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A regional-scale hydrogeological study for identifying karstic aquifers with high water resource potential in Iran

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Abstract
The study of karst water potential is one of the most important and attractive studies of this type of distinctive landform. This study has been carried out with the aim of identification of areas of extensive karstification and consequently groundwater resource potential carbonate rocks in Iran considering the role of the chief factors affecting karst water potential. Accordingly, 25 different data layers where interrogated in a GIS platform. Subjective karst map was developed on the basis of what is considered to be a proper combination of these factors. The most important parameters are categorized to three driving factors include chemical, physical, and hydrogeological factors. Thematic map of each parameter was prepared using geographic information system (GIS). Measuring the rate and weight of the maps was performed using analytical hierarchical process (AHP), respectively. The final output map showed different zones of groundwater prospective potential, which was divided into five grades. According to the results, out of the total area of 174,000 km² of carbonate outcrops in Iran, the highest grade of karst water potential was found in the Kopet-Dagh zone in the northeast. So, the significance of karst formations in the Kepet-Dagh region is at least as great as that of the Zagros and Alborz ranges, if not greater. Validation of karstification potential map was done with the existence and location of springs and karst aquifers in the Kopet-Dagh area.

Keywords: Karst Aquifers Potential, Groundwater, AHP, Iran.

Introduction

Groundwater is considered the most important resource for water supply in arid and semi-arid areas. Among the aforementioned areas, including China, Turkey, Iran, Mexico, and the United States, karst groundwater is a major resource. Karst aquifers are generally recognized as the most heterogeneous and complex groundwater flow systems. The inherent difficulty in dealing with hydrogeology of karst terrains has led to the establishment of specialized research groups, mostly in the past 50 years (Auler & Stevanović, 2021). A whole range of hydrogeological mediums from karst conduits and corrosion-widened fractures to tiny fissures and inter-granular porosity within the karst aquifers cause simultaneous presence of contrasting groundwater flows. Due to the complex and heterogeneous character of the karstic massif, their study will require attention and potential attention to various aspects and factors affecting their occurrence. Karstic-carbonate formations cover about 10.5% of the land area in Iran (185,000 km^2), chiefly in a broad western strip, in the northeast, and central parts (Raeisi, 2004; Karimi-Vardanjani, 2019). Evaluation of the distribution of carbonate rocks in Iran dates back to 1991

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(Nassery, 1991). After that, Dumas (1998) developed a karst map base on the outcropping carbonate rocks. Seif and Ebrahimi (2014) also evaluated degree of karstification according to some important factors in carbonate rocks in Iran Using GIS.

Carbonate rocks cover about one fifth of the Earth's surface and over 25 % of the world population either live on the outcrop of karstic formations derive their potable water from karstic aquifers (Gillison, 2004; Ford & Williams, 2007). In the USA, for example, about 20 % of the land surface is covered by outcrop of the karstic formations and about 40% of their water is provided from the karstic resources (Ford & Williams, 2007). About 35 % of France is covered by karstic formations and the proportion of domestic water abstracted from these formations in is similar (Bakalowicz, 2004).

The study of karst water potential is one of the most important and attractive studies of this type of distinctive landform. Mapping of groundwater prospective zones using remote sensing and GIS techniques in the Central Eastern Desert, Egypt was performed by Abdalla (2012). He showed that around 40% of the study area constitutes zones of good to very good groundwater potential. An empirical method for the exploration of groundwater potential zones using remote sensing and GIS was performed by Magesh et al. (2012). This method was widely applied to a vast area with rugged topography for the exploration of suitable sites. Some researchers (Dar et al., 2010; Kumar & Kumar, 2010; Balachandar et al., 2010; Madrucci et al., 2008) have also used similar methods in the exploration of groundwater resources. Several studies are carried out for finding the karstification potential for different purposes and karst hydrogeology in different areas in Iran (Afrasiabian, 1998; Raeisi, 1999; Kazemi, 2003; Ashjari & Raeisi, 2006; Mohammadi et al., 2007; Raeisi, 2008; Saadat & Mohammadi, 2016; Dashti-Barmaki, 2016; Nasseri et al., 2021; Bagheri et al., 2021). The literature about the hydrogeology of karstic features is sporadic and it is impossible to use them on a regional scale. Therefore, the present study was conducted with the aim of a regional-scale hydrogeological study for identifying karstic aquifers with high water resource potential in Iran.

Karstification is generally the result of the interaction between several natural factors. Scientists proposed different opinions about the controlling factors of karstification, according to the complications of the karsts which is the result of the natural processes. There are different studies about the major controlling parameters in karstification potential including, lithology, climate, geomorphology, hydrogeology and tectonic (Anderson & Fairley, 2008; Faulkner et al., 2010; Fairley et al., 2003). Thus a number of specific controlling parameters can be identified that influence the potential for karstification and karst groundwater supply potential. In this study, these parameters are collated, evaluated, and weighted for determining the karstic formations in specific zones and providing an integrated karstification map for the purpose of attaining karstic water in the initial stages of the study.

Overview of geology of Iran and karstification

Iran is located in the Alpine-Himalaya fold belt, which extends from the European Alps to the Himalayas and the Pacific Ocean. It consists of five main structural zones: Zagros, Sanandaj-Sirjan, Central Iran, the East and Southeast, and Alborz, separated by ophiolite-bearing structures.

Zagros is on the northeastern edge of the Arabian Plate, extending from Bandar Abbas to Kermanshah and into Iraq, characterized by large anticlines, small synclines, and continuous sedimentation.

Sanandaj-Sirjan lies south of Central Iran and is separated from it by faults and depressions.

Central Iran has complex geology with rocks ranging from Precambrian to semi-active volcanoes.

Kopet Dagh in the northeast, composed of Mesozoic and Tertiary sediments, was folded during the Alpine Orogeny.

Alborz in northern Iran forms a barrier between the Caspian Sea and the Iranian plateau, with platform-type sediments and rock units from Precambrian to Quaternary.

Karst formations in Iran are mainly associated with limestone and dolomite rock units, which are particularly prevalent in several of the country's geological zones. Karst terrains are shaped by the dissolution of soluble rocks, leading to features such as caves, sinkholes, and underground rivers. The key areas for karst development in Iran include the Zagros and Alborz mountain ranges, as well as parts of Central Iran and Kopet-Dagh.

Zagros: This region is a significant area for karstification due to the extensive limestone units. The karst systems here include large caves and underground rivers, particularly in regions like Lorestan, Kermanshah, and Fars provinces. The geological structure of this region, with its anticlines and synclines, provides ideal conditions for the formation of karst landscapes.

Alborz: In northern Iran, karst formations are found in the limestone and dolomite rocks of the Alborz mountains. This zone contains numerous karst features, including notable caves and springs. The high precipitation in this area further supports the development of karst systems.

Central Iran: Although less extensive, Central Iran also hosts karst formations. These are found mainly in localized areas with soluble rock types, such as parts of the central plateau where carbonate rocks dominate.

Kopet-Dagh: While karst is present in Kopet-Dagh, it is more subdued and less significant than in other regions of Iran, with fewer large-scale karst features but still playing an essential role in local hydrology. Some areas of the Kopet-Dagh show typical karst features such as small caves, sinkholes, and underground drainage systems.

Overall, Iran's karst landscapes play an important role in water resource management, as many underground aquifers are hosted within these formations, providing vital water supplies, particularly in arid regions.

Material and method

Affecting factors on karst water potential

Karstic zones play an important role in feeding the karstic aquifers ،therefore, recognizing the factors affecting the karst mutation and its zonation at the regional scale in relation to karst water resources is the question mark by many researchers. So, introducing and describing the parameters affecting the water karst potential at the regional scale is the first step of the present study. Perhaps the most comprehensive description of the factors affecting the karst water potential is provided by White (1988) (Figure 1).

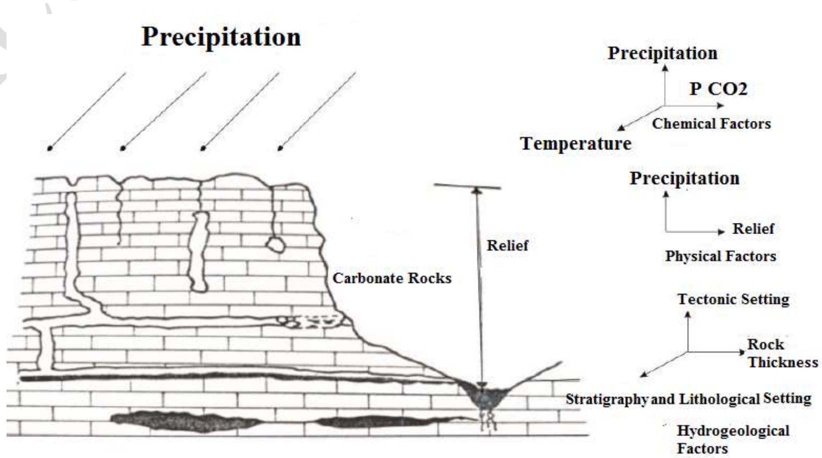

Figure 1. Factors affecting the karst water potential (Adapted from White 1988)

Karstification is the result of interaction between the geological factors as tectonic, lithology, hydrogeology and etc. Thus, these factors are criteria of finding the karstic locations and karstic water and essential material of the study. Generally, the factors affecting karst water potential are divided to three Class including the Chemical factors, Physical factors, and Hydrogeological factors.

Chemical factors (Climate)

Chemical factors, climatic criteria, include Temperature, Precipitation and PCO_2. Present and paleo climate need to be considered in the karstification potential studies. The climate of the area affects the karstification and topography of the karsts by controlling the precipitation. Generally, the precipitation and temperature are regarded as climatological factors, but their effects on the karstification are dissimilar because the temperature variation rates are very low relative to the precipitation. Amount of precipitation is the most important one of all climatic factors, as the magnitude of solution is essentially defined by it (Barany-Kevei, 1999).

Physical factors

In addition to the effect of chemical factors (limestone dissolution), precipitation affects the physical factors affecting karst development, including the amount and intensity of precipitation and, consequently, physical weathering. The development of karst phenomena depends on the ability of water to sink into and flow through karst rocks. The amount of limestone affected by dissolution during the karstification processes mainly depends on the amount and the concentration of the solute (Hyland et al., 2006; Xintong et al., 2022).

Relief and local base level are the main geomorphologic factors that control the regional groundwater flow in karstic aquifers. They define boundary conditions and control the recharge and discharge locations of the aquifer (White, 1988; Palmer, 2000). The location of local base level is inherited from historical and regional tectonic processes. The slope controls water recharge into the subsurface. The residence time of surface runoff in gentle dips is considerably more than in steep dips, so the rate of infiltration in the gentle dips can be more than the steep dips.

The karst relief happens due to the erosion of water in limestone and originated by the drag or accumulation of soluble and disintegrated materials, such as those consisting of carbonates. It is usually common to find phenomena like these in limestone rocks, evaporates (like gypsum and salt), dolomites and quartzite's. This process generates a variety of forms such as canyons, Lapiaz, sinkholes, Karren, etc., entitled External karst relief. The karst relief can also be found in underground areas, giving rise to caves, grottos and other very striking karst landscapes.

Morphology means presence of a network of holes by karst processes. So, morphology of a karstic region and subsequently its hydraulic features and conditions change in long term. Karst morphology is usually described in carbonate rocks like limestone, dolomite and marble. Due to high dissolution or carbonate minerals (particularly calcite) in acidic water, a similar morphology is formed in Silicate rocks and is called Pseudo-karst (Millanovic, 2004).

Hydrogeological factors

Hydrogeological factors include Tectonic setting, Rock thickness, and stratigraphy and lithological setting.

Carbonate pure lithology is more suitable for karst development, as the presence of impurities such as marl and silica minerals may impede the dissolution progress. The thickness of soluble rock layers and the stratigraphic position of them among the non-soluble layers control the extent of karst development. In the case of thin soluble rocks sandwiched between non-soluble layers, it is less likely that karstification occurs (Seif & Ebrahimi, 2014). Furthermore, the impermeable and non-soluble thin layers of rocks as interfering layers in the carbonate layers impede the water movement into the deeper parts, and hence, the dissolution only occurs in the top carbonate sequences (Lowe, 1992; Shabab-Brojeni, 2011).

According to Jameson (2006), in order to study karst evolution, structural features should be identified and analyzed. Also, Kazemi and Davoodi (2011) the regression results indicated that occurrence of karst water resources were highly correlated to geological structural elements (Kazemi & Davoodi, 2011). The experiences show that the water movement is higher in the structural features such as anticline and syncline in hard formations (Ashjari & Raeisi, 2006). Higher concentration of the fractures in the axis area of the anticlines results to the higher water movements and low discharge springs are present in the limbs. The folding map of the area is necessary in the karst studies for determining the geometry of the aquifers, the reservoir volume and drainage pattern. Providing the geological map of the area in different directions considering the height of the springs, the highest impermeable core and the presence of the faults is applied for the study of the possibility of hydraulic movements in different directions in the folds. Faults and fractures represent the effects of the tectonic setting. Most fractures are caused by the tectonic forces, weathering, and mechanical breakdown.

Methods

Base maps

Aforementioned factors in previous part are criteria of finding the karstic locations and karstic water and essential material of the current study. In the first step, the controlling parameters in karstification are defined. These parameters and their effects on the karstification are evaluated in different areas and then each parameter is presented in a map based on its effect on the karst distribution. Data were mapped, classified, weighted and managed in separate layers in GIS software. Using GIS as the basic analysis tool for karst groundwater potential mapping can be effective for spatial and data management and manipulation, together with some reasonable models for the analysis. The required data and information more than 25 data layers were gathered from the updated data with proper scale (generally 1:250.000) and detailed references in geological survey and Mineral Exploration of Iran. These data are: Thickness (m), Structure, Humidity, Permeability, Fault, Temperature (^{0}c), Infiltration Coefficient, Paleo weathering, Precipitation (millimeter/year), Spring, weathering, Paleo climate, DEM (m.a.s.l), Cave, Age, Quality (EC), Purity, Layering, Evaporation (millimeter/year), Paleo morphology, Lithology, Tectonic, Climatology, Hydrogeology, and Geomorphology.

This study includes 4 main steps to achieve an ideal site selection. These steps include; creation of a database, identifying the factors influencing the karstification, scoring the factors and validation of results. The details of each step are presented in Figure 2. This article is based on geological and hydrogeological properties as study were carried out in the Geological Survey of Iran. The effect of each of these parameters on the karstification is shown in Table 1. The values presented in this table are often obtained experimentally.

Iran faults and folding map

The outer rigid surface of the Earth is divided into chunks known as tectonic plates. These plates move around at the rate of a few centimeters per year. The Iranian Plate is a small tectonic plate thought to underlie Iran and Afghanistan, and parts of Iraq and Pakistan. It is compressed between the Arabian Plate to the southwest, the Eurasian Plate to the north, and the Indian Plate to the southeast. This compression is likely a cause for the very mountainous terrain of the area including the Zagros Mountains. Tectonic features of Iran include faults (3 types) and folding map (anticlines and synclines) are mapped from geological survey and Mineral Exploration of Iran (Figure 2).

Climate parameters maps

Iran is a country with an arid-to-semiarid climate (an average precipitation of 240 mm/year), with the exception of the northern parts which receive up to 2,000 mm precipitation per year. High precipitation such increases the karstification potential but dryness negatively affects the karstification. Precipitation map is used in this article (Figure 2). Precipitation is classified to four classes (Table 1) between less than 100 and more than 500 millimeters per annual (mm/a).

Climate map of Iran is prepared based on some parameters such as temperature, precipitation and evaporation. Temperature is classified to three classes (Table 1) between less than 20 and more than 25 degrees Celsius. Also, evaporation is classified to three classes (Table 1) between less than 2500 and more than 3500 millimeters per annual. Final, Climate map of Iran based on mentioned parameters is classified to three classes include humid, semi-humid, and dry climates.

Karst geomorphological features maps

Morphology means presence of a network of holes by karst processes. So, morphology of a karstic region and subsequently its hydraulic features and conditions change in long term. Karst morphology is usually described in carbonate rocks like limestone, dolomite and marble.

Table 1. Main factors controlling the karstification

Lithology	Mineralogy	Limestone Dolomite Impure Lime Impure Dolomite	Geomorphology	Cave	< 1000 1000 - 3000 > 3000
	Age	Cenozoic Upper Cretaceous Mesozoic Paleozoic Proterozoic - Paleozoic Proterozoic		Weathering	Chemical Mechanical
	layering	Thin Medium Thick Massive		Paleo weathering	Chemical- Mechanical Chemical Mechanical
	Thickness (meter)	< 100 100 - 300 > 300		Paleo-morphology	Non-glacial Semi-glacial Glacial
Climate	Precipitation (millimeter/year)	< 100 100 -250 250 - 500 > 500	Hydrogeology	Spring	Distribution Discharge
	Temperature (^{0}c)	< 20 20 - 25 > 25		Quality (EC)	< 1000 1000 - 2000 > 2000
	Evaporation (millimeter/year)	< 2500 2500 - 3500 > 3500		Permeability	High Low Impermeable
	Climate	Humid Semi-humid Dry			

Surface and subsurface karst morphologies are the key components for understanding the nature and genesis of cave and karst systems (De-Waele et al., 2009; Hamed et al., 2024). The experiences show that anticipating the surficial karstic features to be an absolute representative of the karstic features in the depth might result to many mistakes in hydrogeological studies (Ford & Williams, 2007).

The karst resources in mountainous areas are focused on distribution and protection in various forms despite the low level of anthropogenic disturbance. The karst water resources in the plain areas have development potential and may be used to meet the needs of large-scale agricultural irrigation and urban water use, although it is necessary to quantitatively specify the limits on water exploitation in order to prevent natural disasters (Jiang et al., 2021). According to Seif and Ebrahimi (2014) densities of caves and springs show a good correlation with the evaluated karstification. The investigation of caves in Iran (about 850 caves) shows the predominant role of hypogene processes in the formation of many of them (Karimi-Vardanjani, et al., 2017). The caves maps of Iran are used in this stage. Distance to Caves are the main factor in this stage, less than 1000 to more than 3000 meters (Table 1). Limestone is susceptible to both physical and chemical weathering. So, present and paleo climate need to be considered in the karstification potential studies. The paleo climate can affect weathering over time, so paleo weathering mapping was on the agenda (Figure 2) include chemical and physical weathering (Table 1).

Lithological maps

The lithological studies in this article are classified to mineralogy, age, layering and thickness. The primary type of porosity is the inter-particle porosity but it is affected by different types of diagenetic features such as cementation dissolution and fracturing in carbonates. Different types of barriers such as impermeable and cemented layers might stop the fluids in different directions in the subsurface. Dissolution is very important in hydrogeology and engineering geology because different volumes of fluid might entrap in dissolution enlarged pores. This is very important in drilling a well or making an underground structure such as a tunnel. The dissolution potential is classified to three factors including the mineral and chemical composition, purity of the mineral, compaction and cementation. The purity of carbonate rocks, mineralogy, based on the data bank of the geological survey of Iran are classified to four classes include pure and impure limestone and dolomite rocks (Figure 2 and Table 1). The thickness of soluble rock layers and the stratigraphic position of them among the non-soluble layers control the extent of karst development. In the case of thin soluble rocks sandwiched between non-soluble layers, it is less likely that karstification occurs (Seif & Ebrahimi, 2014). So, the thickness of carbonate rocks is classified in this article (Table 1). The layering of the carbonate formations is used in the map (Figure 1). This parameter is mapped based on four classes (Figure 2). Other parameter related to lithology is permeability of carbonate rocks which shows at Figure 2. This parameter is classified to three categories include high permeable, low permeable and non-permeable rocks (Table 1).

Most of the outcropping carbonate rocks are of Cretaceous and Tertiary age. From the hydrogeological point of view, the most important karst aquifers in the Zagros region are Sarvak (Cretaceous) and Asmari (Palogene - Neogene) Formations, in the Alborz region is Lar Formation (Jurassic), in the Kopet-Dagh region are Mozduran and Tirgan Formations (Cretaceous), and finally in the Central Iran are Jamal (Permian), Shotori (Triassic), Esfandiar (Jurassic), and Qom (Neogene) formations. In this article, carbonate rocks at three Era (Paleozoic, Mesozoic, and Cenozoic) in Iran are considered.

Water resources maps

Springs are important sign in the hydrogeological and karst studies. The discharge and distribution of the springs are controlling factors in this category (Table 1). One of the most important characteristics of every spring is its rate of discharge. Considering an average discharge (Qs), the karstic springs in Iran may be classified as two classes include lower and higher than 25 liters per second (Figure 2). Quality of the water is very important which needs to be determined in the next step. Karami et al. (2016) characterized by a high rate of precipitation and recharge via highly permeable fractured karstic formations.

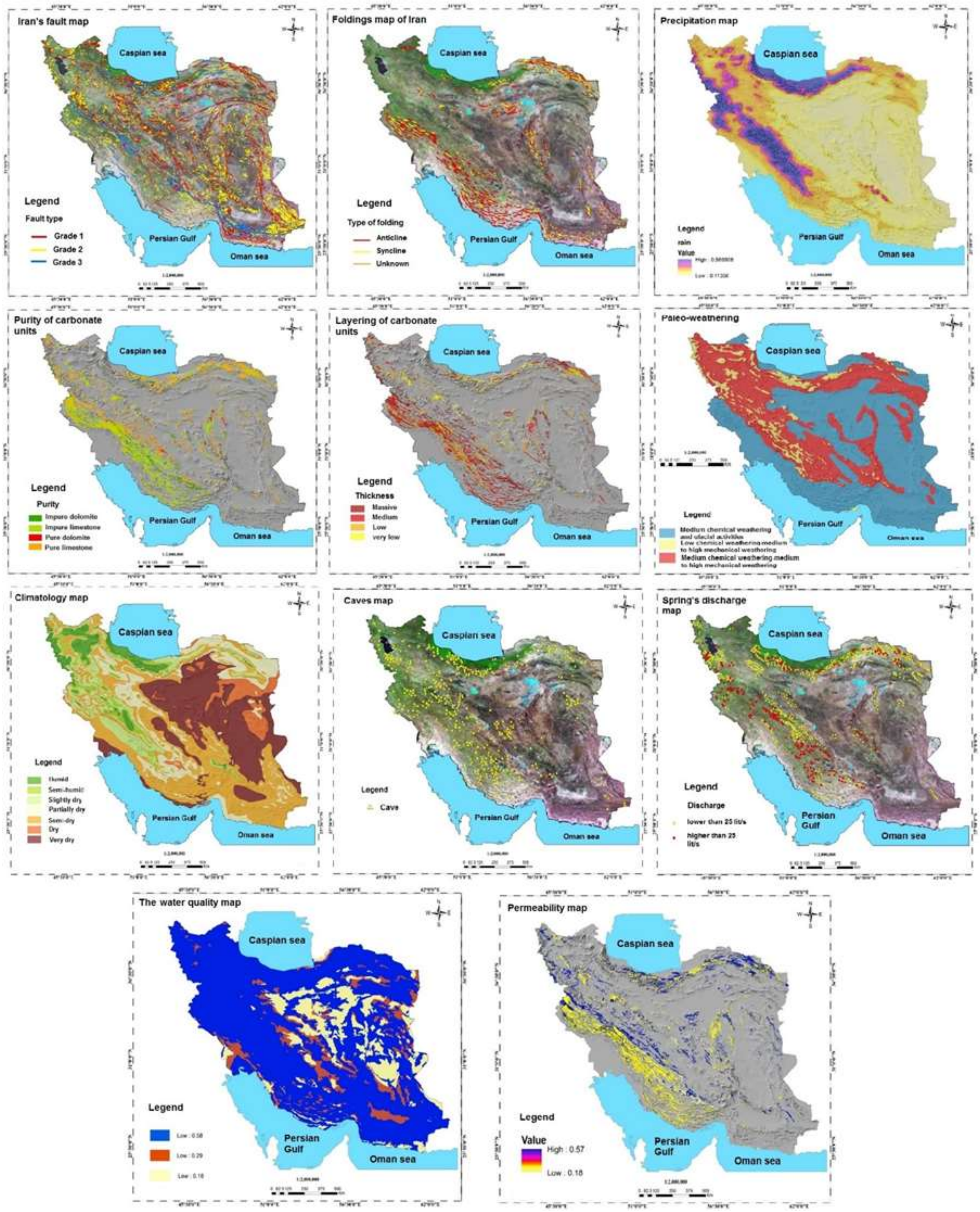

Figure 2. The important geological and hydrogeological parameters in karst distribution in Iran

To investigate groundwater spring flow, the physicochemical parameters include major cations and anions, discharge, EC, pH, and temperature were studied by Karimi et al., 2018. The drainage pattern is distinguished from other types of lineaments to highlight its role on karstification (Hassanpour & Mohammadnejad, 2015; Shokri et al., 2014).

Parameter classification maps

Classification of the study area based on affecting components on karst water potential include tectonic, hydrogeology, lithology climate and geomorphology is next step of methodology. Karstification potential maps based on factors include tectonic, hydrogeology, lithology, climate, and geomorphology are shown in Figure 3.

Tectonic condition

In hard rock areas, fractured zones are important to be identified and characterized since they lead to preferential groundwater flow pathways and enhance well productivity.

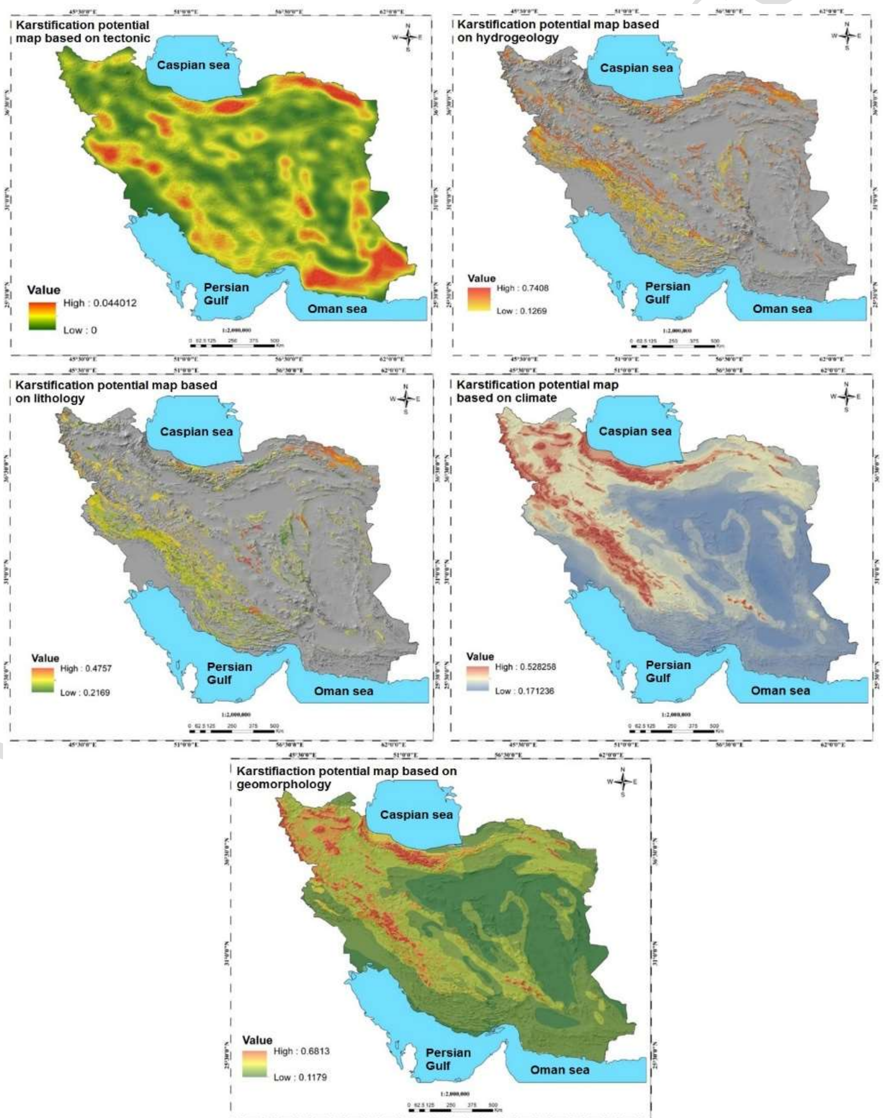

Figure 3. Classification of the area based on tectonic, hydrogeology, lithology climate and geomorphology

Faults can guide water to penetrate into the ground; therefore, karstic processes can developed along them and result in a variety of karst morphologies (Jafarbeyglou et al., 2012).

The zones with the highest lineament density are often those with the most intense karst development (Goldscheider & Drew, 2007). Active tectonics causes periodic changes in karst base level, folding structure and faults, and due to these processes, some parts of old conduits are truncated and deactivated (Chitsazan et al., 2015). Large faults are rarely represented by a single surface fracture. Minor faults usually feather off at acute angles as a consequence of the wrenching of the rock. Shear fractures are often oriented parallel to or close to the associated structures (Ford & Williams, 2007). The faulting zones and fractures affect different aspects of the hydrogeological systems (Hauselmann, et al., 1999; Faulkner et al., 2010; Fairley et al., 2003; Wibberley & Shimamoto 2003; Sharifzadeh & Kargar, 2007; Altafi-Dadgar et al., 2017). One of the most useful methods in karst water resource evaluation is comprehensive analysis of karst related features (lineament, fault, joint) from aerial photo, satellite image, geological map, fieldwork data and also hydrological data processing. The majorities of karst poljes are predisposed by tectonics and thus are formed and shaped by the influences of exogenous factors and processes (Milanovic, 2004; Nassery & Alijani, 2009). Faults control domain vessels of the water movements (Anderson and Fairley 2008). Vertical faults show higher capability of water conduction to the depth (Zarei et al., 2010). Generally, the karstification pattern obey the faults and fractures direction. The normal faults in extensional system are more effective for the hydraulic movements in comparison to the reverse faults in tensional system. The effect of different features such as fault breccia (which makes the water movements easier), joints (where the pressure on the joints decreases by erosion) or thrust faults (affecting extensive area) are important in hydrogeology. The effect of fractures on hydrogeological properties depends on: 1) the spatial direction and density (number of the fractures in a specific length), 2) the connection between the fractures, 3) the width of the fractures, 4) roughness and the hydraulic conductivity of the fracture filling materials. Based on the Figure 1a, normal faults are distributed vastly. These areas are considered for the highest potential of the karstic features in comparison to the other two types of faults in the first levels of karstic potential study. The major and minor faults and their effects are studied in addition to the kinematic classification of the faults and their effect on karstification. Opportunities for karst development are most likely in the center of the fault zone. The distribution of this parameter is shown in Figure 3.

Hydrogeology

Karstification potential maps based on hydrogeological factors include discharge rate, distribution, and quality of springs, as well, as permeability coefficient is shown in Figure 3. Karst aquifers are those in which caves or conduits form an important part of the flow path. Conduit permeability ranges from pipe-like openings greater than one centimeter in aperture to caves many meters in aperture. Discharge from karst aquifers is through large springs. Spring discharge tends to respond rapidly to storm flow. So, the discharge rate and location of springs are the main components in hydrogeological karst potential. Permeability is the capacity of an aquifer for transmitting water and it represents the relative ease with which the aquifer transmits groundwater. Permeability of karst areas is another effective component in hydrological karst potential. Finally, water quality can be considered for prepare the hydrogeological component of karstification potential map.

Lithology

Lithology is a key component in the development of karst, and the difference in erosional resistance between lithology will influence the landscape as a whole. Limestone is susceptible to both physical and chemical weathering. It must be noted that the harder is the lime stone, the more is the probability of karst landforms formation; because soft rocks are crumbled quickly and different landforms are not created in them (Hajati-Ziabari et al., 2014). Generally, limestone shows higher potential for dissolution in comparison to dolomite. Dolomite is the diagenetic type of carbonate rocks thus shows higher resistivity to dissolution and different types of environmental alterations. The lithology of the carbonate rocks is important in the porosity, permeability, and consequently the karstification potential. Karstification potential maps based on lithological factors include mineralogy, age, layering and thickness is shown in Figure 3 each of which is described in detail in the previous section

Climate

Iran is a vast country, and has different types of climate: mild and quite wet on the coast of the Caspian Sea, continental and arid in the plateau, cold in high mountains, desert and hot on the southern coast and in the southeast. Karstification potential maps based on climatically factors include precipitation, temperature, evaporation, and finally climate categories are shown in Figure 3. The impact of changes in the height could be checked at climate factor, value and type of precipitation as well as value of temperature. For this reason, the height factor based on Digital Elevation Model (DEM) is considered, less than 1000 and more than 3000 meters above sea level (m.a.s.l).

Geomorphology

Karstification potential maps based on geomorphological factors include cave, weathering, paleo-weathering, and paleo-geomorphology is shown in Figure 3. Karst landscapes and Karst aquifers are formed by the dissolution of carbonate rocks by water rich in carbon dioxide waters. There are more than 850 caves in Iran which the length of most of them is less than 1000 meter. The short term length of these caves has been attributed to the active and developing nature of the orogenic belts in the country and the continuous shifts in the erosional base level. Although karst landscapes are often dominated by underground drainage networks that interrupt and capture surface water flow, the landforms result mostly from chemical weathering of the host rock and the progressive integration of subsurface cavities. So, paleo-weathering and paleo-morphology are main factors in karst water potential. Therefore, the role of geological age of karstic outcrops is an important point that should be considered.

Weighting and analysis

One of the most important steps in the site selection process is assigning a value or weight to each factor or information layer (Hassanpour et al., 2017). Veress (2020) presented hierarchical classification of the Earth's postgenetic karsts and described karst types (Veress, 2020). The Analytic Hierarchy Process (AHP) is used for weighting of selected criteria in this study. Generally, the AHP method converts a multi-dimensional to a one-dimension issue and simplifies a complicated problem for making a rational decision. This is a subjective process which can result in differences in opinions between specialists in each of the main parameters. Thus, the approximate weight of the parameters was averaged. Finally, these parameters evaluated based on the different views among the experienced expert. The result of AHP weighting the considered criteria of karstification is presented in Tables 2, 3, and 4. All the controlling factors in the third layer, second layer and the first layer are presented in the table.

Table 2. Final overall priority results based on specialists' opinions and List of data layers and their classes prepared and weighted for evaluating the zonation maps (layer 1: expert judgment)

AHP Matrix (Thickness (m))

	< 100	100 - 300	> 300	Weight
< 100	1	0.6	0.3	0.17
100 - 300		1	0.5	0.28
> 300	C.I= 0.004		1	0.55

AHP Matrix (DEM (m.a.s.l))

	> 3000	1000 – 3000	< 1000	Weight
> 3000	1	1.6	2.7	0.51
1000 – 3000		1	1.6	0.31
< 1000	C.I= 0.004		1	0.19

AHP Matrix (Fault)

	Normal	Reverse	Strike Slip	Weight
Normal	1	1.2	1.1	0.36
Reverse		1	0.8	0.29
Strike Slip	C.I= 0.02		1	0.34

AHP Matrix (Purity)

	Calcite	Dolomite	Impure Calcite	Impure Dolomite	Weight
Calcite	1	2.3	2	3.3	0.46
Dolomite		1	0.9	1.4	0.2
Impure Calcite			1	1.6	0.23
Impure Dolomite	C.I= 0.004			1	0.14

AHP Matrix (Precipitation (mm/year))

	> 500	250 -500	100 – 250	< 100	Weight
> 500	1	2.5	1	4	0.44
250 -500		1	0.5	1.7	0.17
100 – 250			1	3.8	0.38
< 100	C.I= 0.006			1	0.1

AHP Matrix (Layering)

	Massive	Thick	Medium	Thin	Weight
Massive	1	1.2	1.4	2	0.33
Thick		1	1.2	1.7	0.28
Medium			1	1.4	0.23
Thin	C.I= 0.02			1	0.16

AHP Matrix (Structure)

	Anticline	Syncline	Flat	Weight
Anticline	1	1.8	3	0.55
Syncline		1	1.7	0.29
Flat	C.I= 0.004		1	0.17

AHP Matrix (Cave)

	< 1000	1000 – 3000	> 3000	Weight
< 1000	1	2.7	7.5	0.67
1000 – 3000		1	2.7	0.24
> 3000	C.I = 0.001		1	0.09

AHP Matrix (Temperature (^{0}c))

	> 30	20 – 30	< 20	Weight
> 30	1	0.8	0.7	0.28
20 – 30		1	0.9	0.35
< 20	C.I= 0.02		1	0.37

AHP Matrix (weathering)

	Chemical	Mechanical		Weight
Chemical	1	1.4		0.58
Mechanical		1	C.I = 0.001	0.42

AHP Matrix (Spring)

	Density	Discharge		Weight
Density	1	1.3		0.57
Discharge		1	C.I = 0.001	0.43

AHP Matrix (Humidity)

	Wet	Medium	Dry	Weight
Wet	1	2	3.5	0.56
Medium		1	1.8	0.28
Dry	C.I= 0.005		1	0.16

AHP Matrix (Infiltration Coefficient)

	> 60	40 – 60	< 40	Weight
> 60	1	0.7	0.4	0.21
40 – 60		1	0.6	0.31
< 40	C.I= 0.001		1	0.48

AHP Matrix (Age)

	Cenozoic	Mesozoic	Paleozoic	Weight
Cenozoic	1	0.8	0.9	0.56
Mesozoic		1	1.1	0.28
Paleozoic	C.I= 0.002		1	0.16

AHP Matrix (Evaporation(mm/year))

	> 3500	2500 - 3500	< 2500	Weight
> 3500	1	0.7	0.4	0.2
2500 - 3500		1	0.5	0.28
< 2500	C.I= 0.001		1	0.52

AHP Matrix (Permeability)

	High	Medium	Low	Weight
High	1	2	3.8	0.57
Medium		1	1.8	0.28
Low	C.I= 0.003		1	0.15

AHP Matrix (Paleo weathering)

AHP Matrix (Paleo climate)

	Pluvial	Subglacial	Glacial
Pluvial	1	0.7	0.4
Subglacial		1	0.6
Glacial	C.I= 0.002		1

Weight	
Pluvial	0.21
Subglacial	0.31
Glacial	0.48

	Wet	Medium	Dry
Wet	1	2.5	5.2
Medium		1	2.1
Dry	C.I= 0.002		1

Weight	
Wet	0.63
Medium	0.25
Dry	0.12

AHP Matrix (Quality (EC))

	> 2000	1000 – 2000	< 1000
> 2000	1	0.6	0.3
1000 – 2000		1	0.5
< 1000	C.I= 0.001		1

Weight	
> 2000	0.18
1000 – 2000	0.29
< 1000	0.53

AHP Matrix (Paleo morphology)

	Pluvial	Subglacial	Glacial
Pluvial	1	0.5	0.2
Subglacial		1	0.4
Glacial	C.I= 0.002		1

Weight	
Pluvial	0.13
Subglacial	0.25
Glacial	0.63

Table 3. Final overall priority results based on specialists' opinions and List of data layers and their classes prepared and weighted for evaluating the zonation maps (layer 2: AHP method)

AHP Matrix (Lithology)

	Thickness	Purity	Layering	Age		Weight	
Thickness	1	0.6	1	3		Thickness	0.26
Purity		1	2	5		Purity	0.42
Layering			1	3		Layering	0.23
Age	C.I= 0.001			1		Age	0.09

AHP Matrix (Climatology)

	Precipitation	Temperature	Humidity	Evaporation	Paleoclimate	Weight	
Precipitation	1	2	2	4	0.5	Precipitation	0.24
Temperature		1	0.9	2	0.3	Temperature	0.12
Humidity			1	2	0.3	Humidity	0.13
Evaporation				1	0.1	Evaporation	0.06
Paleoclimate	C.I= 0.005				1	Paleoclimate	0.45

AHP Matrix (Hydrogeology)

	Spring	Infiltration Coefficient	River	Permeability	Quality	Weight	
Spring	1	1.2	1.8	1.4	2	Spring	0.28
Infiltration Coefficient		1	1.4	1.1	1.6	Infiltration Coefficient	0.22
River			1	0.8	1.1	River	0.16
Permeability				1	1.4	Permeability	0.2
Quality	C.I= 0.014				1	Quality	0.14

AHP Matrix (Geomorphology)

	DEM	Cave	Weathering	Paleo weathering	Paleoclimate	Weight	
DEM	1	0.6	1	1.2	1.2	DEM	0.19
Cave		1	1.5	1.7	1.8	Cave	0.29
Weathering			1	1.1	1.1	Weathering	0.19
Paleo weathering				1	1.1	Paleo weathering	0.17
Paleoclimate	C.I= 0.019				1	Paleoclimate	0.16

AHP Matrix (Tectonic)

	Fault	Folding		Weight	
Fault	1	1.9		Fault	0.65
Folding		1	C.I= 0.001	Folding	0.35

Table 4. Final overall priority results based on specialists' opinions and List of data layers and their classes prepared and weighted for evaluating the zonation maps (layer 3: AHP method)

AHP Matrix

	Lithology	Tectonic	Climatology	Hydrogeology	Geomorphology	Weight	
Lithology	1	1.1	1.6	1.2	2	Lithology	0.26
Tectonic		1	1.4	1	1.8	Tectonic	0.23
Climatology			1	0.7	1.2	Climatology	0.16
Hydrogeology				1	1.7	Hydrogeology	0.22
Geomorphology	C.I= 0.001				1	Geomorphology	0.13

The weights of the criteria and defining the weight vector is determined by the following two equations, first by normalizing the pairwise matrix (Eq. 1) and second by determining the average of each row (Eq. 2).

$$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \tag{1}$$

$$W_i = \sum_{i=1}^{n} r_{i/n} \tag{2}$$

The final grade is determined by assimilating the data layers' coefficients (Eq. 3).

$$V_H = \sum_{k=1}^{n} W_k(g_{ij}) \tag{3}$$

Results and discussion

Figure 4 indicates the karstification potential map based on the five main criteria (tectonic, hydrogeology, geomorphology, lithology and climate) in the second layer of data processing. The first layer is the result of weighting and selection of the best locations from the capable areas based on the karstification potential. The susceptive karstic water in the area is presented in a map (Figure 4) based on the drainage basins. The extent of the first to fifth grade susceptive aquifers is also presented in this figure. According to the figure the highest potential is related to the north east of Iran. The significance of each parameter is based on its impact on the feasibility and cost of the project.

Validation of the results

As illustrated in Figure 4, the significance of karst formations in the Kepet-Dagh region is at least as great as that of the Zagros and Alborz ranges, if not greater. However, due to the fact that this mountain range lies along a border and there is a possibility of water flowing out through the northeastern borders, it has not received the attention it deserves. So, the limestone formations in this region, particularly those of Mozdouran and Tirgan, have significant potential to develop into karst systems. These formations have contributed to the creation of distinctive karst landscapes and, more importantly, have given rise to valuable karst water sources. The caves of Dera Al, Bezli Dash, Qarachal, Qazlaq, Salima, Mazdooran, Karde, and Bezegan are among the most important limestone caves in the region. Validation of karstification potential map was done with the existence and location of springs and karst aquifers in the Kopet-Dagh area. According to these studies, geophysical studies were carried out by Geological Survey of Iran in the Kopet-Dagh area.

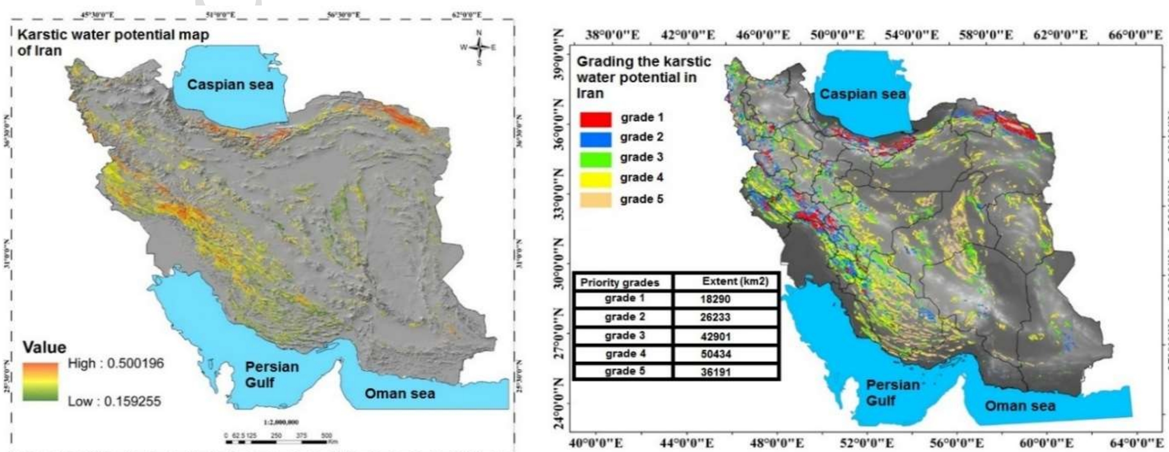

Figure 4. The highest possibility of karstification based on the studies in the provinces (first layer)

This basin is located in the northeastern of Iran. From Middle Jurassic, it was covered with a vast continental shelf sea (Berberian & King, 1981). In this basin, a thick sequence of continuous marine and continental sediments was deposited (about 10 km). No major sedimentary gap or volcanic activities during Jurassic to Oligocene have ever been reported. The Kopet-Dagh sedimentary rocks were placed in their current position due to uplifting at the end of Miocene (Ghorbani, 2013). The in Kopet-Dagh basin in the north east of Iran is selected for drilling the experimental wells based on the priorities such as the urgency of the water request, filed studies and the grade of the location based on the classification. This area is classified as the grade 1 based on the possibility of karstification. The presence of high discharge springs in the high potential area is good sign that improves the possibility of the presence of karstic water. After geophysics, drilling boreholes and water wells with high discharge in the area showed high aquifer potential. Maps and field verification were used to determine the weights of factors. This karst aquifer can be used for the domestic use of the Mashhad city.

Conclusion

There are different carbonate formations with karstification potential in Iran. Karst groundwater is a major water resource in many regions of Iran. In this study, the high potential locations of karstification and karst water resources are detected based on the geological factors which are important in karstification in carbonates. Lithology, climate, geomorphology, hydrogeology and tectonic setting are the main controlling factors of karstification. More than 25 layers are defined based on these factors in GIS software. Then a map is prepared from the high potential locations of karstification in carbonate formations in the Iran based on the experts' assessments for each of these 25 layers and their overlap by AHP. According to the results, there is a significant karst water source in the north east of Iran in the Kopet-Dagh zone. The high potential of karstification in the Kopet-Dagh zone based on the results of this study which was controlled by geophysics, drilling of boreholes and water wells, can be used as a water resource in this area like the Mashhad city.

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