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Identification of suitable areas for small water storage reservoir construction using various decision-making methods (case study: Zanjan Province)

Hassan Ojaghlou[1]✉, Zahra Alimohammadi[1], and Zahra Amiri Abdobochali[1]

[1]Department of Water Science and Engineering, Faculty of Agriculture, University of Zanjan, Zanjan, Iran

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***Corresponding author**
H. Ojaghlou
✉ ojaghlou@znu.ac.ir

ABSTRACT

Location identification for the construction of small water storage reservoirs is currently receiving significant attention, particularly in regions experiencing reduced precipitation, such as arid and semi-arid areas. This study utilized various Multi-Criteria Decision-Making (MCDM) techniques, including the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), and Boolean logic, to pinpoint the suitable areas for placing small water storage reservoirs (SWSRs). Criteria such as distance to water resources, water salinity, topography, land use, geological attributes, road accessibility, and climatic conditions were considered. The zoning maps of criteria were prepared, and after conducting pairwise comparisons and determining their weight coefficients, the final land classification map was produced. The findings revealed that access to water resources emerged as the most critical criterion. The location maps generated through the AHP and ANP methods showed that 50.2% and 51.7% of the total study area were deemed suitable, respectively, with 18.2% and 16% classified as unsuitable. In comparison, the Boolean method indicated that 5.6% of the area was suitable for constructing SWSRs, while 94.4% was unsuitable. Finally, AHP and ANP techniques are suggested for determining the appropriate locations for constructing SWSRs.

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1. Introduction

Water resources in arid and semi-arid regions like Iran are scarce, making it vital to implement scientific approaches for their optimal extraction and use. The analysis of water resource systems consider various environmental, social, and economic factors (Zhang et al., 2015). In various regions of Iran, rainfall is distributed unevenly, both in space and time, with much of it not coinciding with the irrigation season. Groundwater is a valuable resource for agriculture, as it provides a reliable source of irrigation water even during periods of drought. However, excessive extraction of groundwater can lead to declining water levels, which may adversely affect the sustainability of this vital resource and the health of aquatic ecosystems. In this context, surface water resources are significant and viable water resources (Jozaghi et al., 2018). To address the impending water shortage, farmers are exploring alternative strategies for sourcing water from surface water resources. Consequently, the construction of SWSRs seems to be the most effective solution (Alkaradaghi et al., 2022). SWSRs help manage water supply during dry periods and mitigate flood damage by regulating surface runoff and decreasing peak flood flows (Hagos et al., 2022). These small water structures are built to collect surface runoff to meet the irrigation needs of agricultural fields during periods of water scarcity (Yasser et al., 2013). Developing a decision support system can help establish criteria and identify suitable locations for constructing SWSRs. Scientists have reported promising results from the application of MCDM techniques integrated with Geographic Information Systems (GIS) for identifying and selecting suitable sites for water harvesting (Xu et al., 2021). These techniques designed to evaluate a variety of criteria and employed to identify the most suitable sites for constricting SWSRs. By integrating MCDM with GIS, we can analyze the combination of various criteria and parameters to produce a single outcome. (Ahmad et al., 2024; Raaj et al., 2022). A key consideration is determining which factors are more important than others, as this will influence how other criteria are prioritized during the decision-making process (Saaty, 1987). Three of the most widely used MCDM techniques are known as AHP, ANP and Boolean logic (Cheng & Thompson, 2016; Rahman et al., 2015; Tsolaki-Fiaka et al., 2018). The AHP is considered as one of the most comprehensive MCDM technique that has been used in variety of fields. This assessment is performed via a series of pairwise comparisons, often in the form of a pairwise comparison chart, also known as a pairwise comparison table or matrix (Russo & Camanho, 2015). This approach offers two main advantages: it considers both quantitative and qualitative factors in addressing the issue, and it facilitates the analysis of complex problems by organizing these factors hierarchically (Saaty, 2004). The ANP provides a comprehensive framework for addressing decisions related to the interdependent relationships among various decision levels and attributes, whereas the AHP does not facilitate the measurement of potential dependencies among factors (Chen et al., 2019; Yüksel & Dagˇdeviren, 2007). In Boolean logic, input values are represented as either 0 or 1. When applied to site selection, a primary limitation of Boolean logic is its inability to prioritize regions with varying degrees of suitability (Hafeznia et al., 2017). A little research has been conducted to identify suitable locations for constructing SWSRs by utilizing prioritization techniques (Hagos et al., 2022; Jozaghi et al., 2018; Karakuş & Yıldız, 2022; Rane et al., 2023), While most studies have focused on locating underground dams (Dortaj et al., 2020; Talebi et al., 2019). Zare Bidaki et al. (2021) employed the AHP method to identify regions suitable for constructing short earthen dams within the Beheshtabad watershed. The authors considered various criteria, including geomorphology, topography, availability of financial resources, land use, proximity to groundwater, distance from roads, and soil depth. They indicated that geomorphological and geological factors were the most significant among those evaluated. Recent advancements in remote sensing (RS), geographic information systems (GIS), and decision-making processes have provided valuable tools for mapping the dam site suitability (Raaj et al., 2022). This study is a piece of applied research focused on identifying optimal locations for constructing SWSRs in Zanjan province. To achieve this, it employs three distinct methods: AHP, ANP, and Boolean logic. Several factors were examined, such as accessibility to water resources, water slainity, topography, land use type, climate, distance from faults, geological formations, and road accessibility. Ultimately, the zoning map of Zanjan province was categorized and evaluated based on the suitability for constricting SWSRs.

2. Materials and Methods

2.1 Study area

Zanjan province covers an area of 22,164 km² and has a cold semi-arid climate. It is situated in the northwestern part of the country, positioned between longitudes 46.47 to 46.49 and latitudes 35.59 to 23.37 degrees (Fig.1). Surface water sources are essential for sustaining life and supporting ecosystems in Zanjan Province. These sources, including rivers and springs, account for a significant portion of agricultural activities. As a result of the decline in groundwater levels in recent years, farmers will need to collect and provide the water required for agriculture from surface water sources. The creation of SWSRs not only retains surface water during dry periods but also offers multiple benefits for the surrounding ecosystem and community. These small reservoirs are typically constructed as storage pools using natural materials, often made of clay and covered with a geomembrane. The capacity of these reservoirs is designed and constructed to hold between 100,000 and 500,000 m³.

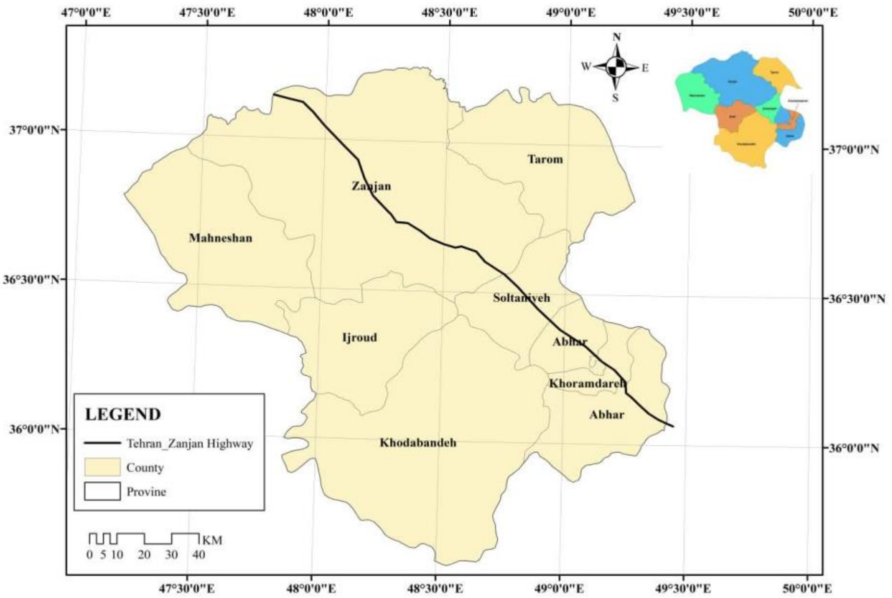
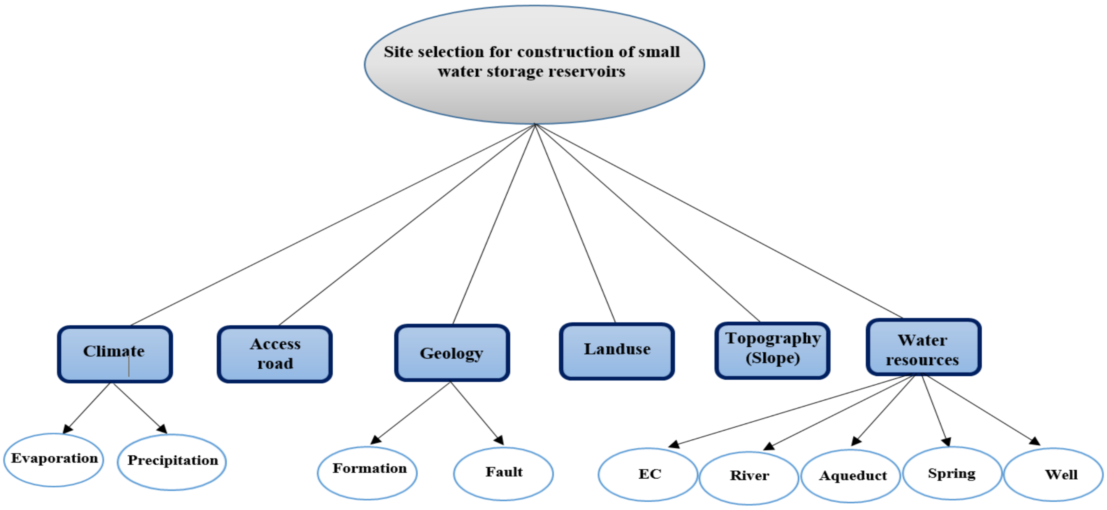


Fig. 1 The geographic location of the study area, Zanjan Provinc, Iran

2.2. AHP method

Accurate and timely decisions are crucial for achieving objectives, highlighting the need for a strong method to assist researchers. One of the most effective techniques is AHP, originally developed by Saaty in 1987 (Saaty, 1987). The AHP process consists of three key components: identifying a hierarchy of objectives, criteria and alternatives; conducting pairwise comparisons of the criteria; and integrating the results from these comparisons to determine the relative importance across all levels of the hierarchy (Omolabi & Fagbohun, 2019). Identifying these components and their interconnections ultimately leads to developing a hierarchical framework. This study focuses on finding appropriate locations for constructing SWSRs. The criteria encompass the accessibility and quality of water resources, climate, topography, road accessibility, land use, and geology, with each category containing its sub-criteria. A decision tree was created to identify the suitable treatment decision process, utilizing priorities established by the AHP method (Fig. 2).

Fig. 2 The structure of the hierarchical analysis process to identify suitable area for the construction of SWSRs



Once the decision tree is completed, pairwise criteria comparisons are conducted, and the results are analyzed. In the pairwise comparison matrix, each criterion is assigned a value between 1 and 9, where 1 indicates equal importance among the criteria, and 9 signifies the absolute importance of one criterion over another, as outlined in Table 1 (Saaty, 2004). When comparing all possible pairs of criteria, the weight of each criterion, which is later used in the suitability analysis, is calculated.

Table 1 The scale of paired comparison of criteria (Noorollahi et al., 2022)

Definition	Score
Equally preferred	1
Moderately preferred	3
Strongly preferred	5
Very strongly preferred	7
Absolutely preferred	9
Intermediate situation	2, 4, 6, 8

2.3 ANP method

The analytic network process was developed by Saaty in 1996 (Saaty, 1996). The ANP is a multi-criteria decision-making approach that closely resembles the AHP method. The nodes within this network are defined by the user's objectives, criteria, and choices, while the directional vectors connecting these nodes represent the influence and relationships among them. Like the AHP method, the ANP technique determines the weight of criteria and the attractiveness of options by gathering people's opinions and employing pairwise comparisons. Calculation method in the ANP approach involves inserting the weights derived from pairwise comparisons into the supermatrix. This matrix illustrates the relationships among network components, derived from specific vectors representing these relationships. This matrix can be divided into different blocks, with each block reflecting the weights determined from the pairwise comparisons of the rows (such as indicators) with the columns (like options or indicators). The ANP and AHP methods share similar analytical principles. Both techniques rely on pairwise comparisons as their foundational analysis method. Consequently, the similarities and differences between the two methods can be examined regarding their application and how preferences are expressed. Both approaches were developed to establish the priority of elements, relying on pairwise comparisons as the foundation for determining these priorities. In the AHP approach, each component is assessed relative to its immediate predecessor. In contrast, the ANP model allows for more flexibility, with comparisons influenced by the model’s design and the designer’s perspective. Furthermore, the final weights in the AHP model are calculated by multiplying the importance of each element within its respective cluster. Meanwhile, the ANP determines the final weights through a more complex process that involves calculating a supermatrix (Chen et al., 2019).

2.4 Boolean logic method

Boolean logic method employs simple logic and calculations, operates quickly and has been utilized in numerous studies. This MCDM technique was created and advanced in the 1800s, aiding in simplifying the understanding of intricate statements and propositions (Cheng & Thompson, 2016). Boolean modeling involves the logical combination of binary maps that result from applying conditional operators. In this framework, the basis of giving weight is zero and one, indicating whether it is suitable or unsuitable, respectively (Updegrove et al., 2016). If one of the criteria has received a code of 0 for a region, that region is classified as a non-suitable area, regardless of the values of the other criteria. Ultimately, the land zoning map is categorized into two parts: suitable areas and unsuitable areas.

2.5 Preparation of spatial databases

The values of some criteria are quantitative, while others are qualitative. Therefore, it is essential to normalize these values first. To achieve this, raster layer for each sub-criterion was created using the interpolation toolset in ArcGIS software. Subsequently, all the prepared layers underwent a reclassification process to assign new scores. The data on the accessibility of water resources, including the locations of wells, springs, aqueducts, and rivers, was obtained from the Zanjan Water District Company. Buffer layers were generated around the water resources to illustrate the distances from water resources. The quality of water resources was assessed based on salinity, and different salinity levels were rated. For this purpose, the irrigation water quality classification guide provided by the Food and Agriculture Organization (FAO) was used (Ayers & Westcot, 1985). The scoring for each sub-criterion of the AHP, ANP, and Boolean methods was conducted based on the information presented in Table 2.

Table 2 Re-scoring criteria in AHP, ANP and Boolean methods (FAO 1985)

Boolean		AHP and ANP		Sub-Criteria	Criteria
Score	Value	Score	Value		
0	<500	6-9	>1000	Distance from the well (m)	Water Resources
1	>500	1-5	<1000		
1	<2000	5-9	<2000	Distance from the spring (m)	
0	>2000	1-4	>2000		
1	<2000	5-9	<2000	Distance from the aqueduct (m)	
0	>2000	1-4	>2000		
1	<2000	4-9	<2000	Distance from the river (m)	
0	>2000	1	>2000		
1	<2000	3-9	<4000	Electrical conductivity (μmhos.cm^{-1})	
0	>2000	1-2	>4000		
1	<15	4-9	<30	Slope (%)	Topography
0	>15	1-2	>30		
1	Irrigated Land-Garden-Surface water reserves	1	Uncultivated and Salty-Residential-Industrial-Urban		Land use
		2	Pasture-Forest-Wet lands and Greenbelt		
		5	Rain-fed Land		
0	Other Landuse	9	Irrigated Land-Garden-Surface water reserves		
0	<2	1	<2	Distance from the fault (km)	Geology
1	>2	9	>2		
1	Limestone-Igneous rock-Marlstone-Sandstone-Alluvial-Granite	5	Marlstone-Sandstone-Alluvial-Granite	Formation	
0	Others	7	Limestone-Igneous rock		
1	<2000	6-9	<2000	Distance from road (m)	Accessibility
0	>2000	1	>2000		
0	<200	6-9	>250	Precipitation (m)	Climate
1	>200	5	<250		
1	<2000	6-9	<2000	Evaporation (mm)	
0	>2000	3-5	>2000		

A Digital Elevation Model (DEM) with a scale of 1:25,000 was applied for the examination of topographic factor. Gentle slopes were deemed the most suitable, while steep slopes were considered the least favorable for building SWSRs. In order to investigate the impact of faults on the optimal placement of SWSRs, a 2 km buffer zone around the faults was created and deemed an acceptable limit for the placement of tanks. In assessing geological structure, areas with hard formation received a high rating, while areas with unstable materials were rated poorly. A land use map was generated for the study area. Agricultural fields, gardens, and rainfed lands were identified as appropriate locations. For the road accessibility criteria, the areas near the road receive a high score, while the score of areas decreases as the distance from the road increases. The climate criterion included two sub-criteria: average annual precipitation and evaporation. Areas with higher precipitation or lower evaporation rates received a higher score, while areas with lower precipitation or higher evaporation rates received a lower score. Rainfall and evaporation zoning maps were created using data from 7 synoptic stations, 15 evapotranspiration stations, and 24 rain gauge stations throughout Zanjan province.

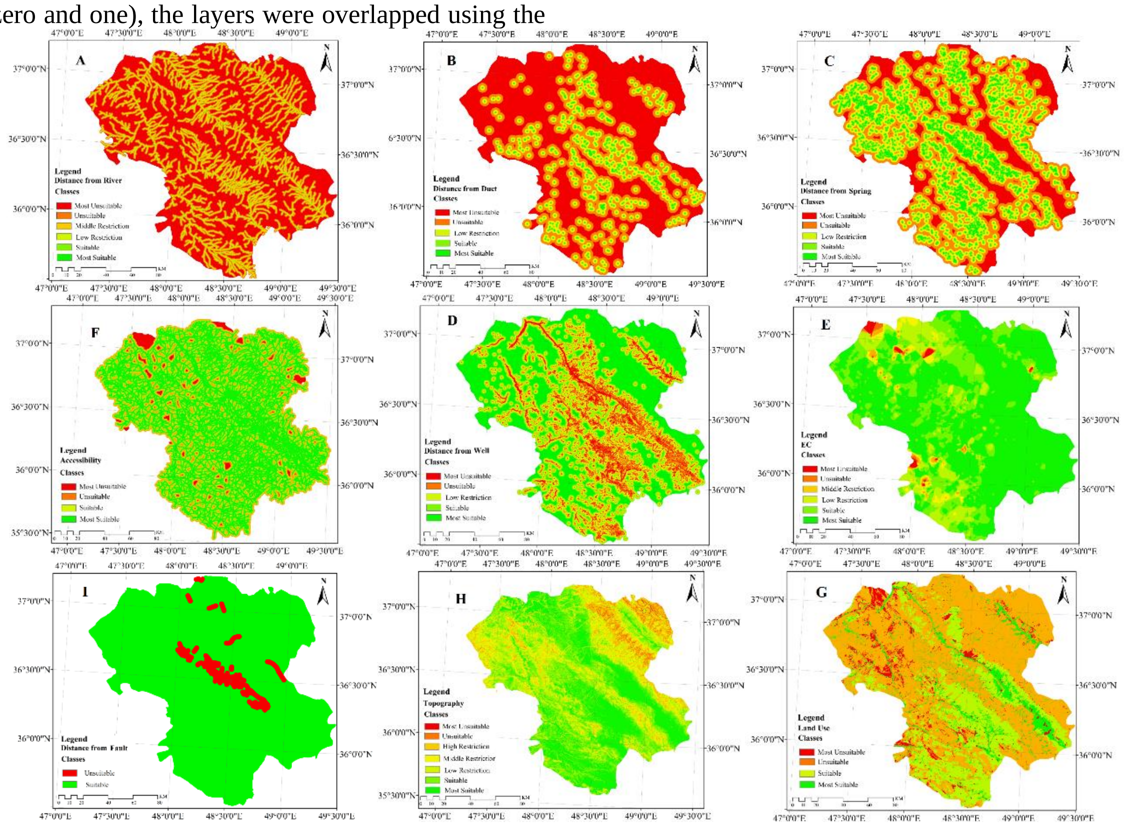
2.6 Implementation of decision-making methods

After providing scored information layers, experts assess the importance of each criterion by filling out a paired comparison matrix. For the AHP method, this is possible in ArcGIS software using the extAhp extension. After comparing all possible criteria, the weight of each criterion can be calculated. This task was performed for the ANP method utilizing Super Decision software. The weight for each criterion is calculated by geometrically averaging the scores from each row of the pairwise comparison table and subsequently normalizing the results. Possible inconsistency in the pairwise comparison was examined by the Consistency Indices (CI). If the mentioned index value is below 0.1, the resulting weights will be considered acceptable. Ultimately, the classified land map was created using the derived weights on the zoning maps corresponding to each criterion and summing the pixel values. In the Boolean method, after generating scored layers (with values of zero and one), the layers were overlapped using the raster calculator tools to identify suitable areas for constructing SWSRs.

3. Results and Discussion

3.1 Zoning maps of criteria

Fig. 3 displays zoning maps of 12 sub-criteria analyzed, which encompass five sub-criteria of water resources, two related to geology, two concerning climate, land use, topography, and road accessibility. Zoning maps were categorized according to the scores obtained. Zoning maps illustrating water resource accessibility and salinity were created using the prepared geodatabases. The zoning maps of geological factors were achieved by the polygon data regarding formation types and faults within the province, along with establishing boundaries at specified distances. The zoning maps of climatic sub-criteria were developed using data from 46 meteorological stations located in the Zanjan province, Iran. Slope and land use classification maps were created using 1:25,000 scale maps. The zoning map for road accessibility was generated by establishing boundaries at various distances from the roads. An analysis of the zoning maps reveals that considering factors such as water salinity, proximity to wells, road accessibility, distance from faults, and topography (slope), there are generally no significant limitations for constructing SWSRs in most areas of Zanjan province. However, in certain regions, water resources accessibility and the formation types have caused restrictions on the construction of these reservoirs. Regarding climate conditions and land use, most area of Zanjan province experience low to moderate limitations. According to the latest meteorological information, the Zanjan province has a semi-arid to Mediterranean climate, with an average annual precipitation of approximately 303 mm.



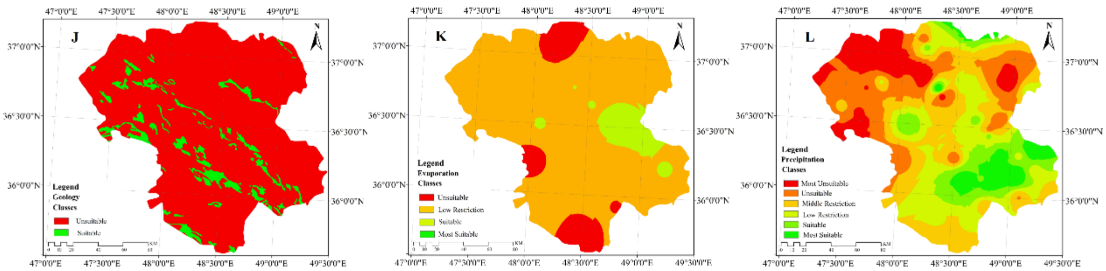


Fig. 3 The zoning maps of the criteria: a) Distance from river, b) Distance from duct, c) Distance from spring, d) Distance from well, e) Electrical conductivity, f) Road accessibility, g) Land use, h) Topography, i) Distance from fault, j) Geology, k) Evaporation, l) Precipitation

3.2 The weighting coefficients of the criteria

Following the paired comparisons of the relevant criteria, the weight coefficients for each criterion were determined to prioritize the lands for the construction of SWSRs. Table 3 displays the coefficients obtained from the AHP and ANP methods. It indicates that the water resources criterion holds the highest weight and significance in both prioritization methods. The climate criterion was the second most important factor influencing decision-making. The criteria for road accessibility and land use were nearly equal in significance, placing them in third and fourth positions, respectively. Topography and geology were assigned the least significance relative to other criteria.

Table 3 The weighting coefficients of the criteria in both the AHP and ANP methods

Method	Climate	Road Accessibility	Geology	Land use	Topography	Water Resources
AHP	0.220	0.070	0.0240	0.056	0.040	0.590
ANP	0.145	0.081	0.044	0.088	0.022	0.620

It is important to mention that certain criteria, like water resources accessibility, climate, and geology, include their sub-criteria. As a result, prior to conducting pairwise comparisons of the main criteria, pairwise comparisons were first performed on the subcriteria. A final map associated with the main criterion was then created based on the weight and significance of the subcriteria. Among the sub-criteria related to water resources accessibility, the distance from the spring and the distance from the river carried the greatest weight. In the climate criterion, the significance of precipitation relative to evaporation was emphasized. In contrast, in the geological criterion, the distance from the fault was deemed more important than the type of formation. Raaj et al. (2022) indicated that rainfall and stream order were the most significant factors influencing the dam site location. In other research, it has been found that the accessibility of water resources is the most important factor in selecting an optimal dam site (Noori et al., 2018).

3.3 Land classification maps

Suitability maps derived from the AHP and ANP methods for constructing SWSRs in Zanjan Province, Iran are presented in Fig. 4.

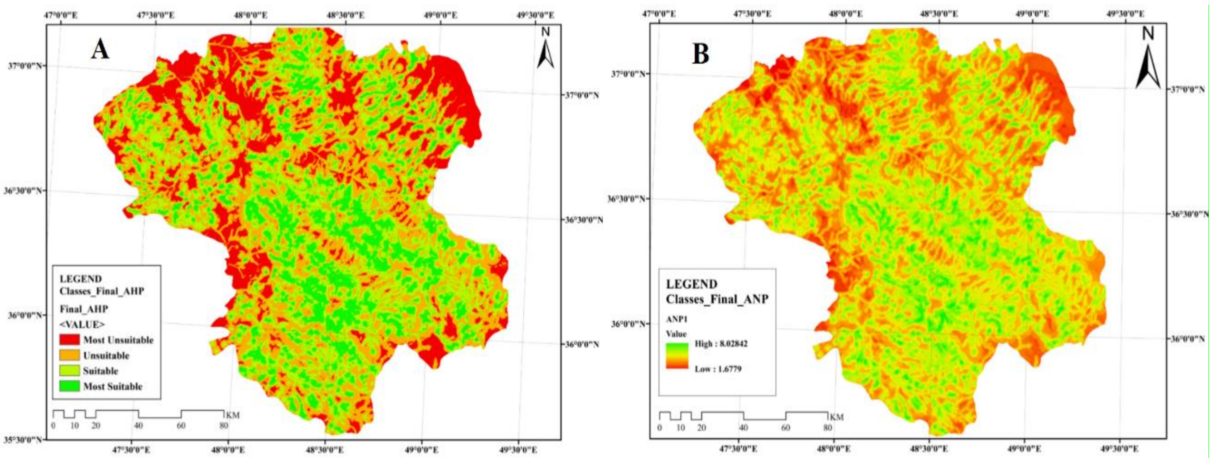


Fig. 4 Classified map of lands in terms of the construction of small water reservoirs: a) AHP and b) ANP

According to the classified maps, the central and eastern parts of Zanjan Province scored the highest, indicating these areas are most suitable for constructing SWSRs. The accessibility of water resources in these regions is favorable, which is why they are categorized as appropriate or fully appropriate on the final classification map. In addition, the rainfall in these areas is relatively high, which is another reason they are considered suitable. Analyzing the final classified maps indicates that the

AHP and ANP methods yield similar results, with no substantial differences between the classification maps produced by the two methods. Fig. 5 illustrates the land classification map created using the Boolean logic approach.

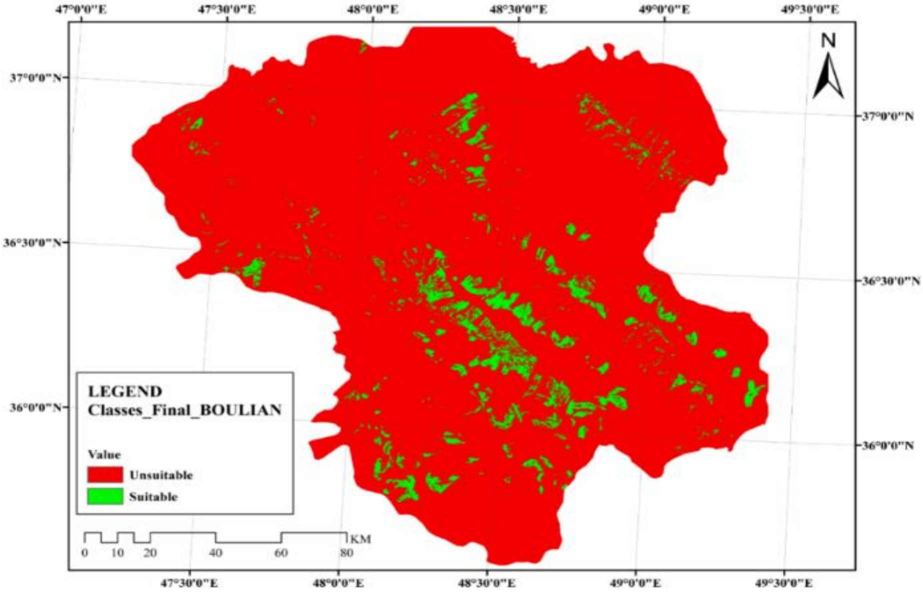


Fig. 5 Classified map of lands in terms of the construction of small water reservoirs - the Boolean method

This method categorizes land into two groups: suitable and unsuitable. Based on the results from the Boolean logic method, a large portion of the province's land is unsuitable for constructing SWSRs. As shown in Fig. 6, the land area and percentage of suitability were calculated for each method. Under the AHP method, about 50.2% of the Zanjan province was considered suitable, 31.6% faced low limitations, and 18.2% was unsuitable. The ANP method found that 51.3% of the study area was suitable or highly suitable, 32.6% faced low limitations, and 16% was unsuitable. In comparison, the Boolean logic method showed only 5.6% of the land as suitable, while 94.4% was deemed unsuitable. This suggests that Boolean logic may not be an effective method for site selection studies, such as identifying suitable locations for constructing SWSRs and other agricultural-related objectives. This method will produce a map that identifies only those areas with high scores across all criteria as suitable locations for achieving the objective. It is important to note that expert judgments are typically not absolute but rather relative; thus, the evaluation of land suitability cannot be conducted in an absolute manner.

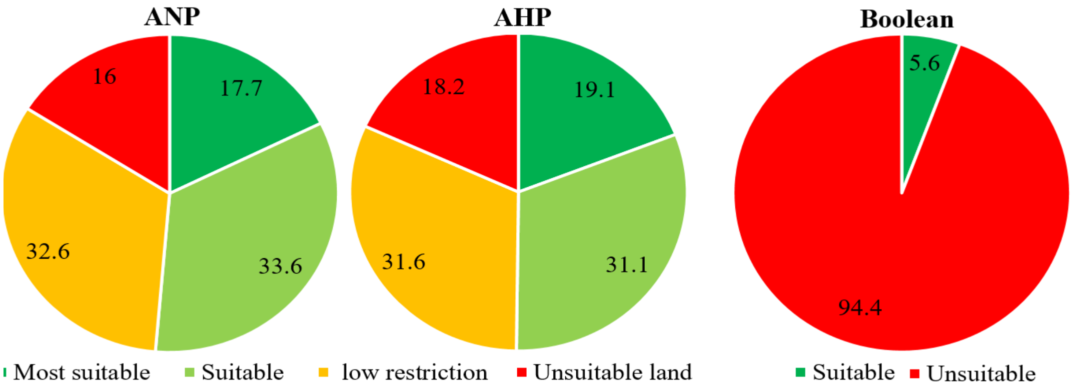


Fig. 6 The percentage of different land classes in terms of the construction of small water reservoirs

Various studies have explored the AHP and ANP methods, with numerous researchers reporting positive outcomes (Coban et al., 2018; Liu et al., 2018; Omolabi & Fagbohun, 2019). The results of this study point that AHP and ANP can be considered useful and reliable tools for selecting and ranking optimal sites for building SWSRs. This study enabled the identification of suitable places for the construction of SWSRs, thereby saving time and money through the use of a decision support system.

4. Conclusion

This study pinpointed suitable locations for constructing SWSRs in Zanjan province using various MCDM techniques. The research led to the following conclusions:

1. Choosing the suitable locations for constructing SWSRs is critical and depends on multiple factors such as water resources accessibility, climate factors, geology, land use, road accessibility, and topography.

2. The results from the AHP and ANP methods were similar when analyzing land classification maps, making these methods preferable to the Boolean logic.

3. About 50% of Zanjan Province, particularly in the central and eastern regions, was identified as suitable or highly suitable for constructing SWSRs. Some areas were found to bear either low or significant restrictions due to road and water resources accessibility.

4. The performance of both the AHP and ANP methods is considered reliable, and their use is recommended during the project planning phase.

Considering the importance of SWSRs in managing water supplies for agriculture, industry, and drinking, it is recommended to carry out decision-making studies using larger-scale maps, spatial data, and satellite imagery across various regions. These studies can greatly improve the placement of water reservoirs, ensuring the success of water management projects.

Statements and Declarations

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Data availability

The data used in this research are provided in the text of the article.

Conflicts of interest

The author of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

Z. Alimohammadi: collected the data, prepared the maps, and wrote the initial version of the manuscript; H. Ojaghlou: conceived the presented idea, analyzed the results, and revised the manuscript; Z. Amiri Abdbouchali: completed the maps and contributed to the final version of the manuscript.

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