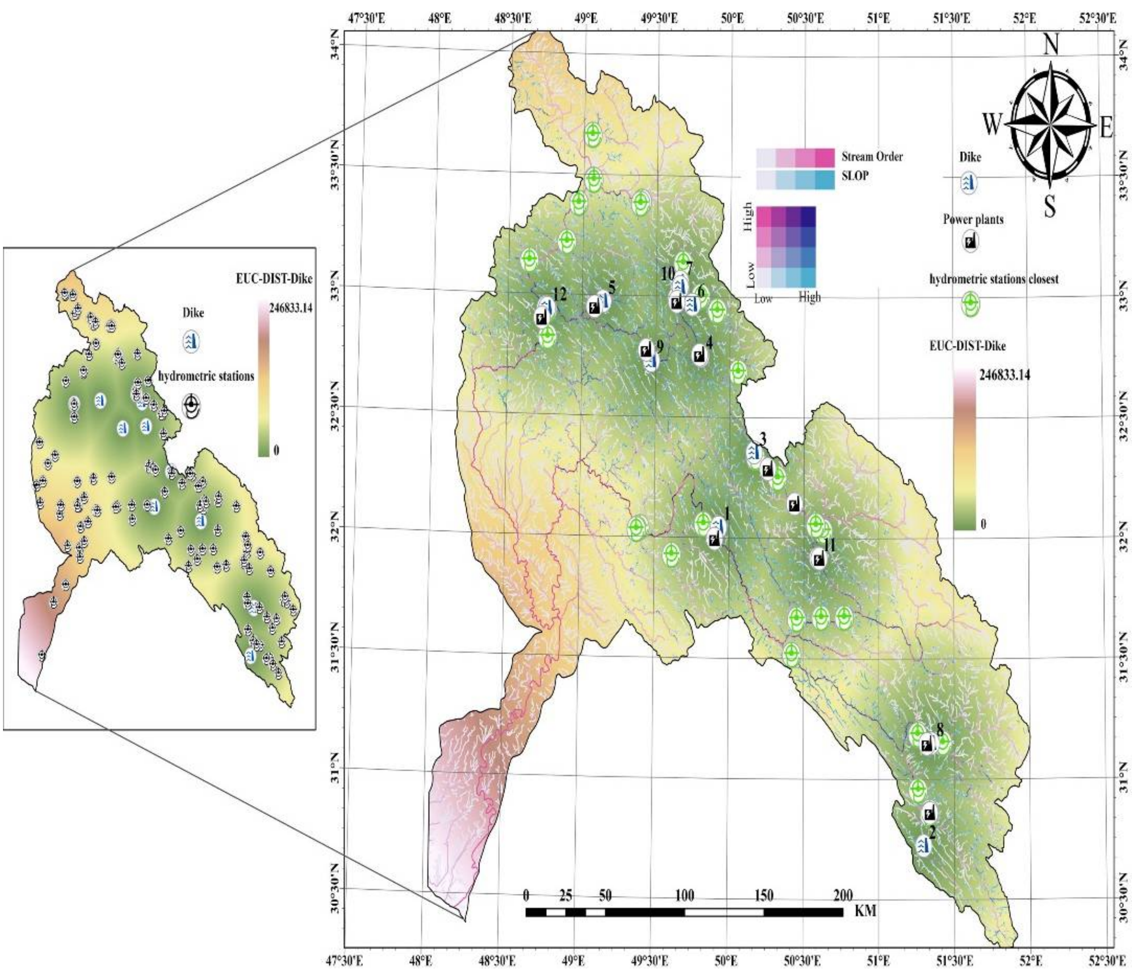
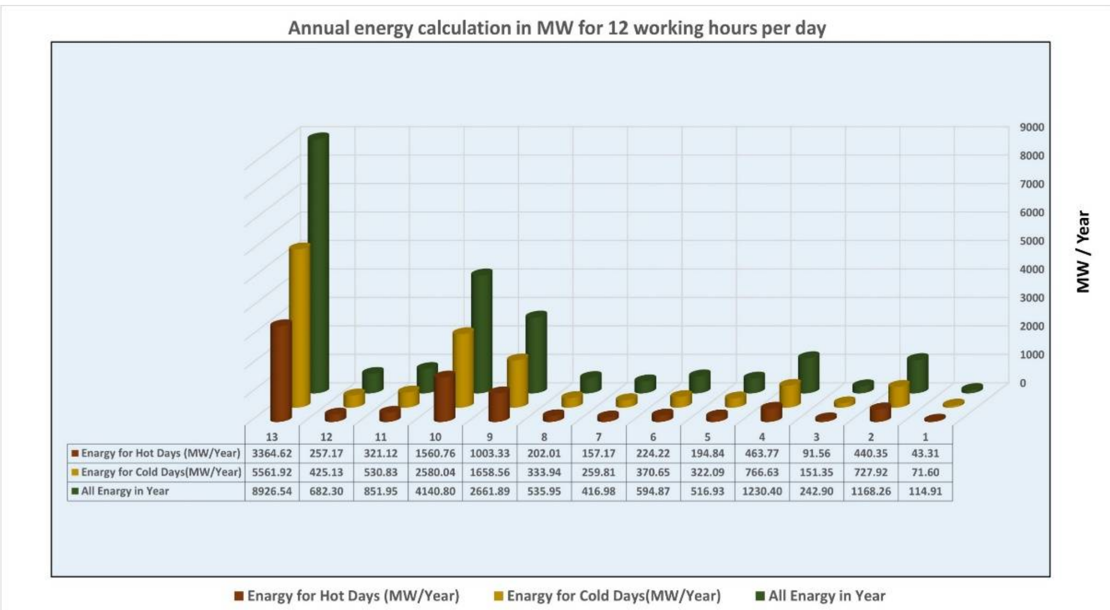


Figure 13. Identification of the nearest hydrometric stations



	13	12	11	10	9	8	7	6	5	4	3	2	1
Enargy for Hot Days (MW/Year)	3364.62	257.17	321.12	1560.76	1003.33	202.01	157.17	224.22	194.84	463.77	91.56	440.35	43.31
Enargy for Cold Days(MW/Year)	5561.92	425.13	530.83	2580.04	1658.56	333.94	259.81	370.65	322.09	766.63	151.35	727.92	71.60
All Enargy in Year	8926.54	682.30	851.95	4140.80	2661.89	535.95	416.98	594.87	516.93	1230.40	242.90	1168.26	114.91

Figure 14. Annual energy calculation in MW for12 working hours per day

Using the method of Euclidean distance, we have determined the nearest hydrometric station to calculate the discharge at the dike location (Figure 13). Using formula 2, the calculated discharge for the dike points (Table 5):

Utilizing the formulas in the third part, the energy from power plants can be described as follows: Furthermore, two periods of 182.5 days have been considered for hot and cold days throughout the year. On the basis of these two time periods, calculations have also been made taking into account environmental discharge and evaporation. Assuming twelve working hours per day for one year, the energy calculated for the 13 located power plants is according to Figure 14.

5-Conclusion

Based on the results obtained in this study by using the AHP method, it was concluded that the weights found from three geographical, technical, and biological criteria are respectively 0.57, 0.29, and 0.14. Using the AHP method, there are nine layers that cover technical and environmental criteria, and there are no internal connections between the layers. Moreover, the ANP method incorporates three layers related to geographical criteria and there is internal connection between the layers. As a result of applying the fuzzy method to 12 layers and applying the 0.9 gamma analyzer to it, a zoning that is most appropriate to the area on the eastern side was determined. Additionally, it has been determined that 12 suitable dike sites can be found when combining the zoning map with the physiographic map. Among the 12 power stations that have been identified, there are 13 power plants. This is due to the fact that the location of one of the dikes may be perfectly suited to the construction of two power plants due to its favorable location. It should be noted that an energy calculation was also made using the discharge from the hydrometric station which is closest to the dike for 12 hours per day for one year in conjunction with the construction of the water basins for each of the 12 dike points in order to calculate the energy production.

From this field, a total of 22,084.69 megawatts of electricity has been able to be generated each year. It has been estimated that this amount of energy can reduce greenhouse gas emissions by 5.8 tons a year, based on the latest energy balance sheet released by Iran.

As seen in this study, a hybrid approach was used to locate small hydroelectric power plants, but this approach can also be applied to other renewable energy plants such as solar and wind power plants. Furthermore, according to the selected criteria in the technical and environmental sectors, the construction costs of power plants are negligible and the environmental damage caused by their construction is minimal.

Data availability statement

It is possible to obtain processed data on demand: (hossein.joulaei98@gmail.com)

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