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RESEARCH PAPER

Prospectivity Modeling of Karstic Groundwater in the southeast of Damavand Mountain, Iran

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Abstract
Due to the unsustainable groundwater utilization in the alluvial water resources, groundwater exploration in the karstic areas is the key concern for many developing countries. The purpose of this study is groundwater prospectivity modeling for recognizing karstic water-bearing zones in the southeast of Damavand Mountain, Iran. To do so, seven major geological and hydrogeolgical factors, including lithology, slope, distance from faults, vegetation, temperature, precipitation, and fracture density were considered. Then, all these thematic layers were weighted and combined using fuzzy logic and Analytical Hierarchy Process (AHP) operators by employing GIS software to generate four different models. Finally, the zoning map was classified into three classes (low, medium, and high), and the resultant maps verified by discharges of karstic springs in the study area. The results indicated that AHP-Fuzzy method has better performance than other models. According to this model, around 62.23% of the study area is classified as being at low and 15.72% as moderate groundwater potential while the remainder is categorized as high potential. The proposed model provides an appropriate approach to assess the groundwater potential for the study area, therefore, it can be concluded that RS and GIS coupling with other algorithms such as fuzzy and AHP are reliable tools in evaluation of karstic groundwater resource potential areas.

Keywords: groundwater prospectivity modeling, karstic water, fuzzy logic, Analytical Hierarchy Process (AHP), Damavand Mountain.

Introduction

Water scarcity is among the main challenges to be faced by the modern world in the 21st century regarding to the population growth and climate change impacts (Kraiem et al., 2014). In recent years, development of groundwater for various purposes has significantly increased, resulting groundwater depletion in many of the alluvial aquifers due to overdrafting. This has increased the attention to the karstic aquifers. Karst regions represent 7–12% of the Earth's continental area, and one in every five persons in the world is completely or largely dependent on drinking water from karst aquifers (Ford & Williams, 2007). About 10.5% of the Iran country are underlain by karstic formations (Karimi-Vardanjani et al., 2018) and karst groundwater is one of the primary water resources in most provinces of the study area.

Karst aquifers have a different hydraulic structure and behavior than porous media and the groundwater potential varies spatially, sometimes even within a few meters distance (Stevanovic, 2015; Imran Dar et al., 2010), and random drilling of wells in a karstic aquifer can result in failure. Therefore, investigation of this resource is extremely significant and developing a sustainable groundwater management plan requires delineation of groundwater prospect zones in order to utilize this vital resource, properly.

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Some researchers provide different approaches to assess the potential occurrences and characteristics of groundwater resources in karstic aquifers (Nhu et al., 2020; Bagheri et al., 2021). One of the most commonly used methods for groundwater exploration assessment is the weighting method which it takes into account several parameters in the geological and hydrological environments. The geographic information system (GIS) has proven to be effective due to the analytical capability of the various spatially distributed data required for delineation of groundwater prospective areas. Geospatial techniques are most utilized to provide and integrate different types of thematic layers (Dinesan et al., 2015). GIS facilitates evaluation of multiple criteria from a specific context that can measure a unique property. Applications of remote sensing and GIS provide rapid and cost-effective tool and an advantage of accessibility to large coverage, and producing valuable data such as geology, geomorphology, lineaments, slope, etc. Therefore, applications of this approach for the exploration of groundwater prospective zones are carried out by many researchers around the world (Magesh et al., 2012; Kumar et al., 2016; Siddi Raju et al., 2019), and it was found that this method can be a successful approach for considering aforementioned factors which affect the groundwater occurrence in karstic areas (Mohammadi-Behzad et al., 2019).

Although the selection of many parameters in the weighting overlay method increases the statistical accuracy of the model, this method has also some disadvantages, that the most important is the deterministic rating system especially in the class borders. Considering the spectral nature of hydrogeological parameters, deterministic classification can cause an area belongs to lower or higher categories by the slight change. Using fuzzy method, membership functions are used for maps in which each pixel has a membership degree to each category. Integrating GIS and fuzzy rule-based techniques are particularly useful for modeling hydrogeologic parameter fuzzy inputs because they have uncertainty (Dixon, 2005b). Therefore, in this research the combination of GIS and fuzzy utilized to improve the method. Then, in order to optimize the model, the weights of all parameters have been modified through using Analytic Hierarchy Process (AHP). This process has been applied to compute the ratings and used in the model in order to modify the initial weights in assessing the groundwater potential.

There are many karst springs in the southeast of Damavand Mountain. Due to the importance of groundwater in the drinking water supply of the region and the occurrence of recent droughts, the demand for exploration of karst water resources in this area has increased. However, in the study area, no detailed study was conducted to identify the potential of karst water resources. Therefore, the present research aims to develop an effective and feasible procedure for exploring groundwater potential areas in the karstic formations in the southeast of Damavand Mountain.

Description of the study area

The study area shown in Figure 1 is located in the southeast of Damavand Mountain, occupying approximately 352.4 km2. The study area is part of the Central Alborz Mountain Range, where the geological formations have been folded into parallel NW–SE anticlines and synclines since the Miocene (Mozafari & Raeisi, 2017). Based on the measurements from 2010 to 2020 operated by the Iranian Meteorological Organization, the average annual precipitation and the mean annual temperature in the study area are 378.8 mm and 11.33°C, respectively. The main geological formations, oldest to newest, include Shemshak shale and sandy shale (Upper Triassic, Lower Jurassic), Dalichai calcareous marly limestone (Middle Jurassic), Lar massive limestone (Upper Jurassic), Tizkuh limestone (Lower Cretaceous), Karaj tuffs (Middle Eocene), and recent quaternary sediments. A large portion of the study area is underlain by soluble formations of limestone, therefore the potential for karstification is high.

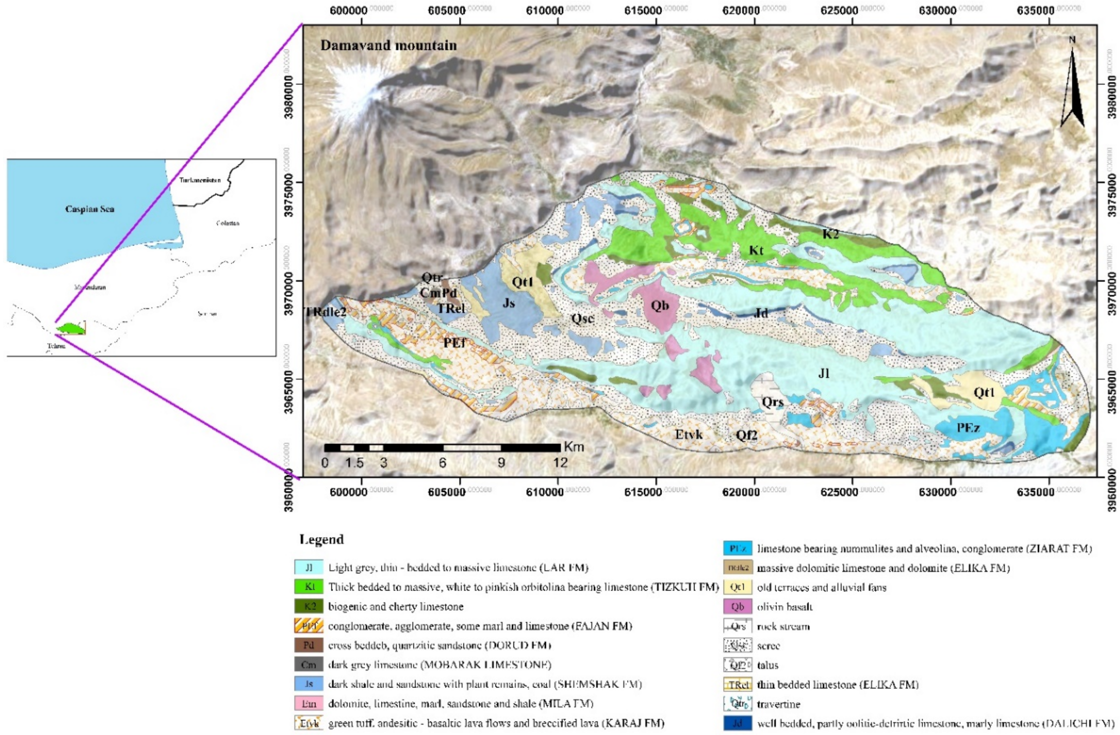

Figure 1. Location and geological map of the study area

The main karst features in the study area include karren, grike, caves, small karst valleys and springs. Karrens with different sizes and shapes including rillenkarren, rain pits, and grikes, are well developed in the exposed karst limestone, distributed at all elevations. There are a few caves on this plateau, but the most of them are not very deep. The karst valleys array at the study area shows that their formation and location were influenced mostly by the faults since most of them were formed along the faults, particularly those with N-S trending. Several karst springs with discharge range from 0.02 to 26 L/s are well exposed frequently at elevations lower than 2500 m.

Data and methodology

The assessment of groundwater potential zones has been subject to many researches during the past years and a variety of methods have been applied. Parameter weighting and rating models are the most widely used which classify various parameters and also consider relative weight coefficients for each factor. The methodology developed for the present study is shown in Figure 2. This method considers seven influencing factors of the geological and hydrological environment, including lithology, slope, distance from faults, vegetation, temperature, precipitation, and fracture density. These elements are combined in the model to generate the groundwater potential zonation map. Initially, these thematic layers are evaluated with reference to a numeric rate ranged from 1 to 10 that is weighted based on their relative importance in groundwater prospects ranged from 1 to 5. The lithology layer was obtained from the various geological sheets in the study area. The Digital Elevation Model (DEM) of the area was used to obtain the ground slope. Landsat 8 satellite images with 30-m resolution acquired from the United States Geological Survey (USGS) was used to derive distance from faults, vegetation, and fracture density maps. Precipitation layer was produced using rainfall data obtained from Iran Meteorological Organization in the study area. All the thematic maps are prepared and integrated in ArcGIS.

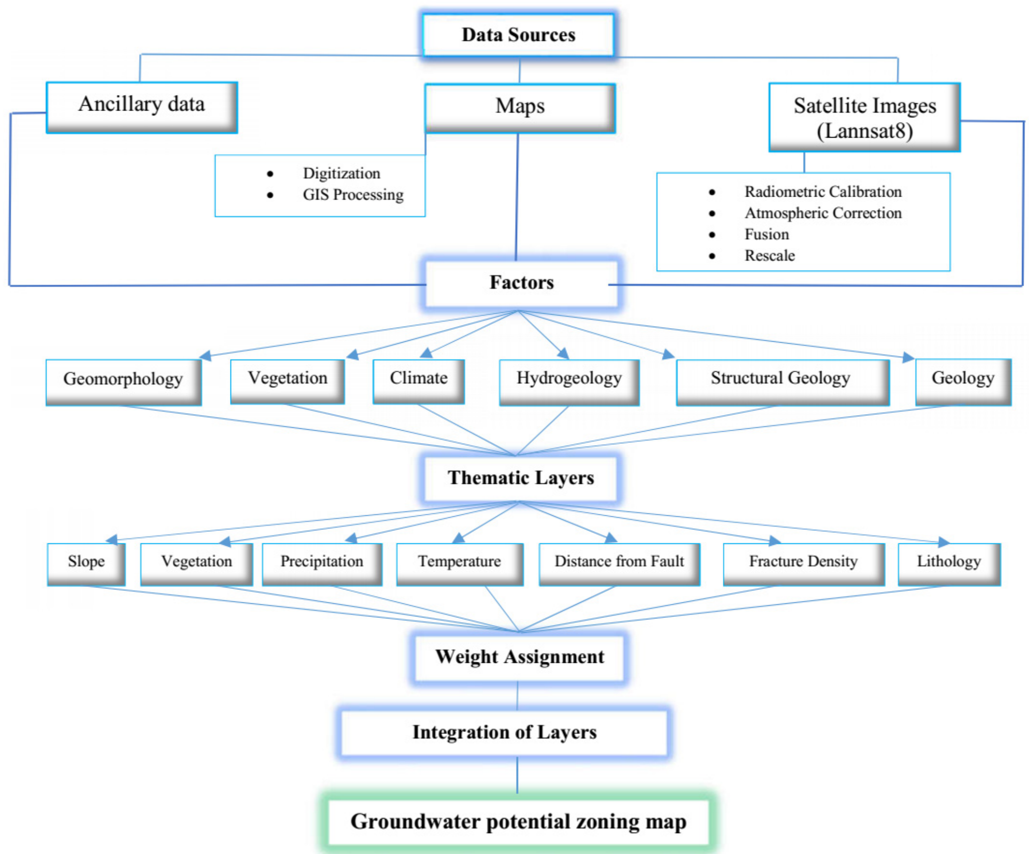

Figure 2. Flowchart for evaluating the groundwater potential zone

To generate groundwater potential zone, scored maps of all the seven thematic with their potential weights were integrated using weighted overlay in spatial analyst tool of ArcGIS. Then, the groundwater potential indices are derived from the summation of multiplied rates and weights of each polygon. A high index value shows a higher potential for groundwater prospect and vice versa. Furthermore, discharges of karstic springs were used to validate predictions of the model in this research. The existence of very good yielding springs can be a sign of high recharge rates to the aquifer and, as a result, the development of groundwater resources in karstic areas and fractured rocks in the study area (Asghari-Moghaddam & Fijani, 2009). Hence, the criterion for the effectiveness of the final model is the correlation coefficient of the groundwater potential and spring discharge.

In order to optimize the results, rating and weighting system was modified using fuzzy and AHP algorithm. In the fuzzy method, fuzzy membership functions is defined for maps in which each pixel has a membership grade range between zero and one. Membership grade equal to one indicates the greatest impact and membership grade equal to zero indicates the least impact on the groundwater potential. The analytic hierarchy process is an accurate approach to quantify the weights of decision criteria. This method is based on pair-wise comparison. In this research, AHP was used to modify the weights of parameters.

Result and Discussion

The groundwater potential zonation map in the karstic formations is initially prepared by combining multi influencing factors with an appropriate assigned weight. The weight and rates of each factor are listed in Table 1.

Table 1. Weight and Classification of the influencing factors (modified after Dashti, 2018 and Gheysi, 2008)

Layer	Weight	Range	Rate	Layer	Weight	Range	Rate
Lithology	8	Shal	1	Vegetation	1	No vegetation	0
		Abnik	4			Low vegetation	2
		Ruteh	5			Medium vegetation	5
		Elika	6			High vegetation	8
		Mobarak	6	Temperature	1	<10	10
		Soltaniyeh	7			10-15	9
		Tizkuh	9			15-17	8
		Lar	10			17-20	5
Slope	1	0-5	10			20-25	2
		5-10	9			25-30	1
		10-15	8	Precipitation	4	>1500	10
		15-25	7			1000-1500	9
		25-40	6			800-1000	8
		40-60	4			600-800	7
		60-80	2			400-600	6
		>80	1			200-400	4
Distance from faults	2	0-50	10			<200	1
		50-100	9	Fracture density	3	>2.25	10
		100-200	8			1.5-2.25	8
		200-350	7			0.75-1.5	6
		350-500	6			<0.75	2
		500-650	5				
		650-800	4				
		800-1000	3				
		>1000	1				

From this point forward, GIS tools are mostly applied to integrate model elements for the preparation, analysis, and display. Figures 3 (a)-(g) shows the thematic maps.

Lithology

The lithology of a rock affects its porosity, permeability, and karstifiability (Goldscheider & Drew, 2007; Mozafari et al., 2020). The most intense karst development requires medium to massive bedding, while dissolution phenomena is usually more dispersed where beds are thin (Ford & Williams, 2007). The karstifiability of carbonate rocks generally decreases with increasing content of non-soluble minerals; the most important of such mineralogical impurities are clays, predominantly illite, and different forms of quartz (Pulido-Bosch, 2021). Therefore, the rate of formations with such lithological evidence like pure limestone bed must be assigned properly high in GIS lithology layer (Fig. 3a). There are eight karstic formations in the study area. Among them, Lar formation consists of massive limestone and exhibited the highest potential for karst development.

Slope

Slope plays an important role in the amount of runoff from rainfall as well as infiltration. Solutional denudation rates have also been found to depend on runoff. Increasing the ground slope increases the velocity of surface runoff and reduces the amount of water infiltrating the ground, therefore it is considered as a negative parameter for recharge (Ford & Williams, 2007).

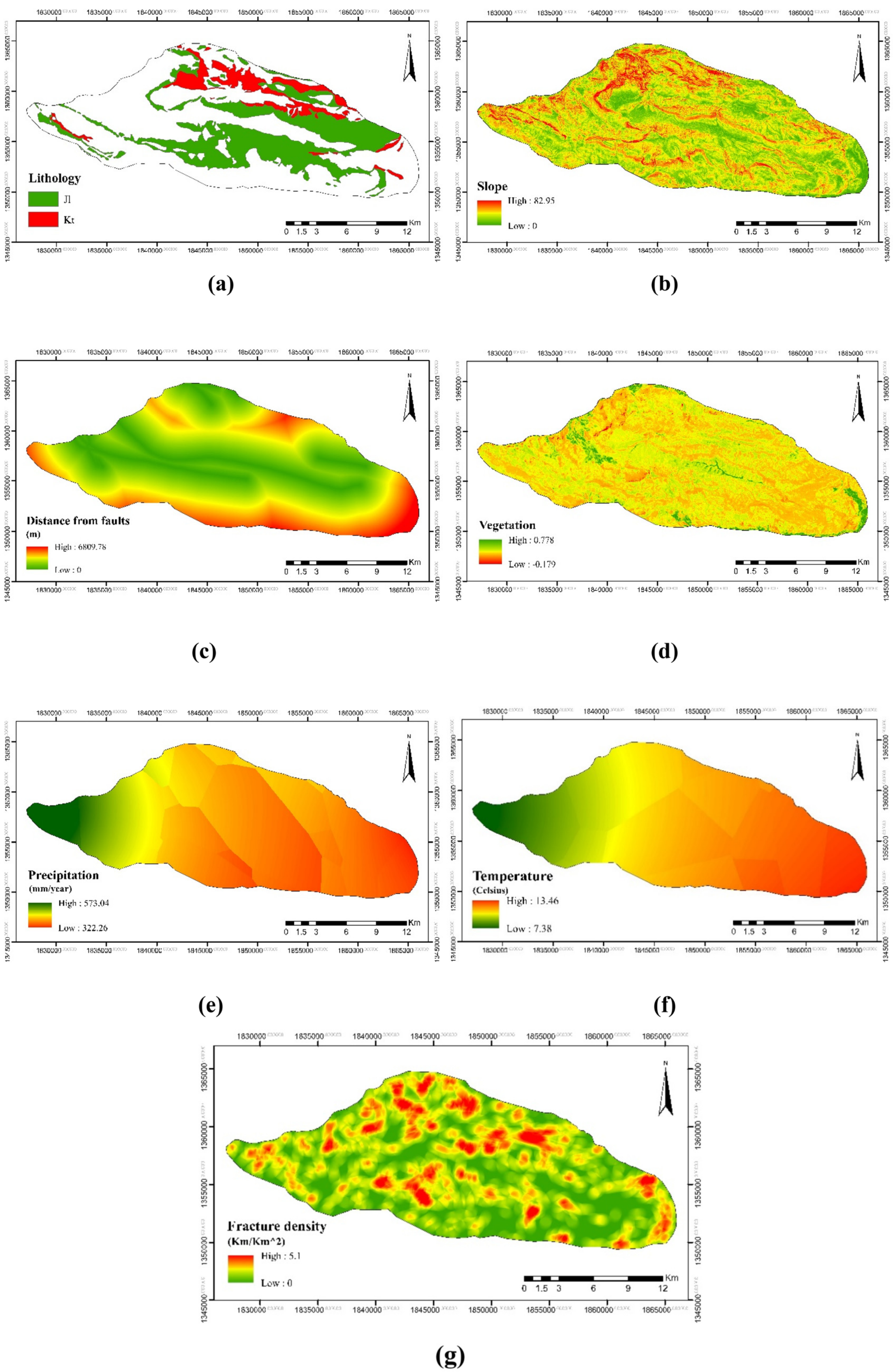

Figure 3. The influencing factors (a) Lithology, (b) Slope, (c) Distance from faults, (d) Vegetation, (e) Temperature, (f) Precipitation, and (g) Fracture density

Distance from faults

Faults, tectonic joints, and bedding planes form part of the secondary porosity of the aquifer. Karst conduits usually follow the path of faults, joints, and bedding planes. Hence, horizons that have two or more faults or intersect each other, are the most prone points for karstification (Singhal & Gupta, 2010).

Vegetation

The higher the density of vegetation, the more runoff from heavy rainfall is prevented, and then the required time for the infiltration of rainfall is provided. In addition, the pressure of plant roots in such areas can cause the fracture in the rocks, which is an effective factor in increasing the permeability.

Temperature

At a particular partial pressure of carbon dioxide, the dissolution rate of calcite decreases with increasing temperature. On the other hand, low temperature causes frost and permafrost phenomenon, and as a result, groundwater flow, vegetation, infiltration, and carbon dioxide pressure are reduced. Therefore, in such areas, the rate of chemical interactions will decrease. In general, in areas where the temperature is very low (below zero), karstification is rare (Ford & Williams, 2007).

Precipitation

The fluidity of water is the most active factor in karst development (Sun et al., 2018). Naturally, karst thrives in areas with higher rainfall and dry or very cold climates prevent the development of karst. Both of these weather conditions have led to a lack of liquid water and therefore limit dissolution.

Fracture density

Well yields in carbonate rocks with secondary porosity and permeability differ widely from place to place. These differences are proven to depend on the number, size, degree of interconnection and distribution of the structural setting, which accounts for the nature and distribution of the solutional openings (Moore et al., 2002). Certain types of fractured lineaments have been correlated with high bedrock well yields in fractured rock aquifers (Degnan & Moore, 2001). Identification of fracture correlated lineaments and high densities of fractures may indicate zones that can store and transmit ground water and potential points of discharge in the study area.

Groundwater potential zones and validation

Multi-Criteria modeling has been widely applied to evaluate groundwater potential. The thematic layers weighted based on expert knowledge and expected importance to groundwater occurrence, as expressed in Table 1, and overlaid using the weighted sum approach in ArcGIS. The lower weight number displays less recharging capability than the higher weight number. Finally, the weight of each thematic layer (W_i) is multiplied by the rates of each thematic layer (R_i), to calculate the final groundwater potential index as:

$$groundwater\ potential\ index = \sum W_i \times R_i \quad (1)$$

where W_i and R_i are thematic layer weight and rate, respectively. Combining the thematic layers results in a range of numerical values named the groundwater potential index. The data layers will be combined based on the equation (1) using the raster calculator functionality within the ArcGIS Spatial Analyst extension. All the layers must be converted to a raster format for integration of the model elements. The resulting raster file will be the layer used to evaluate groundwater potential (Fig. 4a). Index values of this integrated model range from 35 to 166 for the study area, grouping in three categorical index ranges (High, Moderate, and Low).

In addition to investigating where there is potential for groundwater occurrence within the study area, an application of this research is to understand if the model output, in the form of a groundwater potential map, correlates with existing springs discharge data. The weighted overlaid model is tested using springs discharge data and the results have indicated that there is a relative correlation between the high discharge spring and the areas classified as being of high potential (Fig. 4a). Then, in order to improve the model, three more groundwater potential maps have been constructed using fuzzy and AHP methods. Figures 4(b)-(d) show the groundwater potential maps using these models with spring discharge overlaid on the graph as circles.

As mentioned earlier, spring discharge data were used as an indicator to show whether the groundwater potential index correctly represents the actual situation in the study area. For this purpose, both spring discharge and groundwater potential were grouped into three categories including low, moderate, and high. Then, a specific procedure was applied in order to better distinguish the results from different models (Fijani et al., 2013). The number of springs that fell into the same potential and discharge categories was multiplied by 3. The number of springs with a difference of 1 and 2 in the potential and discharge categories was multiplied by 2 and 1, respectively. Then, the obtained amounts were added together. The resultant number, termed as the correlation index (CI), can indicate correlation between model results and spring discharges. Higher CI means higher correlation. The performance result of the models is shown in Table 2.

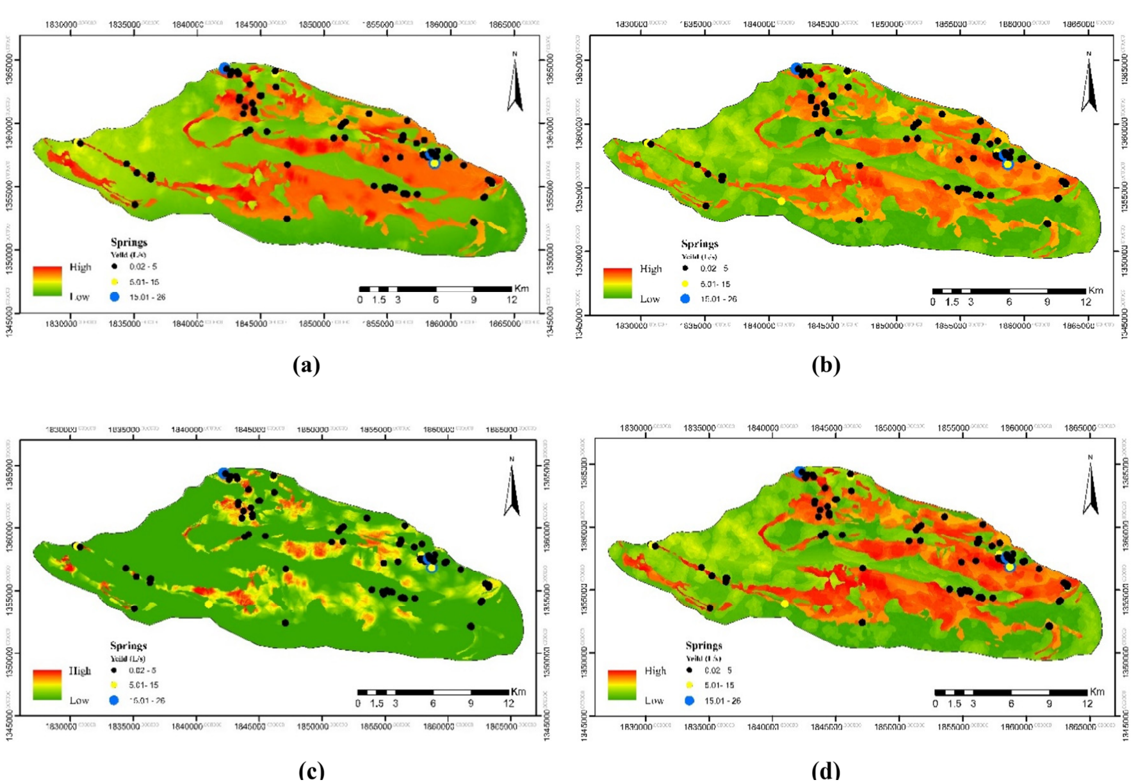

Figure 4. The groundwater potential maps using different methods: (a) Weighted sum method, (b) AHP, (c) Fuzzy, (d), and AHP-Fuzzy

Table 2. The coincidence of springs with three discharge levels and groundwater potential categories predicted by different models in the study area (unit= number of springs)

	Springs Discharge						
	High	Moderate	Low		High	Moderate	Low
Weighted Sum		CI= 262		AHP		CI= 281	
High	4	2	39	High	2	2	32
Moderate	0	2	25	Moderate	2	0	16
Low	0	2	49	Low	0	4	65
Fuzzy		CI= 292		AHP-Fuzzy		CI= 304	
High	3	2	29	High	0	2	16
Moderate	1	0	12	Moderate	3	0	21
Low	0	4	72	Low	1	5	75

CI: Correlation Index

Table 2 concludes that AHP-Fuzzy method performed better than other models. According to this model, around 62.23% of the study area is classified as being at low and 15.72% as moderate groundwater potential while the remainder is classified as high potential that mostly covered western areas of the aquifer.

Conclusion

The aim of this research is the assessment of karstic groundwater potential zones on the basis of hydrogeological conditions of the study area. For this purpose, seven factors including the topographic setting influencing groundwater circulation, the distribution of precipitation available for recharge, the properties of the rocks (which favors solubility of the formations), the structural setting (which accounts for the nature and distribution of solutional openings), the temperature and the vegetation, which found to be either positively or negatively related to groundwater prospecting, were combined. ArcGIS software was applied to create seven thematic layers and finally the groundwater potential maps by overlaying all the layers using different methods. Then, the spring discharge data were used to verify resultant maps. The final validated zoning maps show that the AHP-Fuzzy model has better accuracy than other models, and so it can be more reliable. The results of the final model show a correlation between the high spring discharge and the high groundwater prospecting zones.

This research proposes that the approach provided a convenient estimation of groundwater potential for the study area. However, the results can provide some uncertainty due to insufficient data. For instance, there are no data related to permeability measurements in different areas of the region. In addition, most of the climate stations in the region are located in the plains and there is no station at altitudes, which makes the application of the altitude - precipitation curve with a slight error. Therefore, it is suggested that permeability and hydraulic conductivity be measured in karst rocks of the region. Also, rain gauges should be installed at the heights to increase the accuracy of the Isohyet maps. Considering the importance of the groundwater resources in the study area, and different hydraulic behavior of the karst than porous media that drilling boreholes blind can lead to failure in terms of acceptable yield, exploration of the karstic groundwater in this area is necessary for optimum management of water resources.

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