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# Combination of Boolean Logic and Analytical Hierarchy Process Methods for Locating Underground Dam Construction

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**ABSTRACT** Construction of underground dams is a practical solution to save groundwater in alluvium watersheds, particularly in arid and semi-arid regions where surface water scarcity is an environmental challenge. Considering socio-economic and environmental benefits of underground dams, the accurate locating is the primary consideration for dam construction. The new technologies and methods are a step toward the proper locating to reduce the risk of underground dam construction. In this study, two methods, decision making and geographic information system (GIS) were used for locating suitable places for underground dam construction in Hamedan-Bahar watershed where water shortage has been a serious problem during the last decade. In the first step, the effective factors in locating and construction of the dams underground were identified, and then their GIS information layers were created. The primary selection maps of suitable sites were provided using Boolean logic method in ArcGIS software. The Analytical Hierarchy Process (AHP) was then applied in EXPERT CHOISE. In the next step, the results of Boolean logic and AHP methods were overlapped to provide the final selection map. A consistency rate of 0.06, showed a relatively high accuracy of weighting process. Considering the normal weights, geology and distance of well, springs and qantas were found to be the most and the least effective criteria, respectively. Furthermore, the final selection map suggested the surrounding area and the outlet of the plain as the most suitable sites for dam construction.

**Key words:** *Consistency rate, Decision making system, Hamedan-Bahar Watershed, Semi-arid regions*

## 1 INTRODUCTION

With the increasing demand of underground water consumption and potential effects of global climate change, the world's population would face water scarcity by 2050s (Danilenko *et al.*, 2010). One of the sustainable solutions to maintain this vital resource is underground dam, an ingenious method to store water Beneath the surface of alluvial riverbed. The technology includes the construction of

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Underground continuous wall perpendicular to the direction of the river (Onder and Yilmaz, 2005). There are enormous benefits of underground dam construction, especially in arid and semi-arid regions. Compared with a surface dam, an underground dam has higher functionality and lower construction cost, evaporation loss, and contamination risks as well as no landuse change above the reservoir (Jamali *et al.,* 2013). To locate underground dams properly, key criteria and factors must be considered in the projects. The multi-dimensional aspect of the data could make the decision making process hard and time consuming. To accelerate decision making and avoid additional data collection, Analytical Hierarchy Process (AHP) as a multi-criteria decision making technique (MCDM) is strongly recommended (Davodi Rad *et al.*, 2004).

AHP is a valuable tool to evaluate the possible solutions for any decision making problem, providing the conceptual model, estimating the model criteria, and choosing the best solution (Hashemi *et al.*, 2014; Rassam *et al.*, 2014). In other word, AHP is a multi-criteria method to weight and order the conflicting qualitative/quantitative criteria hierarchically (based on the weight evaluation) and consequently select the best choice (Kheirkhah Zarkesh, 2005). Moreover, AHP technique can provide judgment based on the relative importance of each criterion assigned by experts. This method is also appropriate when different levels of each criterion should be evaluated (Paliska *et al.,* 2010). AHP method along with aerial photographs, satellite images, and field controls provide an effective approach to locate underground dams properly (Golmay and Ashtiani Moghadam; 2005).

Considering some physical conditions including distance of fault and qanat, geology of upstream areas, low slope (< 5%) areas, as well as suitable land use (rangeland, bare land, waterway bed) are necessary for underground dam construction (Salami, 2006; Chezge *et al.,* 2010; Jafari *et al.*, 2013; Esavi *et al.*, 2013).

Researches for locating suitable sites for construction of underground dam are limited. In this regard, Giovanni Forzieria *et al.* (2008) presented a methodology to assessment the suitable sites for small underground dams implementation in Kidal region in Mali. Their selection criteria were defined both in a qualitative and quantitative ways based on a territorial analysis using satellite data and hydrological and climatological information. While, the method provided 66 suitable sites, 17 sites passed the proposed selection criteria. Esavi *et al.* (2012) used AHP and FUZZY-AHP methods to determinate appropriate area for underground dams Construction. From total of 56 output points, AHP and FUZZY-AHP techniques provided 26 and 15 points, respectively, which overlapped with suitable and accessible areas. The results showed that the Fuzzy-AHP method has more flexibility and ability to determine appropriate areas. Karimi Mobarakabadi (2012) used AHP method to provide a model for optimal location of subsurface dam in Khomein City in Markazi Province. A total of nine potential sites for dam construction were evaluated using AHP technique. The accuracy of the weights assigned to the criteria could be evaluated by using 0.01148 as adjustment rate. Rezaei *et al.* (2013) in their research have applied AHP in fuzzy environment to select the optimal alternative for construction of an underground dam. Their finding showed that AHP in the fuzzy environment improves decision making through considering more important factors in decision making.

Considering above mentioned issues, underground dam construction is a solution for water storage in arid and semi-arid regions where evaporation is relatively high. Hamedan-Bahar Watershed is challenging water crisis such as water shortage, drought, and overexploitation during the last decade. Therefore, underground dam could protect the area from more environmental, social, and economical negative effects of water crisis. The aim of this research is locating the suitable area for underground dam using GIS system in Hamedan-Bahar Watershed. Due to the complexity of effective factors, AHP and Boolean logic methods are used as well.

## 2 MATERIALS AND METHODS

### 2.1 Study area

Hamedan-Bahar Watershed with the latitude of 34° 58′ to 35º 19′ and longitude of 48° 12′ to 59° 18′, is located in the western part of Iran (Figure 1). The whole area is 2492 km², highlands and plains consist almost 1594 and 880 $km^2$ of region, respectively. The outlet is located in the northeastern side of the watershed. The 30-year average annual precipitation is about 321 mm (1971-2010 Hamedan Meteorological Station) with the cold semi-arid climate using Emberger method.

### 2.2 Research Methodology

Area maps, regional geophysical properties, and water level in piezometric wells of the study area were provided and validated by field survey. The topographic (1:25000), geologic (1:100,000), and Land use (1:100,000) maps were used. The maps of effective factors were provided using the following process;

**-Slope map**

Slope is an important factor influencing aquifer volume and the permeability. The most suitable slope for underground dam construction is less than 5% (Moghim, 2012). Slope map was created, from a digital elevation model using ArcGIS v.9.3 software package.

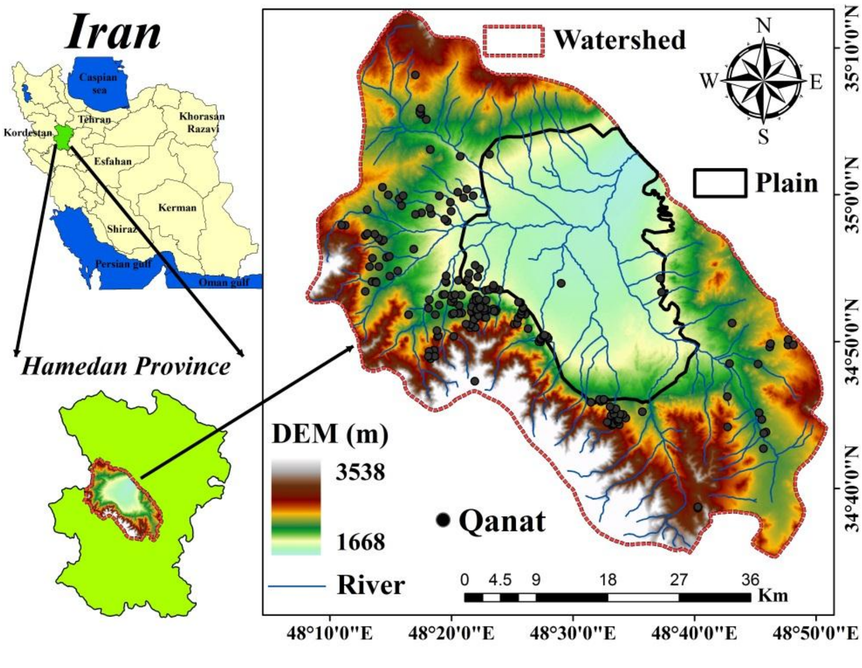


**Figure 1** A general view of study area, Hamedan-Bahar Watershed, Iran





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**- Land use map**

The most suitable land use for construction of underground dams is rangelands and bare land ecosystems. In despite, residential lands, saline lands, plantations, orchards, agricultural systems, industrial sectors, and degraded forest are inappropriate due to contamination, poor quality, environmental protection, low production potential, erosion, water loss, and low economic advantage (Giovanni *et al.*, 2008; Moghim, 2012).

**- Springs, wells and qanat maps**

To create springs, wells, and qanat maps, their location in UTM coordinate system in excel format file was imported into ArcGIS software and intersected with topographic (1:25,000) and geologic (1:100,000) maps. The 100-meter buffer map (Esavi *et al.*, 2012) was also made to avoid any disruption of qanat channels, wells mouth, and springs.

**-Geology and fault map**

Geological condition and recognition the quaternary deposits and formations were also investigated. In term of geology, the upstream region of dam needs to have high permeability and transmissivity to increase dam water storage capability. Therefore, quaternary depositions which are suitable for underground dams were specified on geologic map. As the faults may threat the stability of dam structure and leak out the water (Pirmorady, 2010; Moghim, 2012), a 100-meter buffer map was created.

**-The aquifer thickness**

Aquifer thickness influences transitivity, and consequently the volume of water retention (Pirmoradi, 2010). The aquifer thickness map was obtained from Hamedan Regional Water Company.

**-Map of the potential sites for underground dam construction**

The potential map of underground dam was created using Boolean logic, weighting the layer units by 0 and 1 to assign suitable/ unsuitable regions. For this purpose, low slope areas (<5%), rangelands, bare lands, quaternary formations and stream beds by 100 meters distance from qantas and wells were isolated and valued by one, while the rest of the region valued by zero. Finally, all the created maps were overlaid to zone the appropriate areas for underground dam construction.

**-Prioritizing the suitable sites**

As the zoning map by Boolean logic only shows suitable and unsuitable areas, AHP method was used to prioritize the suitable zones.

All the properties are classified and rated based on questionnaires and expert opinion with the value of 1 to 5. Then, the rates values were normalized using the relative frequency method (Chowdary *et al.*, 2013; Rahmati *et al*, 2014).

In this method, the information layers are classified, and then each class of each layer valued 1 to 5 based on their effective rate as suggested by the experts.

The effective rates were normalized using relative frequency method (Saaty, 1980; 1990) as follow:

$R = a_{ij} / (a_{ij} + \ldots a_{nj})$

$a_{ij}$=Effective rate of layer j of class i

R=Normalized effective rate of layer j of class i

**-The criteria weighting and consistency rate calculation**

AHP and eigenvector methods are used to weight the criteria and sub-criteria based on the relative importance of each parameter (Saaty, 1990). The Saaty rating scale (1-9) was also used for pairwise comparisons (Table 1), using the in EXPERT CHOISE software.





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It should be mentioned that consistency rate of the weights are calculated by weighting procedure (Saaty, 1980). The consistency ratio is calculated using the following (Eqs. 1 and 2):

$$CI = \frac{\lambda\text{-n}}{\text{n-1}} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

Where, CR, CI, λ, n, and RI are represented consistency ratio, consistency index, average consistency measure, number of properties, and random index depends on n, (Table 2) respectively.

If the decision-making process is perfectly consistent; λ= n, and CR =0. With (CR) < 0.1, the pair wise comparison are consistent and with CR >0 it is inconsistent and AHP may not give significant results.

Finally, the results of Boolean logic and AHP methods were overlaid and map of the area with the value of priority for underground dam construction was created.

## 3 RESULTS AND DISCUSSION

### 3.1 Initial Maps and Class Rates

The initial maps of geology, distances of fault, springs, well, and Qanat, land use, slope and aquifer thickness were generated for the study area as shown in Figure 2. The results of the class rate; including initial and normalized rates, are also summarized in Table 3.

**Table 1** Saaty rating scale (Saaty, 1980) for pairwise comparisons of study factors

| Importance | Definition |
|---|---|
| 1 | Equal importance |
| 3 | Relatively more importance |
| 5 | High importance |
| 9 | Very high importance |
| 8, 4, 6, 2 | Intermediate values |

**Table 2** Random index (RI) as a function of the number of properties (n) (Saaty, 1980)

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.4 | 1.45 | 1.49 |





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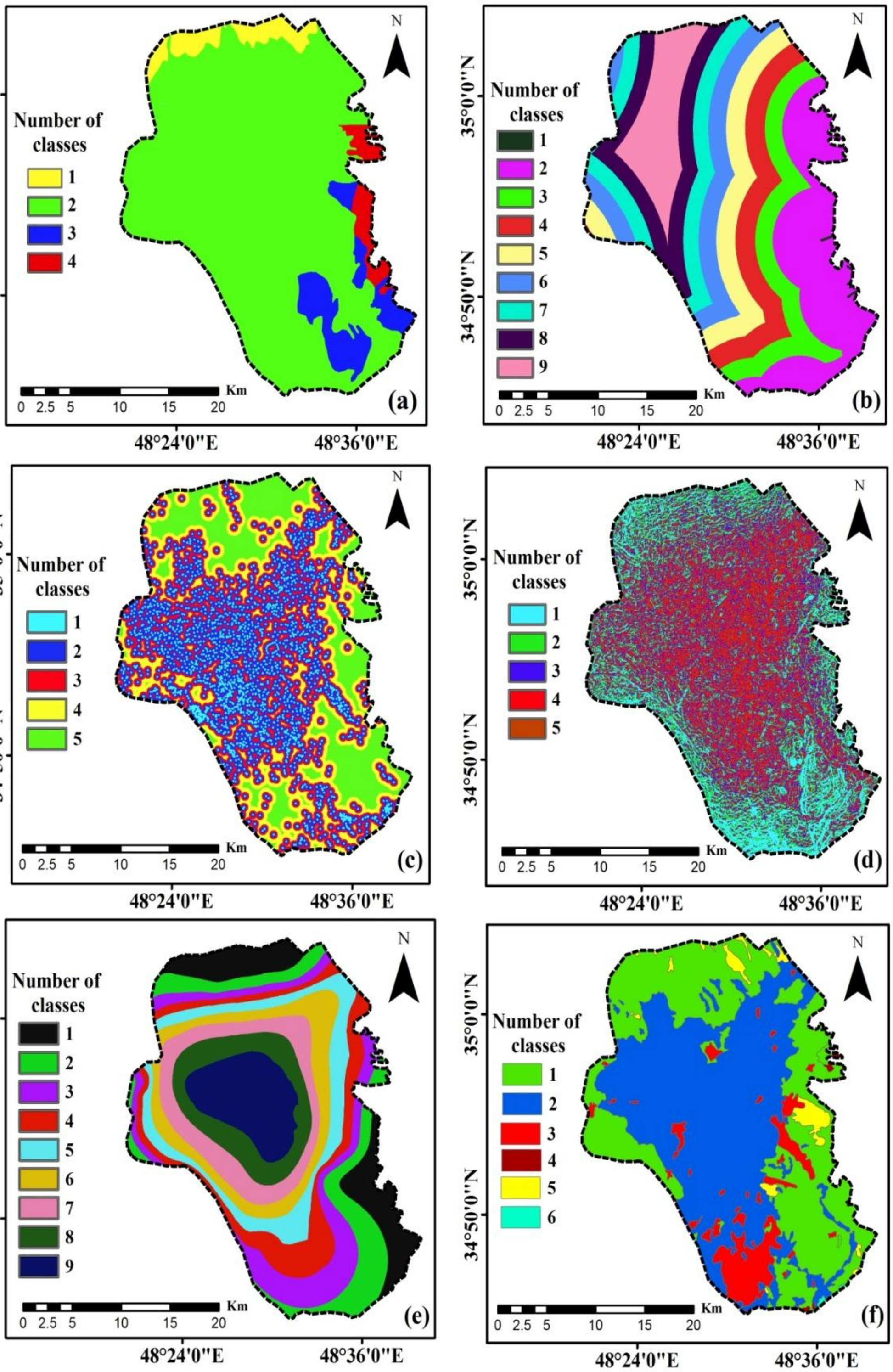


**Figure 2** Initial maps; (a) geology, (b) distance from fault, (c) distance from well, spring and qanat, (d) slope, (e) aquifer thickness and (f) land use

**Table 3** Class rates for initial maps of the study area

| Digital layers | Number of classes | Classes | Initial rate | Normalized rate |
|---|---|---|---|---|
| **Geology** | 1 | Marn | 1 | 0.125 |
| | 2 | Alluvium | 5 | 0.62 |
| | 3 | Marn | 1 | 0.125 |
| | 4 | Limestone and sandstone | 1 | 0.125 |
| **Distance from fault (m)** | 1 | 0-100 | 1 | 0.037 |
| | 2 | 100-4965 | 1.5 | 0.055 |
| | 3 | 4965-6764 | 2 | 0.074 |
| | 4 | 6764-8779 | 2.5 | 0.092 |
| | 5 | 8779-10721 | 3 | 0.111 |
| | 6 | 10721-12520 | 3.5 | 0.129 |
| | 7 | 12520-14104 | 4 | 0.148 |
| | 8 | 14104-15615 | 4.5 | 0.166 |
| | 9 | 15615-18421 | 5 | 0.185 |
| **Distance from well, spring and qanat (m)** | 1 | 0-100 | 1 | 0.037 |
| | 2 | 100-161 | 1.5 | 0.055 |
| | 3 | 161-215 | 2 | 0.074 |
| | 4 | 215-282 | 2.5 | 0.092 |
| | 5 | 282-363 | 3 | 0.111 |
| | 6 | 363-498 | 3.5 | 0.129 |
| | 7 | 498-727 | 4 | 0.148 |
| | 8 | 727-1091 | 4.5 | 0.166 |
| | 9 | 1091-3449 | 5 | 0.185 |
| **Slope (%)** | 1 | 0-1.26 | 5 | 0.249 |
| | 2 | 1.26-1.77 | 4 | 0.235 |
| | 3 | 1.77-3 | 3 | 0.175 |
| | 4 | 3.8-3 | 2 | 0.117 |
| | 5 | 3.8-5 | 2 | 0.117 |
| | 6 | 5-64 | 1 | 0.058 |
| **Aquifer thickness (m)** | 1 | 6-11 | 1 | 0.037 |
| | 2 | 11-16 | 1.5 | 0.055 |
| | 3 | 16-21 | 2 | 0.074 |
| | 4 | 21-28 | 2.5 | 0.092 |
| | 5 | 28-43 | 3 | 0.111 |
| | 6 | 43-58 | 3.5 | 0.129 |
| | 7 | 58-80 | 4 | 0.148 |
| | 8 | 80-113 | 4.5 | 0.166 |
| | 9 | 113-121 | 5 | 0.185 |
| **Land use** | 1 | Dry farming | 4 | 0.235 |
| | 2 | Irrigated farming | 1 | 0.058 |
| | 3 | Urban | 1 | 0.058 |
| | 4 | Good pastures | 3 | 0.175 |
| | 5 | Intermediate Pastures | 3 | 0.176 |
| | 6 | Weak pastures | 5 | 0.294 |





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### 3.2 The normalized weights of the criteria

The consistency ratio (CR) of 0.06 which obtained based on the calculation of consistency ratio, confirming the consistency of paired wise comparison and weights. The final normalized weights are shown in Table 4.

### 3.3 The final map of the suitable area for underground dam construction

The map of suitable/unsuitable areas for the underground dam construction was generated based on Boolean logic (Figure 3), and then overlaid with AHP map to priority suitable areas (Figure 4).

**Table 4** Normalized weights of different criteria using AHP

| Geology | Distance from fault | Distance from well, spring and qanat | Slope | Aquifer thickness | Land use |
|---|---|---|---|---|---|
| 0.420 | 0.080 | 0.029 | 0.156 | 0.270 | 0.045 |

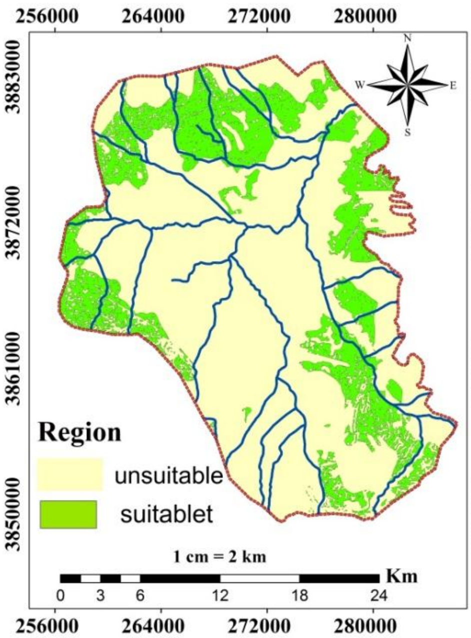


**Figure 3** Map of the suitable areas based on Boolean logic

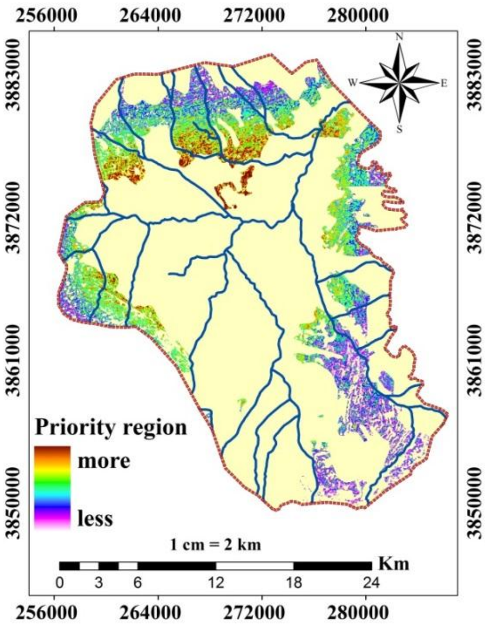


**Figure 4** Final priority map of suitable areas based on AHP and Boolean logic

## 4 DISCUSSION AND CONCLUSION

To create the zoning map of Hamedan-Bahar Watershed for underground dam construction, AHP, criteria weighting, and consistency rate calculation were used. The consistency rate of 0.06 suggested the accuracy of weighting process. This is consistent with previous finding (Rahmati *et al.*, 2015) that suggest a value of 0.1

as a maximum acceptable inconsistency rate in AHP method

The most and least effective criteria are geology (normal weight = 0.42) and Distance of well, spring and qanat (normal weight = 0.029) in this research, confirming unequal, importance of the criteria and sub-criteria in AHP method (Jafari *et al.*, 2013). The key role of geological properties for underground dam construction is also suggested by previous findings (e.g., Chezge *et al.*, 2010; Esavi *et al.*, 2013).

The surrounding area of Hamedan-Bahar watershed and the stream outlet into the underground water resources were found the most suitable sites for dam construction due to their proper land use and low slope streams. The previous researches such as Chezge *et al.* (2010) and Esavi *et al.* (2012) were also confirmed the results. The priority map showed the higher suitability for dam construction in the center of the plain which was mostly a result of permeability and thickness of the formation in the center. The results showed that using both AHP and Boolean logic methods could enhance accuracy of the modeling of site selection for underground dam construction comparing to each method separately. Because Boolean logic method divided the area into suitable/unsuitable zones, while AHP method valued the zone for priority consideration. We concluded that the possibility of using multi-criteria decision making technique (MCDM) such as AHP may develop the modeling of site selection for underground dam construction.

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# کاربرد روش منطق بولین و تحلیل سلسله مراتبی در مکان‌یابی مناطق مناسب احداث سد زیرزمینی

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**چکیده** سدهای زیرزمینی از راه‌کارهای کاربردی و مناسب به‌منظور حفظ منابع آب زیرزمینی در حوضه‌های آبرفتی به‌ویژه در مناطق خشک و نیمه خشک با کمبود آب سطحی به شمار می‌روند. با در نظر گرفتن منافع محیط‌زیست و اجتماعی- اقتصادی سدهای زیرزمینی، مکان‌یابی مناسب، اولین مساله مهم در ساخت این سدها می‌باشد. روش‌های جدید به‌منظور مکان‌یابی صحیح، خطرات مرتبط با مکان‌یابی نامناسب و ساخت سدهای زیرزمینی را کاهش می‌دهد. در این تحقیق سامانه اطلاعات جغرافیایی (GIS) و سامانه تصمیم‌گیری به‌منظور مکان‌یابی احداث سد زیرزمینی در حوزه آبخیز همدان- بهار که مساله کمبود منابع آب به یکی از مشکلات اساسی منطقه در دهه‌های اخیر تبدیل شده، به‌کار رفته است. در گام نخست تحقیق، ابتدا معیارهای تاثیرگذار در مکان‌یابی سد زیرزمینی شناسایی و لایه‌های اطلاعاتی مربوطه در محیط GIS تهیه شدند. نقشه‌های اولیه مکان‌های مناسب با استفاده از منطق بولین در محیط ARC GIS ایجاد شدند. در گام بعدی روش تحلیل سلسله مراتبی (AHP) با نرم افزار EXPERT CHOISE روی لایه‌ها اعمال شد. به منظور تهیه نقشه نهایی، لایه‌های ایجاد شده از دو روش منطق بولین و تحلیل سلسله مراتبی روی هم‌گذاری شدند. در نتایج به‌دست آمده در مرحله وزن‌دهی معیارها، میزان سازگاری معیارهای به‌کار گرفته شده در مکان‌های مناسب اجرای پروژه سد زیرزمینی حوزه آبخیز همدان- بهار، ۰/۰۶ محاسبه شد که این رقم تأییدکننده صحت وزن‌دهی انجام شده بود. دو عامل زمین‌شناسی و فاصله از چاه، چشمه و قنات به‌ترتیب دارای بیش‌ترین و کم‌ترین تاثیر روی مکان‌یابی سد زیرزمینی تشخیص داده شد. با توجه به نقشه نهایی به‌دست آمده مناطق حاشیه و خروجی دشت مناسب‌ترین مکان‌ها برای ساخت سد زیرزمینی در این حوضه تعیین شدند.

**کلمات کلیدی:** حوزه آبخیز همدان- بهار، سامانه تصمیم‌گیری، مناطق نیمه‌خشک، میزان سازگاری





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