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A New GIS based Application of Sequential Technique to Prospect Karstic Groundwater using Remotely Sensed and Geoelectrical Methods in Karstified Tepal Area, Shahrood, Iran

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Abstract
In this research, recognition of karstic water-bearing zones using the management of exploration data in Kal-Qorno valley, situated in the Tepal area of Shahrood, has been considered. For this purpose, the sequential exploration method was conducted using geological evidences and applying remote sensing and geoelectrical resistivity methods in two major phases including the regional and local scales. Thus, geological structures and lithological units in regional scale have been investigated for groundwater potential. In this regard, suitable potential maps have been provided in the geographical information system (GIS) environment, using fuzzy data-driven and knowledge-driven methods. To obtain the final karstic water potential model, the prepared maps were combined using fuzzy 'AND' operator. In the local scale, geoelectrical surveys were conducted in the recognized high potential zones. Consequently, the results of geological investigations, analysis of lineaments extracted from satellite imagery and geoelectrical resistivity data modeling and interpretation were integrated to decide on the position of high yield extraction wells. As a result, karstic water zones in the study area were identified, and based on that, two suitable drilling locations to access and extract karstic groundwater in the study area have been suggested.

Keywords: *combined fuzzy data-driven and knowledge-driven method, geoelectrical resistivity method, karstic groundwater potential modeling, sequential exploration approach.*

1. Introduction

Potential mapping is a multi-stage process aimed at generating target areas for further exploration of natural resources [1, 2]. There are several published research works regarding mineral potential mapping [3, 4, 5], groundwater resource exploration [6, 7, 8] and environmental studies [9].

As a result of the vital importance of water, many researchers have developed several techniques for water resource exploration. For prospecting a certain type of natural resource some indicator criteria can be used on the basis of its conceptual model and available data sets [1, 2]. To consider the simultaneous presence of indicator criteria, geographic information system (GIS) can be used as an efficient tool to generate target areas. In this regard, there are several published works in which only surficial evidences were used [10, 11, 6]. There are also some other research works in which authors have used geoelectrical methods following analyses of surficial evidences [12]. Ravi Shankar and Mohan [13] and Subba Rao [14] used a combination of surficial and hydrogeological evidences. In their study, Riyadh et al. [15] successfully integrated surficial, hydrogeological, and geoelectrical evidences. Furthermore, remote sensing techniques have been efficiently utilized to investigate hydrogeological conditions [16, 17, 18, 19], groundwater monitoring [20], as well as groundwater and resource evaluation [21, 22].

In situations lacking adequate geological and hydrogeological information, non-destructive geophysical exploration is an efficient way of exploring subsurface substances. In the past decades, several geophysical approaches have been examined to investigate karstic structures. In this regard, Šumanovac and Weisser [23], Vasconcelos and Grechka [24] and Yang et al. [25] have used seismic methods to investigate karstic zones. Kaufmann and Quinif [26], Zhou et al. [27], Gibson et al. [28], Deceuster et al. [29] and Qarqori et al. [30] have applied electrical resistivity imaging for hydrogeological and geotechnical purposes. Jardani et al. [31] and Suski et al. [32] have also employed self-potential methods to characterize fractures in karstic terrains.

Magnetic resonance sounding (MRS) is a technique that enables geophysicists to obtain information about water content directly and consequently, locate shallow water-filled karst conduits in 20-30 m depth [33, 34]. It provides valuable information to make decision about the position of high yield extraction wells [35] and the spatial position of cavities [36]. Ground penetration radar (GPR) [37, 38] and electromagnetic very low frequency (VLF) [39] have also been used successfully to localize cavities, and to estimate the mean azimuth of the fractures, respectively. In addition, susceptibility models have been used to investigate karst and sinkholes in several cases [40, 41, 42]. Furthermore, the gravimetric method has been utilized by researchers for karst or sinkhole detection [43, 44, 45].

From the aforementioned literatures, it is explicitly illustrated that there are two major phases for karstic water exploration: a) regional scale in which surficial evidences such as geology, precipitation, and fractures density are combined to generate target areas for further exploration, and b) local scale in which appropriate ground-based geophysical surveys are carried out to select drilling sites.

According to literature, various exploration means have been used by researchers. Thus, due to the importance and high quality of karstic water, in this research, an attempt has been made to explore this kind of groundwater by optimizing the use of conventional exploration techniques based on the sequential approach. In this regard, fuzzy data-driven and fuzzy knowledge-driven methods were combined in the first phase, i.e. regional scale, and then in the second phase, i.e. local scale, vertical electrical sounding (VES) and geoelectrical resistivity profiling surveys were conducted along water prospectivity (WP) zones which were extracted from the combined model in the first phase, to decide on the position of high yield extraction wells.

The main purposes of this research work could be summarized as follows:

- Conceptual model inference and designing an efficient exploration strategy. In this study therefore, we have used remotely sensed lineament delineation, integrated with other geological evidences, and geoelectrical investigations including the Schlumberger vertical electrical sounding (VES) and dipole-dipole electrical resistivity profiling, to assess the fresh water productive well location in the Tepal area, where these investigations were conducted in two major steps, including the regional scale and local scale. In this research, the Aster 15 m pixel resolution satellite imagery of the area acquired on Jan. 21, 2001 was applied to extract lineaments by the Sobel filter operation, besides using the geological map of the area (data source in regional scale). Furthermore, the Schlumberger VES and dipole-dipole electrical resistivity profiling surveys were carried out in July 2011, using the Swedish ABEM Company resistivity meter (Terrameter SAS-4000), respectively (data source of local scale).

– Integrating the weights of structural evidence classes based on fuzzy data-driven weighting method, without expert-based assignment of evidential weights, could be proposed as a new approach for water resource prospectivity. Moreover, the lithological evidence map was weighted based on the fuzzy knowledge-driven method.

Finally, the two mentioned fuzzy evidence maps were combined to obtain the WP model. By integrating the results of the above-mentioned methods, suitable locations of drilling water wells were obtained, to explore and extract karstic groundwater.

2. Methodology

In this research work, remote sensing and geological investigations have been implemented in GIS environment, for the zonation of areas with ground water potential. In this regard, fuzzy evidential maps (lithology and intersection point density maps) were combined using fuzzy 'AND' operator. At the end, geoelectrical resistivity surveys were conducted to evaluate the presented karstic WP model.

3. Conceptual model of karstic water resources

The responses of underground materials in the surface with respect to the methods of exploration are affected by a set of complex geological patterns and, hence, interpretation of data obtained from such complicated domains is difficult [46]. So the complexity of the geological setting could be simplified using a multi-stage exploration process [46] such as the sequential approach [46, 47], for sustainable groundwater supplies in the terrain underlying by crystalline basement rocks. For this, in the first step, the conceptual model which characterizes underground resource should be made [47]. Defining a conceptual model of water resource prospectivity in a study area requires knowledge of geological processes of forming water resource in well known (explored) areas. Therefore, it is important to review water resource models, which describe the geological characteristics of specific types (here, karstic water) of water resource in a study area [48]. Furthermore, analysis of spatial distributions of water resource and analyses of spatial associations of water resource and indicators of geological features like host rock and structural feature [49], are useful in making the conceptual model of water prospectivity [49].

3.1. Geological and lithological criteria

The first and indispensable step in karst hydrogeological investigations is the characterization of the geological and geomorphological framework. This includes the interpretation of existing geological literature, maps and section, as well as data acquired from fieldwork [50]. Therefore, geology covers the basis for the effective study and management of water resources [51].

Lithology is one of the major factors that affect porosity, permeability and karstifiability of rocks dependent upon the climatic and tectonic conditions of a region. The purity of the rock [50, 52] as well as geomorphological mainstream and drainage [53] controls the karstifiability. Hence, the weight of lithological evidences such as pure limestone units, mainstream beds and alluviums; must be allocated fairly high in GIS-based karstic water potential modeling.

3.2. Structural and geomorphological criteria

In hard rock areas, it is important to identify and characterize fractured zones, since they lead to preferential groundwater flow pathways and enhance well productivity [54]. Lattman and Parizek [55] investigated the relationship between fracture traces and solution zones in hard rocks. They concluded that fracture traces reflect underlying fracture concentrations and are useful as a prospecting guide in locating zones of increased weathering, solubility and permeability. In addition, structural trends such as discontinuities can be detected in many forms, such as faults, joints, bedding planes or foliations and such discontinuities can be detected in the form of lineaments detected using satellite imagery [56, 57]. Therefore, an effective approach for delineation of fracture zones could be based on lineament indices extracted from satellite imagery [58].

Using remotely sensed satellite imagery, lineaments are detected by alignment trends of features such as vegetation, drainage patterns, outcrop truncations, soil moisture and topography. Such lineaments are indicative of secondary porosity in the form of fractures and if they are intersected by a well at depth, they have the potential to supply large and reliable quantities of water [59, 60, 61, 18]. Thus, sustainable groundwater supplies in the terrain underlying crystalline basement rocks require lineament analysis for proper sitting of boreholes [57].

According to Hung et al. [62] lineament intersection frequency, i.e. the number of intersections of lineaments per unit area under investigation, can be included in lineament analysis, and the zones of relatively high lineament intersection density are identified as zones of high degree of rock fracturing, which are prerequisite for secondary porosity and solution widening in hard rock terrain, and consequently, groundwater conduit development in an area. Therefore, the zones of high lineament intersection density over the study area are considered as feasible zones for groundwater potential evaluation in the present study (Figures 5 and 6).

3.3. Geophysical criteria

Geophysical investigation could be utilized for karstic water exploration in both prospecting and detailed exploration phases. In the electrical resistivity method, water-bearing fractured zones have high resistivity contrast with compact bedrock [63, 64]. Hence, they are good targets for geoelectrical resistivity investigation. In the present research work, geoelectrical resistivity technique was conducted in order to perform the detailed exploration phase.

Figure 1 presents the sequential approach for karstic water exploration in two major phases, regional and detailed exploration phases, which have been followed in this research for the study area.

In the second phase of our exploratory schedule, after inference of karstic water exploration network including regional scale and local scale, the presented sequential design was carried out as discussed in sections 4 and 5 as follows:

4. First phase- regional scale exploration stage

4.1. Combining knowledge- driven and data- driven fuzzy methods

Fuzzy logic modeling was initially developed by Zadeh [65] as a generalization of classic logic. Fuzzification is the processes of converting individual sets of spatial evidence into fuzzy sets. The Fuzzy set is defined as a class of objects with a continuum of grades of memberships; the value 0 means that x is not a member of the fuzzy set; the value 1 means that x is fully a member of the fuzzy set. The values between 0 and 1 characterize fuzzy members that belong to the fuzzy set only partially [66, 2]. Consequently, for karstic WP modeling, the fuzzy score of evidential maps is usually between 0 and 1.

There are two main types of GIS-based approach for potential mapping: knowledge-driven predictive modeling (based on qualitative analysis) and data-driven predictive modeling (based on quantitative analysis) [2]. During the early days of this subject, the fuzzy score of different classes in an evidential map were assigned subjectively by expert judgment, on the basis of his knowledge and experience [67, 68]. However, it was later performed based on the mathematical exploration of data [67]. In conventional data driven predictive modeling, systematic error appears because it is dependent upon exploration data but recently, the mathematical method was developed to avoid this problem for some evidential maps. This method is carried out in order to fuzzify the IPD map, which integrated the fuzzified knowledge-driven lithological map using the fuzzy ‘AND’ operator to construct a karstic WP model.

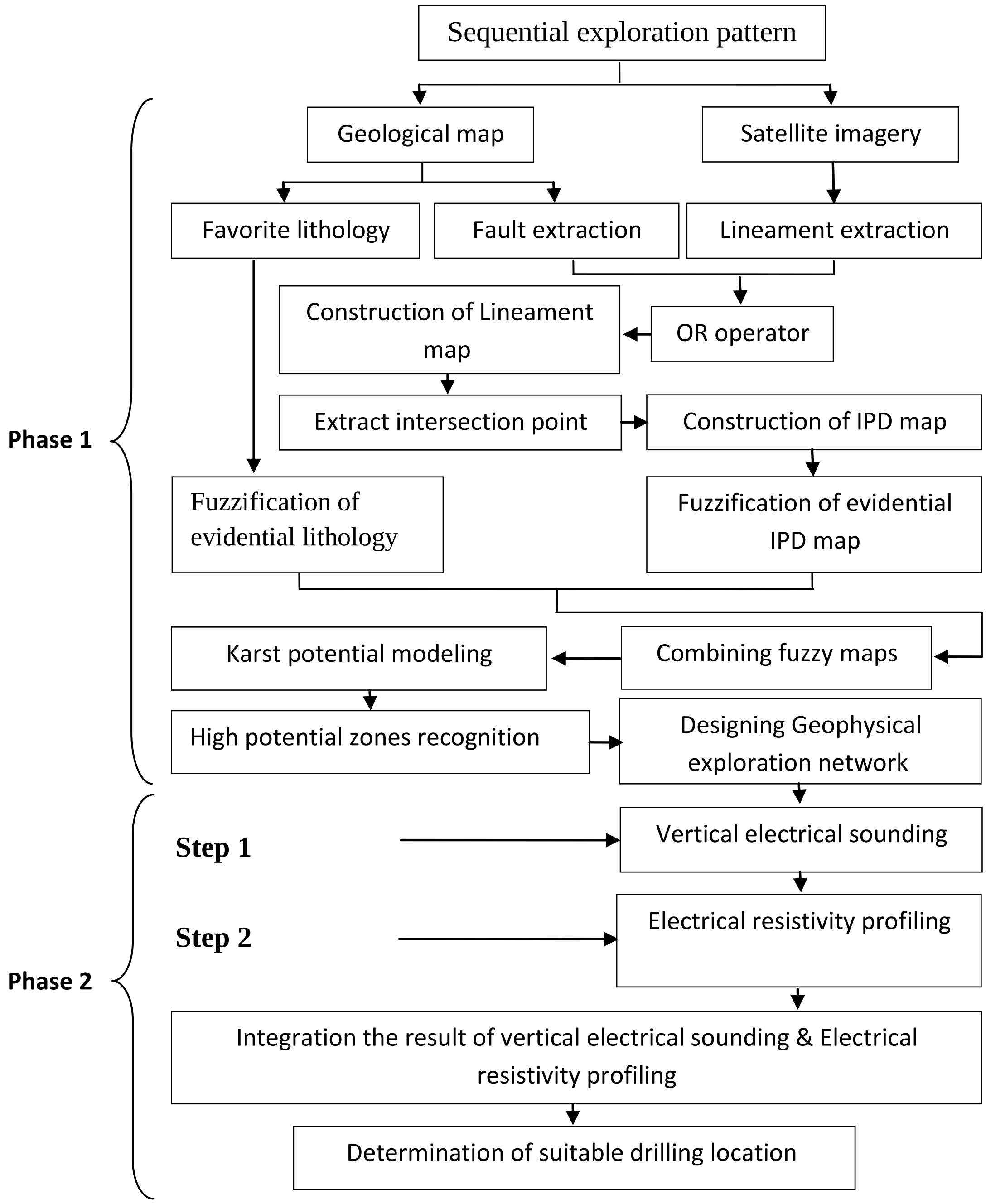

Fig. 1. Main sequences and phases of karstic water potential modeling and exploration in Tepal area, Shahrood

4.2. Fuzzification of evidential lithological map using knowledge driven approach

Since karstifiability is closely dependent on lithology, it demands that the fuzzified evidential lithology map be constructed for integration with other evidence. In this regard, the geological map of Shahrood on a scale of 1:100,000 was investigated, in order to extract the favorite lithological units.

The intended study area (Tepal Mountains), as illustrated in Figure 2, is situated in the west to north-west of Shahrood city. According to the geological map of Tepal area (Fig. 2), the middle to upper Jurassic Lar formation (Jl unite), that is characterized by light grey, thick bedded to massive limestone and cherty limestone, ammonite bearing with absence of marl sequences [69] and mainstream (Qal unit) prepare the favorite lithology and geomorphology condition for karst aquifer development. Thus, fuzzy scores of both Jl and Qal units have been assigned 0.6 and 0.98, respectively, and the fuzzy score of other lithological units have been suggested to be 0.01 based on expert judgment (Fig. 3).

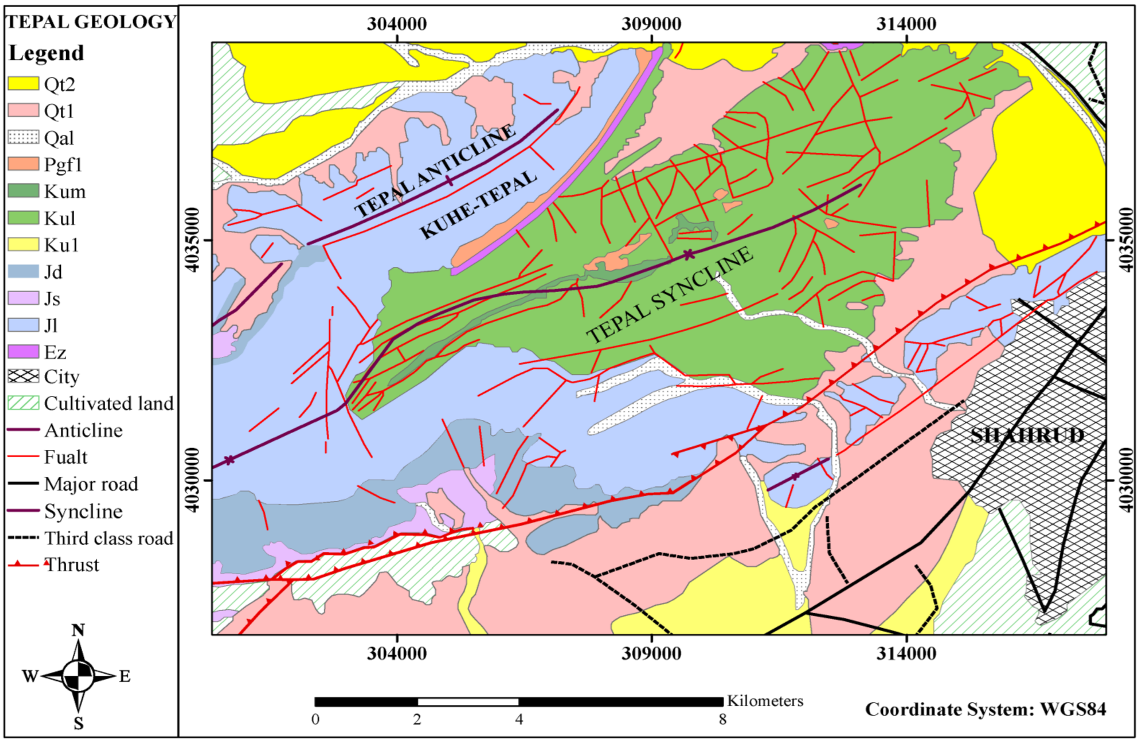

Fig. 2. Geological map of Tepal area [69]

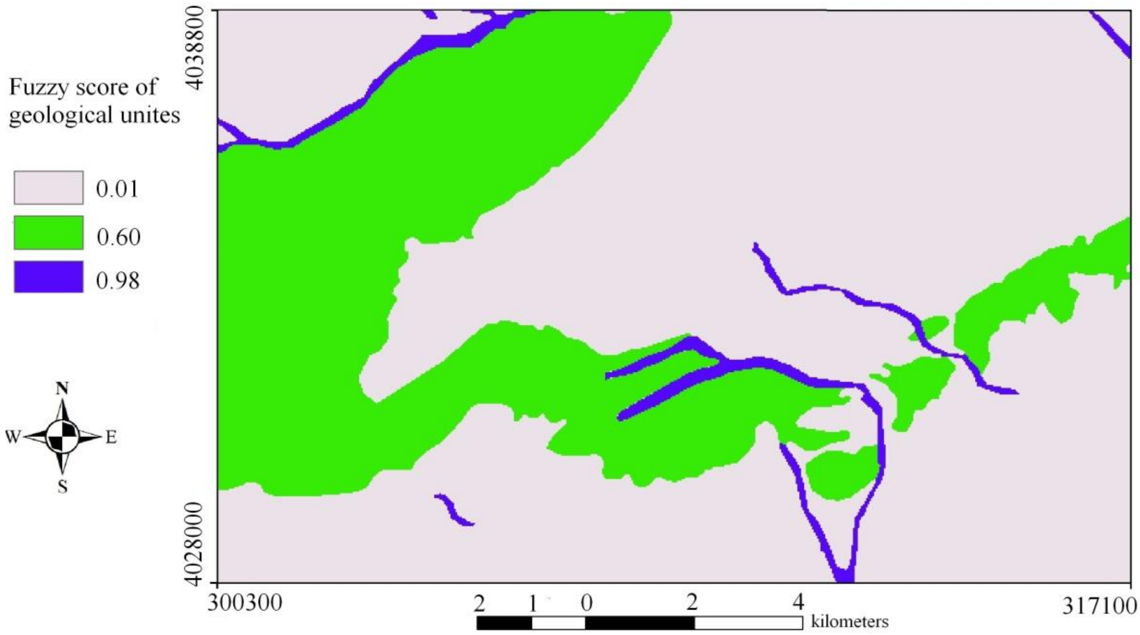

Fig. 3. Fuzzy score of lithological units

4.3. Lineament analysis methodology

4.3.1. Remote sensing

Schowengerdt [16] noted that the Visible and Near Infra-Red (VNIR) region of the spectrum has the smallest spectral error. Furthermore, Hung et al. [58] have demonstrated that, due to high lineament frequency and accuracy, VNIR is the best band for automatic lineament extraction from satellite images. Hence, in this research, VNIR was used and processed by a suitable filter to extract lineaments.

Different techniques have been used for lineament extraction. The most effective method was found to be image enhancement by different filters and visual extraction of lineaments, checking and removal of questionable lineaments and integration of lineaments extracted from different filters in one layer. Here, the procedures that have been used to extract lineaments from Aster 15 m pixel resolution satellite imagery are described. Following Suzen and Toprak [70] for delineation lineaments, directional Sobel filter operation has been applied. Extracted lineaments using directional Sobel filter from aster VNIR band 3 in the study area is shown in Figure 4. Moreover, Figure 4 represents the intersection points of lineaments in the study area.

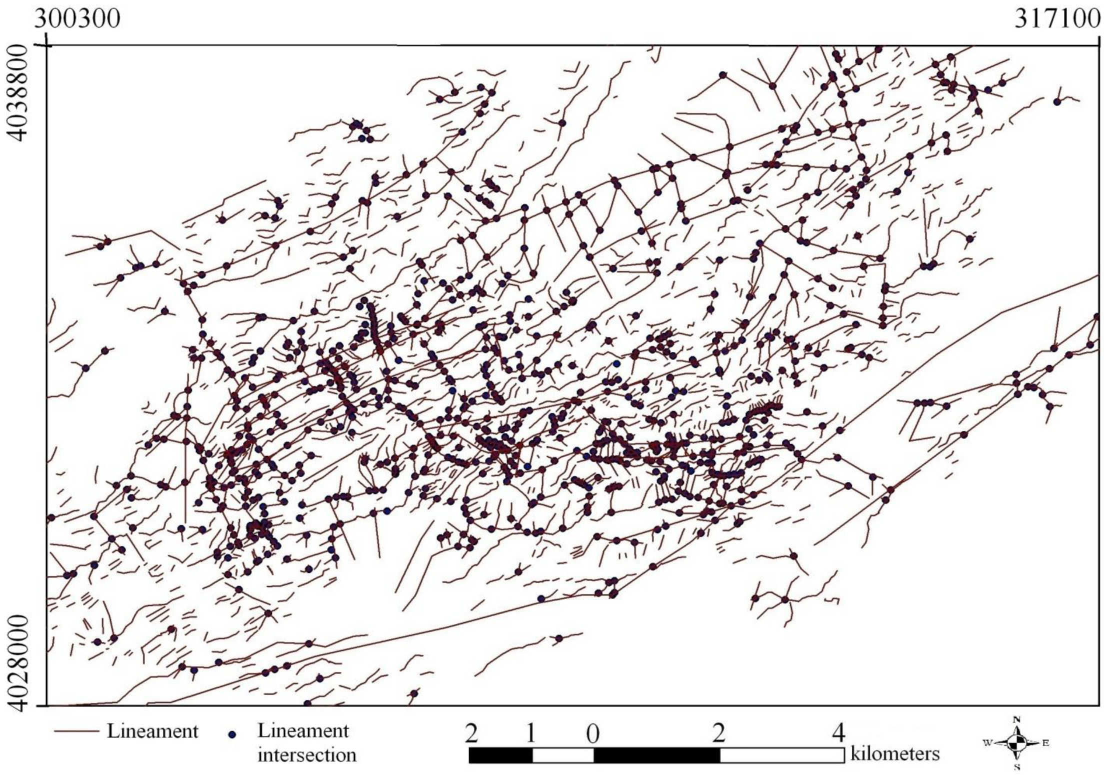

Fig. 4. Lineaments and intersection of lineaments in Tepal area

4.3.2. Intersection point density

According to Hung et al. [62], the intersection points of lineaments, identified as zones of high degree of rock fracturing are essential for increasing secondary porosity in hard rock terrain and they can be qualified as more favorable than lineaments density for water infiltration and solution widening. Therefore, the intersections point density (IPD) map of the study area has been prepared using GIS (Fig. 5).

In GIS-based mapping, selection of a suitable grid resolution for output maps must be based on scientific justification. Generally, the cell size should be fine enough so that the closest point pairs do not fall into the same cell. However, if such a grid is too fine to be visualized or printed at a specified scale, the cell must be appropriately coarsened [71]. In practice, the appropriate cell size can be determined from the density of samples and mapping scale, or the structure of point patterns [71, 72].

The compromise legible cell size can be

determined according to traditional cartographic concept [68, 71, 72], as follows:

$$r = SN \times 0.0005 \quad (1)$$

$$SN = \sqrt{\frac{A}{n}} \times 10^2 \quad (2)$$

where r is the cell size, SN is the scale number, *A* is total area of a map and *n* is the total number of observations.

According to Equations (1) and (2), the cell size of our case study is 30 m. Therefore, a pixel size of 30 m × 30 m was used for this study and the output IPD map is as presented in Figure 5.

4.3.3. Fuzzification of evidential structural map based on data driven approach

According to Figure 5, the values of IPD are non-fuzzy and are not appropriate as fuzzy evidence scores. Thus, following Zimmermann [73] and Porwal [4], the calculated values of IPD were transformed to fuzzy ones by applying the following logistic function:

$$F(IPD) = \frac{1}{1 + \exp(-a(IPD - b))} \quad (3)$$

where *F (IPD)* is a fuzzy score, *b* and *a* are the inflection point and slope, respectively, of the logistic function. The parameters *b* and *a* determine the shape of the logistic function and, hence, the output values. These parameters were chosen arbitrarily. For the present study, the values 0.2 and 20 were considered for *a* and *b*, respectively.

The fuzzy scores of IPD values are as shown in Figure 6. As a result of the fact that the map of logistically-transformed IPD values is a weighted fuzzy evidence layer, it can be integrated with a weighted fuzzy lithological evidential map.

4.4. Integration of fuzzy evidential maps

The fuzzy 'AND' operators were used to integrate the map of fuzzy scores of IPD with the lithological evidential fuzzy map for karstic WP modeling and, hence, detailed exploration phase targeting (Fig. 7). Also, Figure 8 shows the sketch map of conducted geophysical investigation network on the WP models, including the vertical electrical resistivity sounding and electrical resistivity profiling methods.

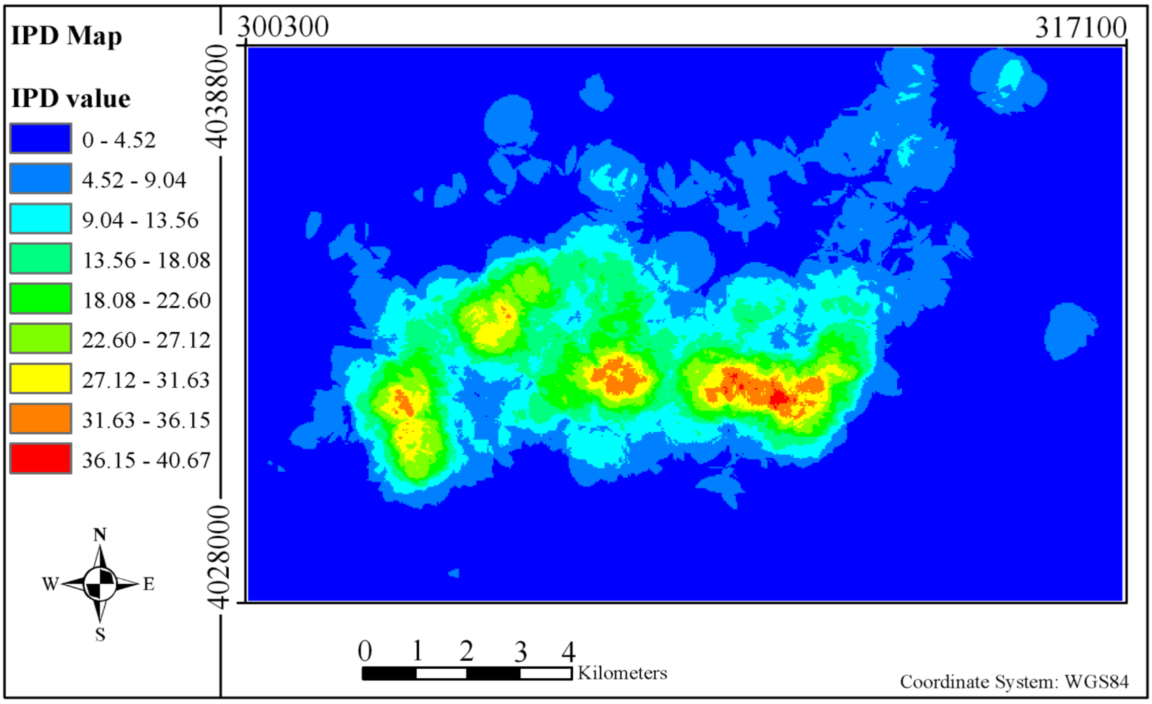

Fig. 5. IPD map of the study area (cell size: 30*30 m^2)

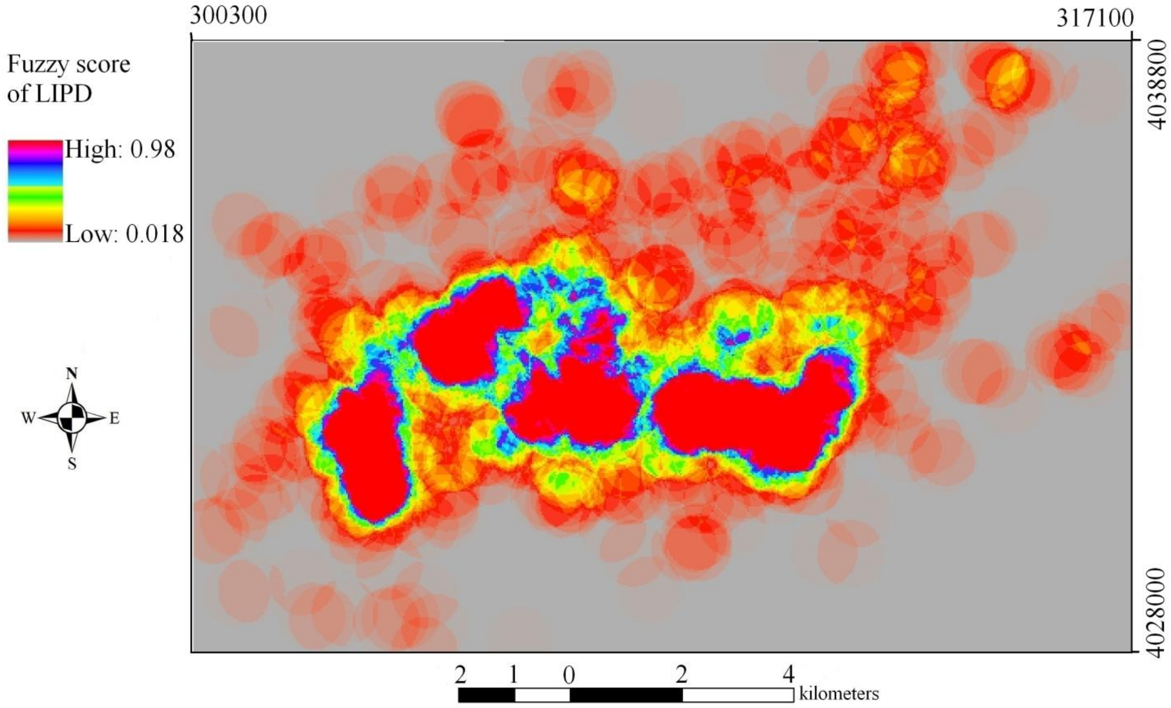

Fig. 6. Fuzzy score of lineament intersection point density (LIPD) (cell size: 30*30 m^2)

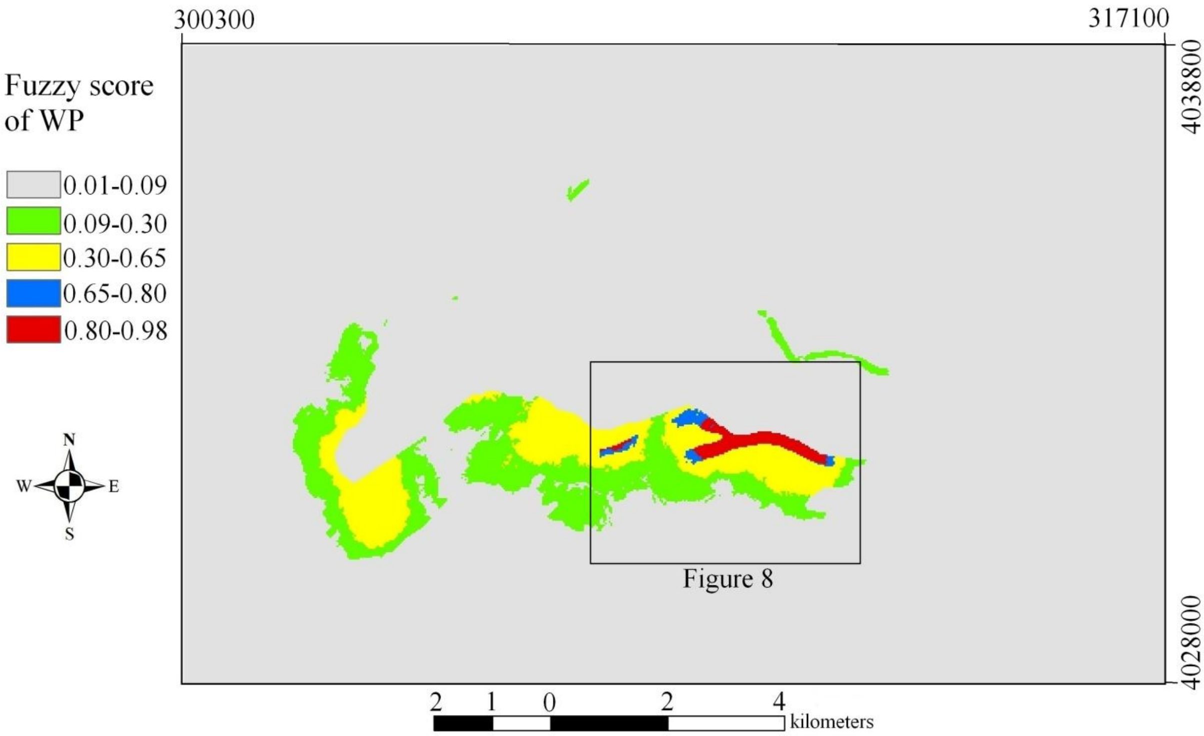

Fig.7. Fuzzy score of water prospectivity in Tepal area, obtained based on fuzzy 'AND' operator

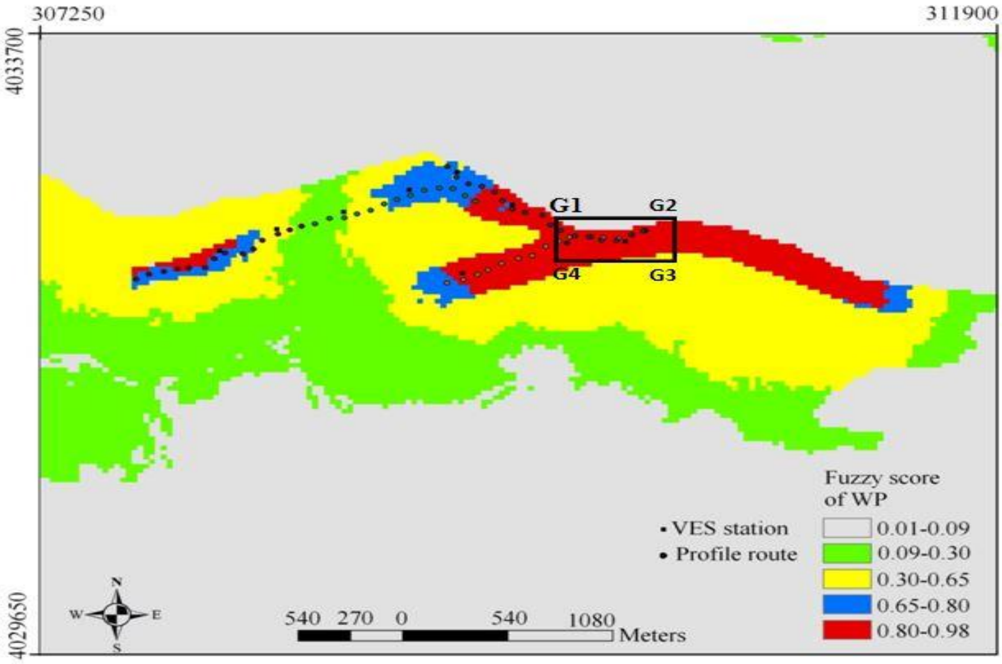

Fig. 8. Sketch map of Fuzzy score of water prospectivity in Tepal area, the position of gravimetry (G1G2G3G4) and geoelectrical data surveys are presented

5. Second phase - local exploration

For a successful groundwater exploration the remote sensing processed results must be backed by airborne or ground base geophysical survey. Fracture zones are spatial targets for geophysical and hydrogeological exploration, because, in general, the geophysical properties of fracture zones and host materials are strongly different. It is, therefore, suggested that the high fuzzy score of WP should be combined with the results of detailed geoelectrical surveys. In Figure 8, the positions of geoelectrical surveying points and lines, composed of the Schlumberger VES points and dipole-dipole profiling lines, are shown. Some other details of geological and geoelectrical investigations are as shown in Figure 9.

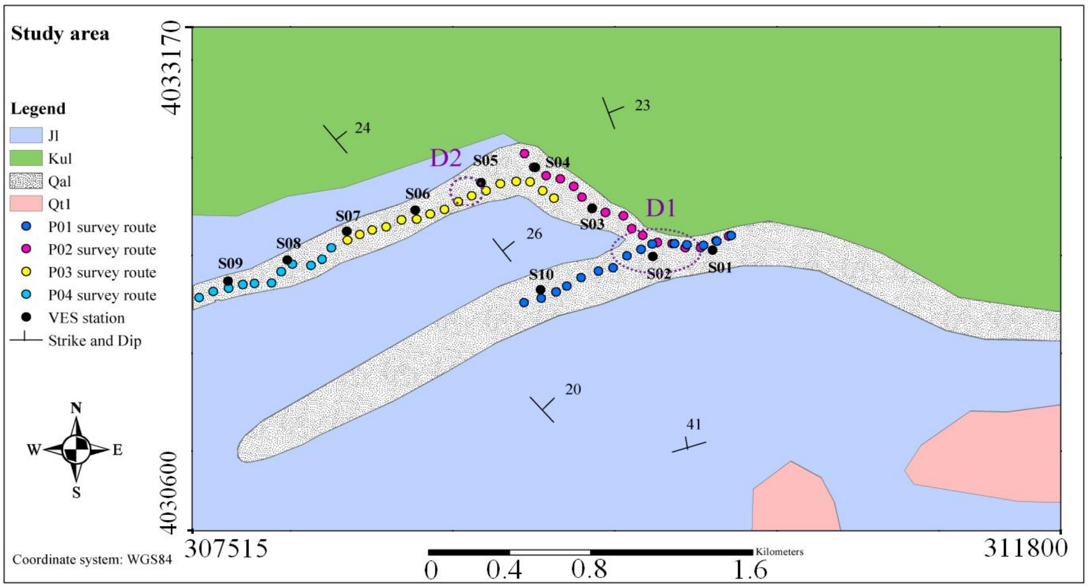

Fig. 9. The geological map of the study area, in which the locations of 10 resistivity sounding points S01 to S10 and 4 resistivity profiling survey lines are denoted. D1 and D2 are the recognized suitable locations for drilling to access and extract karstic groundwater.

5.1. Geoelectrical resistivity VES and profiling

In the electrical resistivity method, one can expect that water-bearing fractured zones have strong resistivity in contrast with the compact bedrock. Thus, these zones are considered as good targets in electrical resistivity investigations.

For direct current (DC) electrical resistivity surveys, the common configurations are the Schlumberger, Wenner and dipole-dipole spreads [74]. Some factors affecting the choice of array type are given in Table 1.

Table 1. Comparison of the Wenner, Schlumberger and dipole-dipole electrode arrays [75].

Criteria	Wenner	Schlumberger	Dipole - Dipole
Vertical resolution	Good	Moderate	Poor
Depth of penetration	Poor	Moderate	Good
Suitability to VES	moderate	Good	Poor
Sensitivity to orientation	Yes	Yes	Moderate
Sensitivity to lateral inhomogeneities	High	Moderate	Moderate
Labor intensive	Yes(no*)	Moderate(no*)	Moderate(no*)
Availability of interpretational aids	Good	Good	Moderate

*****when using a multicore cable and automated electrode array.

The high fuzzy score of the WP area, is determined on the basis of favorite geological and structural evidences due to the existence of bedding with a low dip (20- 26 degrees) (Fig. 9), the water table (Fig. 10 and Table 2) was determined by performing VES surveys, using the Schlumberger array. Due to the presence of essential inhomogeneities in such karstified areas, it is normally required to use several methods in order to obtain enough information from the subsurface ground. Due to the low sensitivity of the Schlumberger array to lateral in homogeneities, as well as the good characteristics of the dipole-dipole array, especially its moderate depth of penetration, low EM coupling between the current and potential circuits and capability of mapping vertical structures, such dykes and cavities relevant to high sensitivity to horizontal changes in resistivity [76], the combination of these two arrays for vertical electrical sounding and electrical resistivity profiling, respectively, can lead to an optimized resistivity survey method in the study area. Hence, VES surveys were carried out in 10 resistivity sounding points S01 to S10 (Figs. 8 and 9) using the Schlumberger array with a maximum electrode separation of 1000 m. In addition, the resistivity profiling surveys were carried out along 4 lines (Figs. 8 and 9) of more than 4 km long using a dipole-dipole electrode array with 75 m electrode spacing and dipole steps 1 to 8 in the study area.

One-dimensional (1-D) modeling and interpretation of the VES data, using theoretical master curves and IX1D software (produced by Interpex Company), and two-dimensional (2-D) modeling and interpretation of the resistivity profiling data using RES2DINV software was performed. The resistivity modeling and interpretation results of the VES and resistivity profiling data are shown in Figures 10 and 11. Besides, Tables 2 and 3 clarify the explanation of VES results.

Based on the VES curves indicated in Figure 10 and the interpretation results (Table 2), we can summarize the interpreted results of all sounding points as illustrated in Table 3.

The interpretation of four soundings, S02, S03, S04 and S08, suggests the presence of water bearing zones as presented in Figure 10 and Tables 2 and 3. In other VES locations, the resistivity values of the subsurface layers are higher than the resistivity values of water-bearing formations; thus, no water-bearing zones could be found in these subsurface layers with relatively high resistivity.

Furthermore, the inversion modeling results of the resistivity profiling data along 4 lines P01, P02, P03 and P04, shown by the resistivity sections in Figure 11, imply various resistive and conductive zones in the subsurface. The conductive zones bounded by white dashed lines in the resistivity sections P01, P02 and P03 represent the favorite karstic water zones.

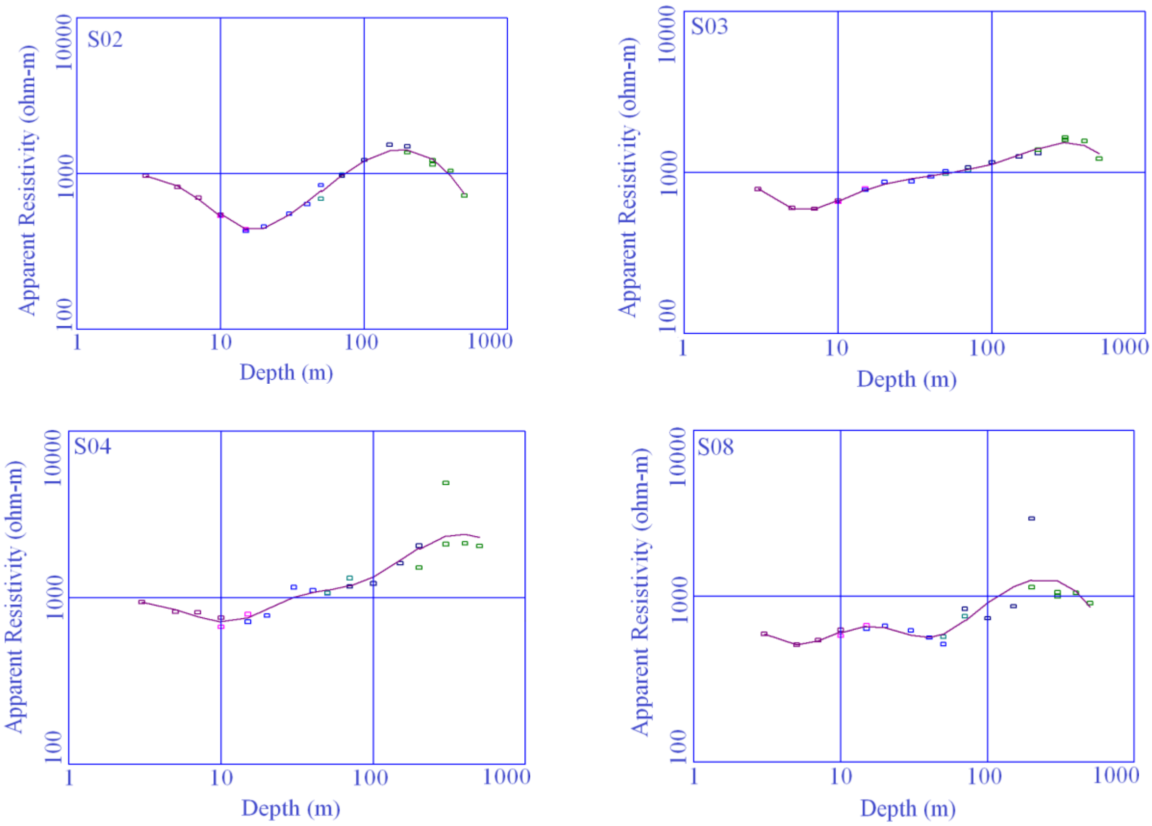

Fig. 10. 1-D modeling and interpretation results of the VES, obtained using IX1D software

Table 2. Corresponding interpretation of VES S01 – S10 (Resistivity (R) and thickness (T) values are in ohm-meter and meter, respectively

VES station	**S02**		**S03**		**S04**		**S08**	
RMS error	**4.77%**		**3.5%**		**19.85%**			
N	R	T	R	T	R	T	R	T
1	1028.1	3.39	1099.3	1.47	985	2.49	738.51	1.67
2	315.16	11.62	325.18	2.49	753.07	1.76	196.5	1.38
3	828.62	10.25	1647.9	3.18	327.57	2.65	1668.7	5.06
4	3834.6	67.83	857.86	7.05	693.97	2.13	165.61	12.02
5	275.64	∞	932.47	11.71	2797.4	9.81	8010.1	39.11
6	****	****	1489.3	16.17	437.16	18.28	757.86	3.69
7	****	****	637.35	21.92	1379.8	14.51	501.69	42.80
8	****	****	1238.4	15.31	13554	52.31	118.34	∞
9	****	****	3442.6	25.65	5076.1	51.33	****	****
10	****	****	5563.4	71.60	233.94	∞	****	****
11	****	****	97.956	∞	****	****	****	****

Table 3. Interpretation of VES surveys in sounding locations or points S01 to S10

Point	**Interpretation**
S02	In the depth of more than 93 m, the resistivity decreases to 275 Ω.m which can indicate a poor to moderate potential of karstic water resource.
S03	In the depth of more than 176 m, the low resistivity layer (98 Ω.m) can be related to a moderate to good potential of karstic water resource.
S04	In the depth of more than 155 m, a geoelectrical layer with a resistivity of 233 Ω.m shows a poor potential of water resource.
S08	Possible existence of a water-bearing zone with a resistivity of 118 Ω.m in the depth of more than 105 m.
Other VES	Absence of water-bearing zone

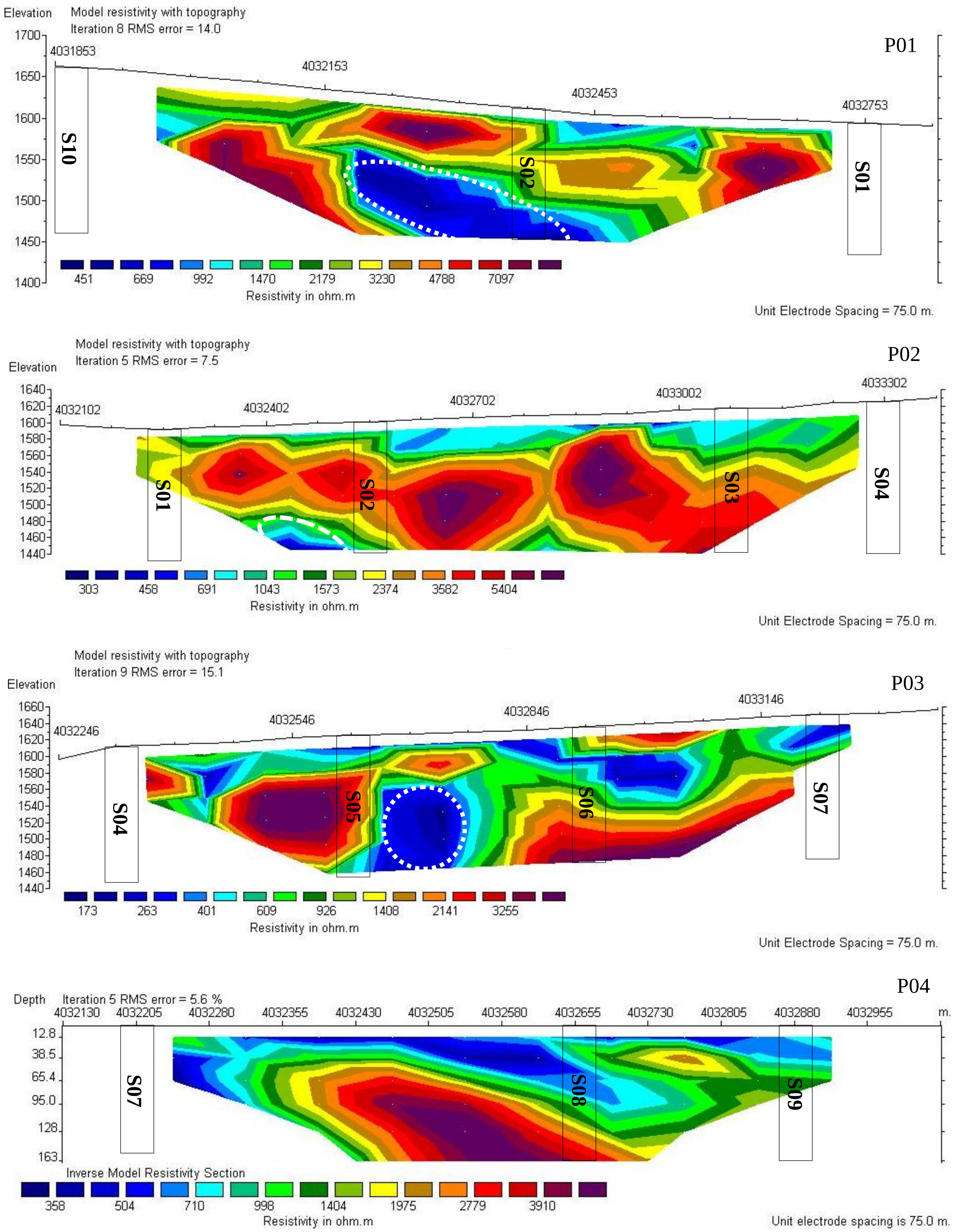

Fig. 11. The 2-D modeling and interpretation results of the resistivity profiling data along 4 lines P01 - P04, obtained using RES2DINV Software. The VES locations or points S01 to S10 across these resistivity profiling sections are also shown.

6. Discussion

As the main purpose of exploration is to achieve success at a reasonable cost in terms of expenditure of time, money, and skill, various exploratory evidences relative to karstic water resources, and proportional to the scale of exploration, should be attended. In this regard, designing an appropriate strategy for karstic water exploration and determination of a high potential location to supply large and reliable quantities of water have been investigated as the two main aims of this research work.

Lithology, faulted zones and the influence of a synclinal fold system around the study area are the favorite criteria controlling certification. The geological map of the study area (Fig. 2) illustrates limestone formations without marl sequences and the development of the mainstream implies favorite lithology, and the IPD map (Fig. 5) implies favorite structural criteria for karstification and occurrence of karstic terrain development in the subsurface. Moreover, the presence of low dip bedding (Fig. 9) and mean annual rainfall of 130 mm in the Shahrood region, provides favorite conditions in the study area. Therefore, based on the information mentioned above, the existence of water-bearing zones in the subsurface can be expected.

To investigate this subject, both knowledge-driven fuzzified lithological evidence and data-driven fuzzified IPD evidence were integrated using the fuzzy 'AND' operator, and as a result, the WP model of the study area was provided for the first phase of groundwater exploration performance in the area.

Sequentially, in the second exploration phase geoelectrical resistivity investigations, comprising of VES (using the Schlumberger array) and resistivity profiling (using dipole-dipole array), were carried out in locations whose WP values are fairly high (Fig. 8).

At the end, the measured geoelectrical data were modeled and interpreted in order to determine high potential location, and to supply large and reliable quantities of karstic water.

As a result of the interpretation of resistivity data, the presence of water bearing zones in the subsurface of sounding points S02, S03, S04 and S08 (Fig. 10 and Tables 2 and 3) could be predicted. In addition, reduction of resistivity values in some districts of P01, P02 and P03 dipole-dipole profiling sections (inside white dashed lines in Fig. 11) can be considered as water bearing zones.

7. Conclusions

The present study highlights the following findings in an attempt to improve existing methods for representation of exploratory evidence by karstic water prospectivity mapping.

1. Sequential approach, including regional scale and local scale exploration phases, could be used to investigate sustainable groundwater supplies in the terrain underlying crystalline basement rocks. In addition, the harmful effects of inherent uncertainty and risk features of exploration activities could be decreased by performing this approach.

2. For karstic water potential modeling, geological evidences such as limestone units, drainage, Quaternary gravels, marls and lineament intersection point density could be utilized, efficiently, in the regional scale.

3. Fuzzy data-driven based on utilized logistic function could reduce the systematic error which occurs during conventional data-driven method, as well as the error of expert judgment in the knowledge-driven method.

4. Based on the geological, hydrogeological and structural features of the study area, the combination of the Schlumberger and dipole-dipole arrays for VES and electrical resistivity profiling, respectively, in the detailed exploration stage, is a proper resistivity survey technique in terms of the necessity for deep investigation, sensitivity to horizontal changes in resistivity as well as time and fund consumption.

5. The obtained section of the P01 resistivity profiling survey, conducted on favorite geological and structural situation with regard to high lineament intersection density, was integrated with favorite lithology units, and as a result, the presumable water bearing zones were thoroughly recognized on a resistivity model (inside white dashed circle or ellipse in Figure 11). Moreover, the VES results in sounding point S02 and the resistivity profiling sections along the P02 line, confirm the aforementioned conclusion. The white dashed circle or ellipse in Figure 11 coincides with the location of the intersection of two main branches of mainstreams (D1 in Figure 9). Thus, it is proposed that the first priority for drilling water well is to access karstic groundwater. Based on interpretation of the S05 VES and P03 profiling section,

district D2 in Figure 9 was introduced as the second priority and proper location for drilling water well, in order to access karstic groundwater.

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