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Arch. Min. Sci. **62** (2017), 3, 509-530

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.1515/amsc-2017-0038

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PROSPECTIVITY MODELING OF KARSTIC GROUNDWATER USING A SEQUENTIAL EXPLORATION APPROACH IN TEPAL AREA, IRAN

MODELOWANIE WYSTĘPOWANIA WÓD GRUNTOWYCH POCHODZENIA KRASOWEGO W REGIONIE TEPAL W IRANIE METODĄ BADANIA SEKWENCYJNEGO DLA POTRZEB PRAC POSZUKIWAWCZYCH

The purpose of this study is water prospectivity modeling (WPM) for recognizing karstic water-bearing zones by using analyses of geo-exploration data in Kal-Qorno valley, located in Tepal area, north of Iran. For this, a sequential exploration method applied on geo-evidential data to delineate target areas for further exploration. In this regard, two major exploration phases including regional and local scales were performed. In the first phase, indicator geological features, structures and lithological units, were used to model groundwater prospectivity as a regional scale. In this phase, for karstic WPM, fuzzy lithological and structural evidence layers were generated and combined using fuzzy operators. After generating target areas using WPM, in the second phase geophysical surveys including gravimetry and geoelectrical resistivity were carried out on the recognized high potential zones as a local scale exploration. Finally the results of geophysical analyses in the second phase were used to select suitable drilling locations to access and extract karstic groundwater in the study area.

Keywords: Water prospectivity modeling; Sequential exploration approach; fuzzy logic; Karstic groundwater

W pracy modelowano przepływy wód gruntowych w celu rozpoznania warstw wodonośnych wód pochodzenia krasowego dla potrzeb prac poszukiwawczych, poprzez analizę danych geologicznych i poszukiwawczych z rejonu doliny Kal-Qorno w regionie Tepal, w północnej części Iranu. W oparciu o analizę sekwencyjną danych geologicznych wytyczono granice obszarów do dalszych badań poszukiwawczych. Analiza obejmuje dwa zasadnicze etapy, z uwzględnieniem skali regionalnej oraz lokalnej. W pierwszym etapie w oparciu o dane o strukturach geologicznych i właściwościach skał modelowano możliwości występowania wód w aspekcie skali regionalnej. Na tym etapie w ramach poszukiwań warstw

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wodonośnych pochodzenia krasowego zamodelowano warstwy struktur skalnych dowodzące występowania wód w oparciu o podejście logiki rozmytej. Po wytyczeniu obszarów docelowych, w drugim etapie badań przeprowadzono szczegółowe analizy geofizyczne z wykorzystanie grawimetrii i badań oporności geo-elektrycznej w strefach potencjalnego występowania wód, w aspekcie badania w skali lokalnej. W końcowym etapie, wyniki analiz geofizycznych otrzymane w drugim etapie procedury wykorzystane zostały do wyznaczenia miejsc wykonania odwiertów do uzyskania wód gruntowych pochodzenia krasowego w badanym terenie.

Słowa kluczowe: modelowanie występowania wód, badanie sekwencyjne, logika rozmyta, wody gruntowe pochodzenia krasowego

1. Introduction

Prospectivity modeling is a multi-stage process to generate target areas for further exploration of natural resources (Bonham-Carter, 1994; Carranza, 2008). Prospectivity modeling methods have been used in mineral exploration (e.g., Zahiri et al., 2006; Porwal, 2006; Carranza, 2008; Yousefifar et al., 2011; Yousefi et al, 2012, 2014), groundwater resource exploration (e.g., Sener et al., 2005; van Beynen et al., 2012; Elez et al., 2013, Nampak et al., 2014) and environmental studies (e.g., Chang et al., 2008).

For prospecting a certain type of natural resource, indicator criteria are extracted based on the conceptual model of the type of natural resource, and are used to generate prospectivity model considering available data sets (e.g., Carranza, 2008; Bonham-Carter, 1994).

In this regard, for groundwater prospectivity modeling, there are several works in which evidence layers were used, which generated only based on surficial data (Jaiswal et al., 2003; Srinivasa Rao & Jugran 2003; Sener et al., 2005). There are also some other research works in which authors used geoelectrical methods following analyses of surficial evidences (e.g., Srivastava and Bhattacharya, 2006), combination of surficial and hydrogeological evidence (Ravi Shankar & Mohan, 2006; Subba Rao, 2006), and integration of surficial, hydrogeological, and geoelectrical evidences (Riyadh et al., 2013).

Furthermore various prospectivity techniques such as multi- criteria decision analysis (Chenini et al., 2010; Gupta & Srivastava, 2010), analytical hierarchy process (Chowdhury et al., 2009), weights- of- evidence (Lee et al., 2012), fuzzy logic (Shahid et al., 2002; Ghayoumian et al., 2007; Rather et al., 2012) have been used for water prospectivity modeling (WPM).

In the situations of lacking sufficient geological and hydrogeological information, non-destructive geophysical exploration is an efficient way to explore subsurface substances (Vasconcelos & Grechka, 2007; Robert et al., 2011). In the past decades, several geophysical approaches have been examined to investigate karstic water and karstic structures. Seismic methods to investigate karstic zones (Vasconcelos & Grechka, 2007; Yang et al., 2013), electrical resistivity imaging for hydrogeological and geotechnical purposes (Gautam et al., 2000; Sumanovac and Weisser, 2001; Kaufmann and Quinif, 2002; Gibson et al., 2004; Deceuster et al., 2006; Qarqori et al., 2012), self-potential methods to characterize fractures in karstic terrains (Jardani et al., 2006a; Suski et al., 2008), magnetic resonance sounding (MRS) to study shallow water-filled karst conduits (Perttu et al., 2012; Legtchenko, 2013), ground penetration radar (GPR) and electromagnetic very low frequency (VLF) (Marcak et al., 2008; Carrière et al., 2013) to localize cavities, and to estimate the mean azimuth of the fractures, respectively, susceptibility models to investigate karst and sinkholes (Garcia-Moreno et al., 2011; Margiotta et al., 2012), and gravimetry method to detect karst and sinkhole (Kaufmann & Romanov, 2009; Chalikakis et al., 2011; Youssef et al., 2012) are examples of such geophysical approaches.

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, fractures density, topography and drainage network with hydrogeological evidences such as groundwater table and charge of the springs are combined to generate target areas for further exploration (e.g, Ford & Williams, 2007; Goldscheider & Drew, 2007), and b) local scale in which appropriate ground-based geophysical surveys are carried out to select drilling sites (e.g., Kirsch, 2006; Zarroca et al., 2011; Maiti et al., 2012; Yeboah-Forson et al., 2014).

The purpose of this paper is to use a sequential exploration phases including both regional and local scale exploration techniques to delineate potential zones for water prospecting. For this sequentially we used fuzzy logic modeling approach (e.g., Yousefi et al., 2012; Ford et al., 2013; Yousefi et al., 2014; Beucher et al., 2014) for WPM in regional scale and ground-based geophysical surveys (gravity and electrical resistivity) to select drilling sites in local scales. To evaluate the sequential exploration approach we selected Tepal area, Iran as case study. Because of the importance and high quality of karstic water in Iran (Afrasiabian, 1998) present work is for exploring this kind of groundwater.

2. Methods and results

In this study, we first generated two fuzzy evidential layers, fuzzy lithological evidence map and fuzzy structure evidence layer. Then WPM was generated by combining the fuzzy evidential maps using fuzzy operators. After generating target areas by making WPM in regional scale, gravimetry, vertical electrical sounding (VES), and geoelectrical resistivity profiling surveys were conducted to delineated karstic water resources potential zones in local scale. So we obtained suitable locations of drilling water wells to explore and extract karstic groundwater.

2.1. Conceptual model of karstic water resources

The responses of underground materials in the surface respecting to the methods of exploration, are affected by complex geological patterns and, hence, interpretation of data obtained from such complicated domains is difficult (Geoffroy & Wignall, 1985). So complexity of geological setting could be simplified using multi-stage exploration process (Geoffroy and Wignall, 1985) such as sequential approach (Geoffroy & Wignall, 1985; Edwards & Bowen, 2013) for sustainable groundwater supplies in the terrain underlying by crystalline basement rocks. For this, in the first step, conceptual model which characterize underground resource should be made (Edwards & Bowen, 2013). 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. So, 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 (Roberts et al., 1988). Furthermore, analysis of spatial distributions of water resource and analyses of spatial associations of water resource and indicator geological features like host rock and structural feature (Rather et al., 2012) are useful in making, conceptual model of water prospectivity (Rather et al., 2012).

2.1.1. Geological and lithological criteria

The first and indispensable step in karst hydrogeological investigations is the characterization of the geological and geomorphological framework (Alammareen, 2010; Ahr, 2011). This includes the interpretation of existing geological literature, maps and section, as well as data acquired from fieldwork (Francese et al., 2009). Lithology is one of the major factors that affect porosity, permeability and karstifiability of rocks dependent upon climatic and tectonic condition of a region (Francese et al., 2009; Alammareen, 2010). The purity of the rock (Ford & Williams, 2007; Goldscheider & Drew, 2007) as well as geomorphological mainstream and drainage (Parizek, 1976) controls the karstifiability. Hence, the weights of lithological evidences such as pure limestone unites, mainstream beds and alluviums; must be allocated fairly high for WPM (Alammareen, 2010; Ahr, 2011).

2.1.2. Structural and geomorphological criteria

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 (e.g., Robert, 2012; Moustafa et al., 2014). Lattman and Parizek (1964) have investigated the relationship between fracture traces and solution zones in hard rocks. They have 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 (e.g., Morelli & Piana, 2006; Mogaji et al., 2011); therefore an effective approach for delineation of fracture zones is recognition of lineament indices extracted from satellite imagery (e.g., Hung et al., 2005; Nag & Saha, 2014). 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 (Meijerink et al., 2007; Kann & Glenn, 2006; Park et al., 2000; Mabee, 1999).

According to Hung et al. (2002) lineament intersection frequency, i.e. the number of intersections of lineaments per unit cell of the study area, can be included in lineament analysis. In this regard, the areas with high lineament intersection density (LID) are high fractured zones, which are prerequisite for secondary porosity and solution widening in hard rock terrain (Mogaji et al., 2011).Therefore, the areas with high LID are suitable for groundwater conduit development, and, so for groundwater prospecting.

2.1.3. 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 (Nguyen et al., 2007). In addition, there is a significant density contrast between compact rock and sinkholes in karst terrains (Martínez-Moreno et al., 2014). Hence, they are good targets for geophysical electrical resistivity and gravity investigation. In the present research, geoelectrical resistivity technique as well as gravity method has been 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.

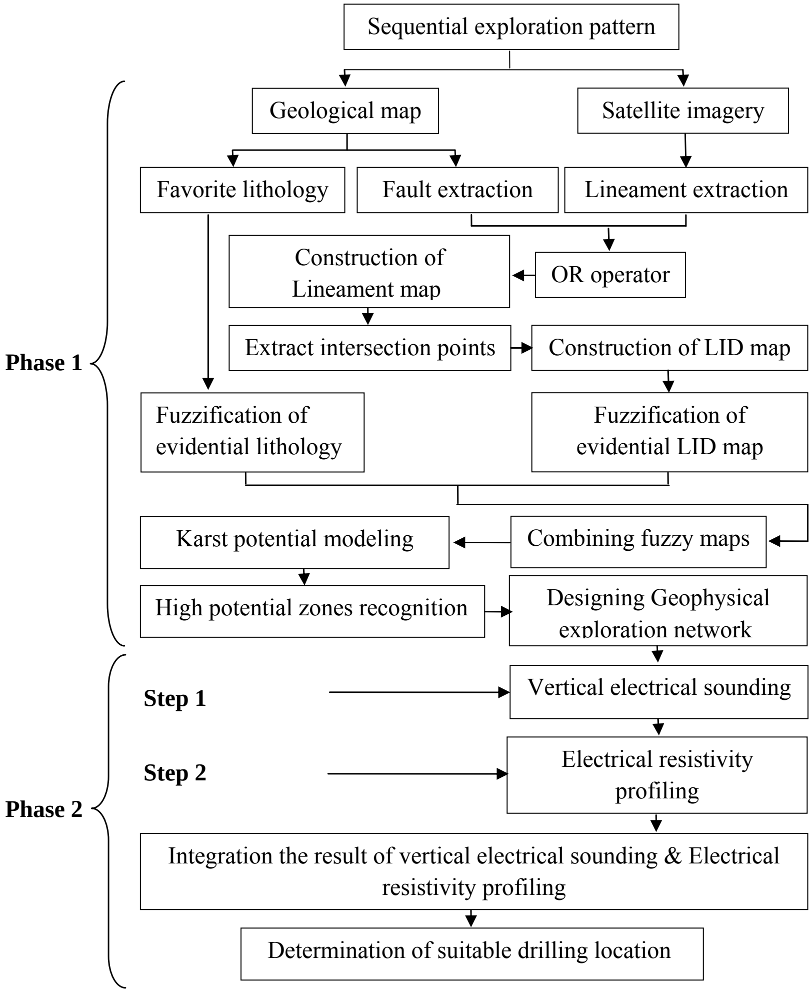

Fig. 1. Main sequences and phases of karstic water potential modeling and exploration in Tepal area, Shahrood

2.2. First phase – regional scale exploration stage

Fuzzy logic modeling has initially been developed based on fuzzy set theories by Zadeh (1965). Fuzzification is the processes of converting individual sets of spatial evidence into fuzzy sets. The Fuzzy set has been 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 (Hall et al., 1992; Carranza, 2008). So, for karstic WPM, the fuzzy score of evidential maps belongs between 0 and 1, afterward the fuzzy 'gamma' operator have been used in order to integrating of fuzzified maps.

There are mainly two 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) (Carranza, 2008). In early days of the subject, fuzzy score of different classes in an evidential map have been assigned subjectively by the expert judgment on the basis of his knowledge and experience (Porwal et al., 2003; Yousefi et al., 2013), whereas later it performs based on exploration data mathematically (Porwal et al., 2003). In conventional data driven predictive modeling, systematic error appears because of its dependent upon exploration data which recently the mathematical method has been developed to avoid this problem for some of evidential maps. This method has been carried out in order to fuzzifying LID map, which integrated with fuzzified knowledge-driven lithological map using fuzzy 'gamma' operator to constructing karstic WP model.

2.2.1. Generation of fuzzy geological evidence layer

Since the karstifiability dependent on lithology closely, it demands the fuzzified evidential lithology map construction for integrating with other evidence. In this regard, geological map of Shahrood on 1:100,000 scale has been investigated in order to extract favorite lithological units. 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 (Vaziri et al., 2001) 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 fuzzy score of other lithological units have been suggested 0.01 based on expert judgment (Fig. 3).

2.2.2. Generation of fuzzy structure evidence layer

For this, in this research, the Aster 15 m pixel resolution satellite imagery of the area acquired on Jan. 21, 2001 has been applied to extract lineaments by Sobel filter operation beside using geological map of the area (data source in regional scale). Furthermore remote sensing techniques have been efficiently utilized to investigate hydrogeological conditions (Mabee et al., 1994; Drury et al., 2001), groundwater monitoring (Rodell & Famiglietti, 2002), groundwater and resource evaluation (Koch & Matter, 1997; Bressan & Anjos, 2003).

Schowengerdt (1997) has noted that the Visible and Near Infra-Red (VNIR) region of the spectrum has the smallest spectral error. Furthermore, Hung et al. (2005) 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 have been 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,

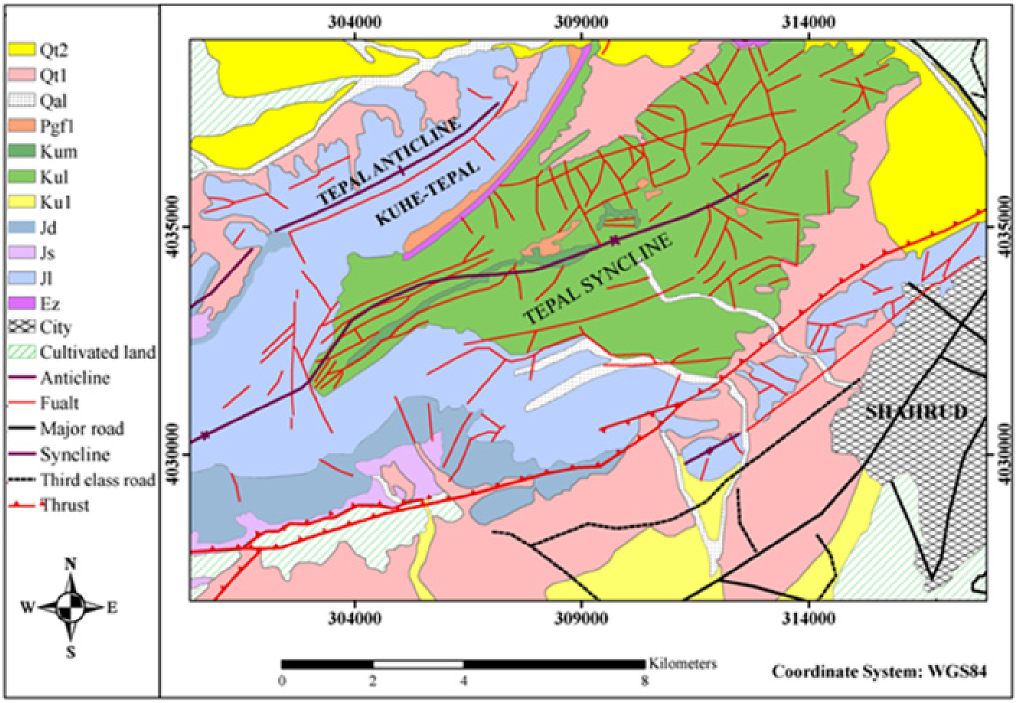

Fig. 2. Geological map of Tepal area (Vaziri et al., 2001)

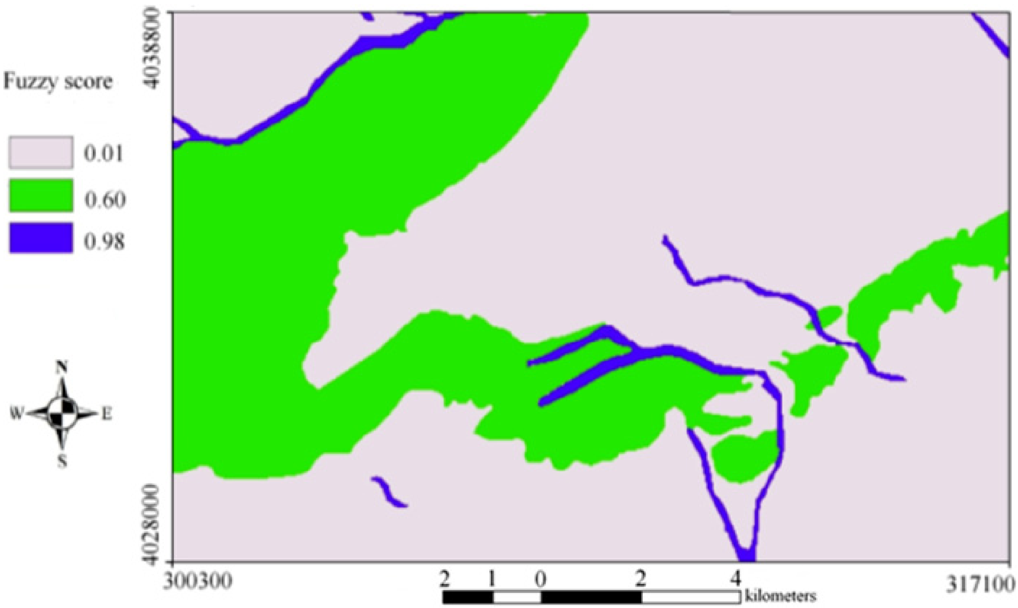

Fig. 3. Fuzzy score of lithological units

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 (1998) 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 have been shown in Figure 4. Moreover, Figure 4 represents the intersection points of lineaments in the study area.

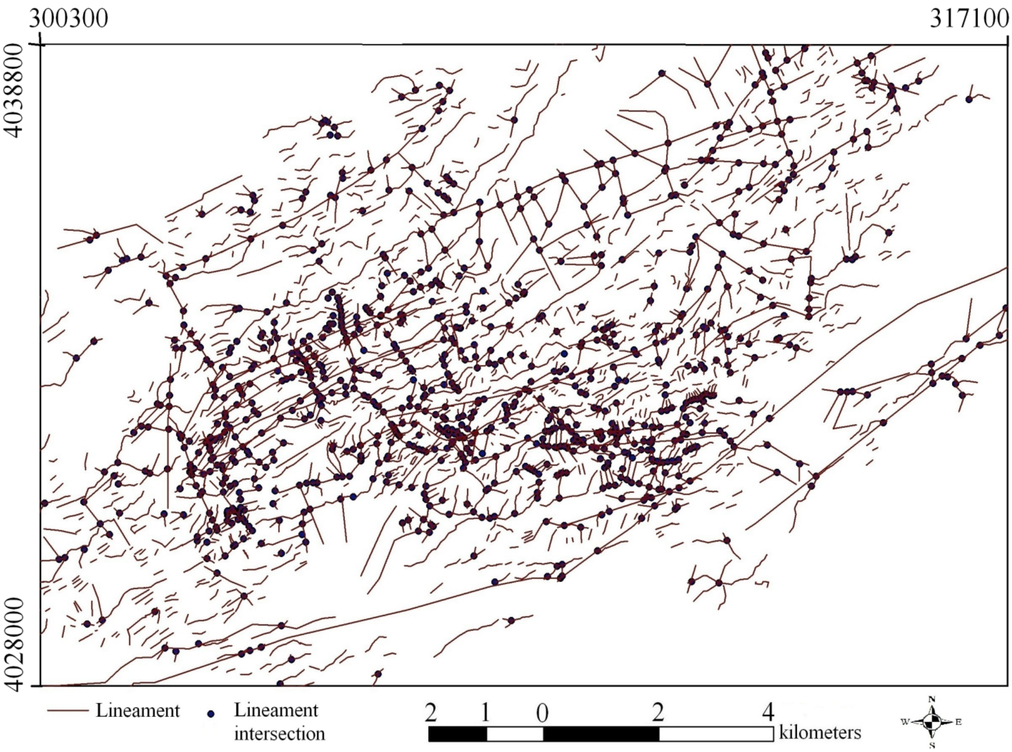

Fig. 4. Lineaments and intersection of lineaments in Tepal area

According to Hung et al. (2002), the intersections point 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 LID map of the study area has been prepared in 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 (Hengl, 2006). In practice, the appropriate cell size can be determined from the density of samples and mapping scale, or the structure of pattern of points (Hengl, 2006; Zuo, 2011).

The compromise legible cell size can be determined according to traditional cartographic concept (Hengl, 2006, Zuo, 2011, Yousefi et al., 2014), as follows:

$$r = SN \times 0.0005 \tag{1}$$

$$SN = \sqrt{\frac{A}{n}} \times 10^2 \tag{2}$$

where r is the cell size in m, SN is the scale number, A is total area of a map in m^2 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, we have used a pixel size of 30 m × 30 m for this study and the output LID map has been presented in Figure 5.

According to Figure 5, the values of LID are non-fuzzy and are not appropriate as fuzzy evidence scores. Thus, following Zimmermann (1991) and porwal (2006), the calculated values of LID have been transformed to fuzzy ones by applying the following logistic function:

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

where *F(LID)* 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 are chosen arbitrarily. For the present study, the values

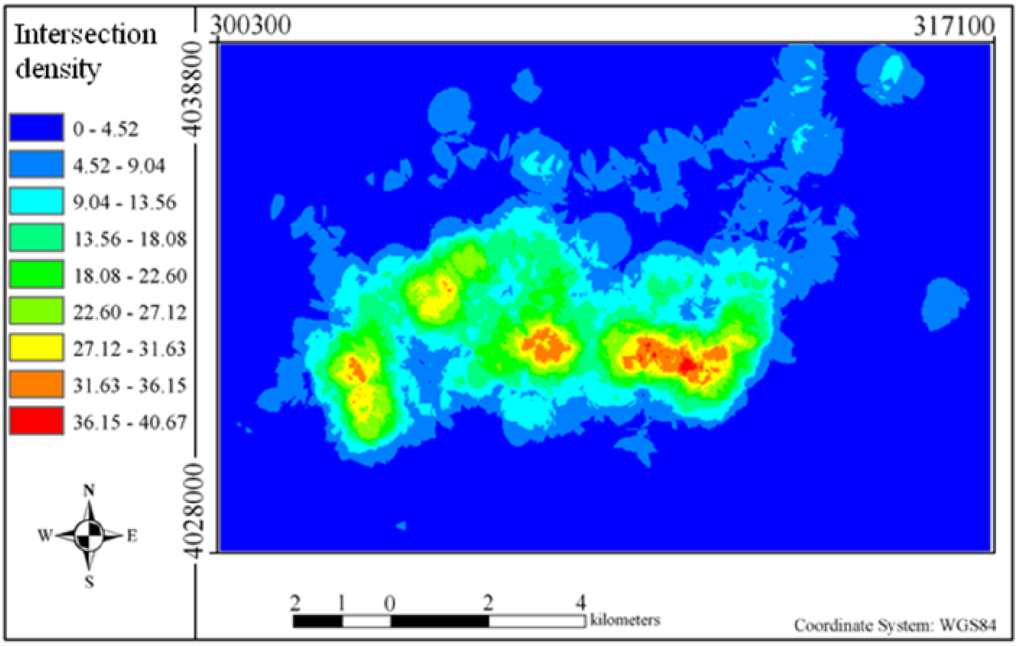

Fig. 5. LID map of the study area (cell size: $30*30\ m^2$)

0.2 and 20 have been considered for *a* and *b*, respectively. The fuzzy scores of LID values have been demonstrated in Figure 6.

Because the map of logistically-transformed LID values is a weighted fuzzy evidence layer, it can be integrated with a weighted fuzzy lithological evidential map.

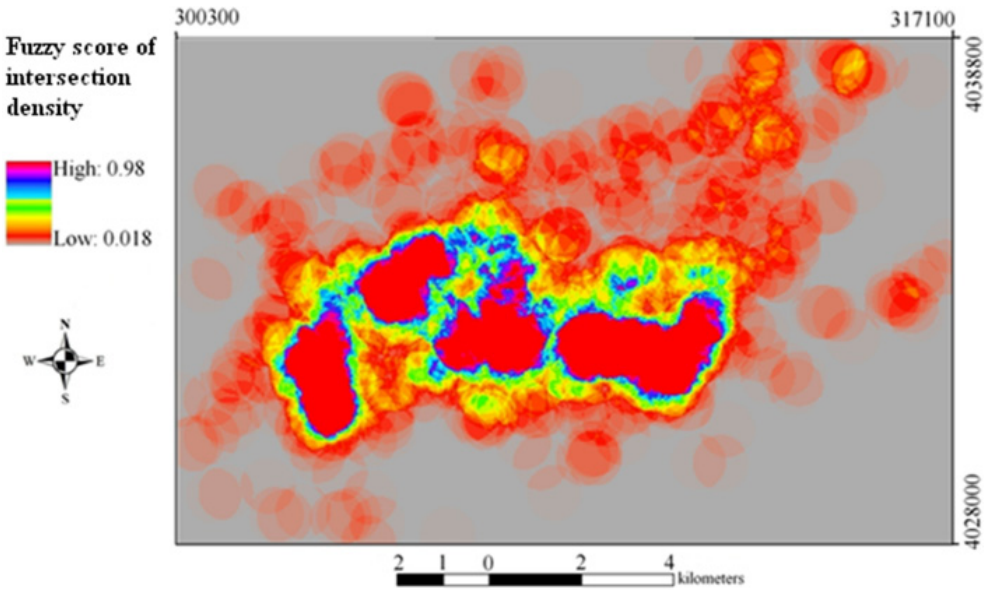

Fig. 6. Fuzzy score of LID (cell size: 30*30 m^2)

2.2.3. Water prospectivity model: integration of fuzzy evidential maps

The fuzzy 'gamma' operator has been used to integrate the map of fuzzy scores of LID with the lithological evidential fuzzy map for karstic WP modeling and, hence, detailed exploration phase targeting. Figure 7A represent fuzzy score of karstic WP based on 'gamma' operator. Also Figures 7B shows the sketch map of conducted geophysical investigation network on the WP models, including gravimetry, vertical electrical resistivity sounding and electrical resistivity profiling methods.

2.3. Second phase – local scale 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 exploration, because, in general, 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 gravity and 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. Furthermore, the area of gravity survey has been indicated by G1G2G3G4 quadrangle district in Figure 7. Some other details of geological and geoelectrical

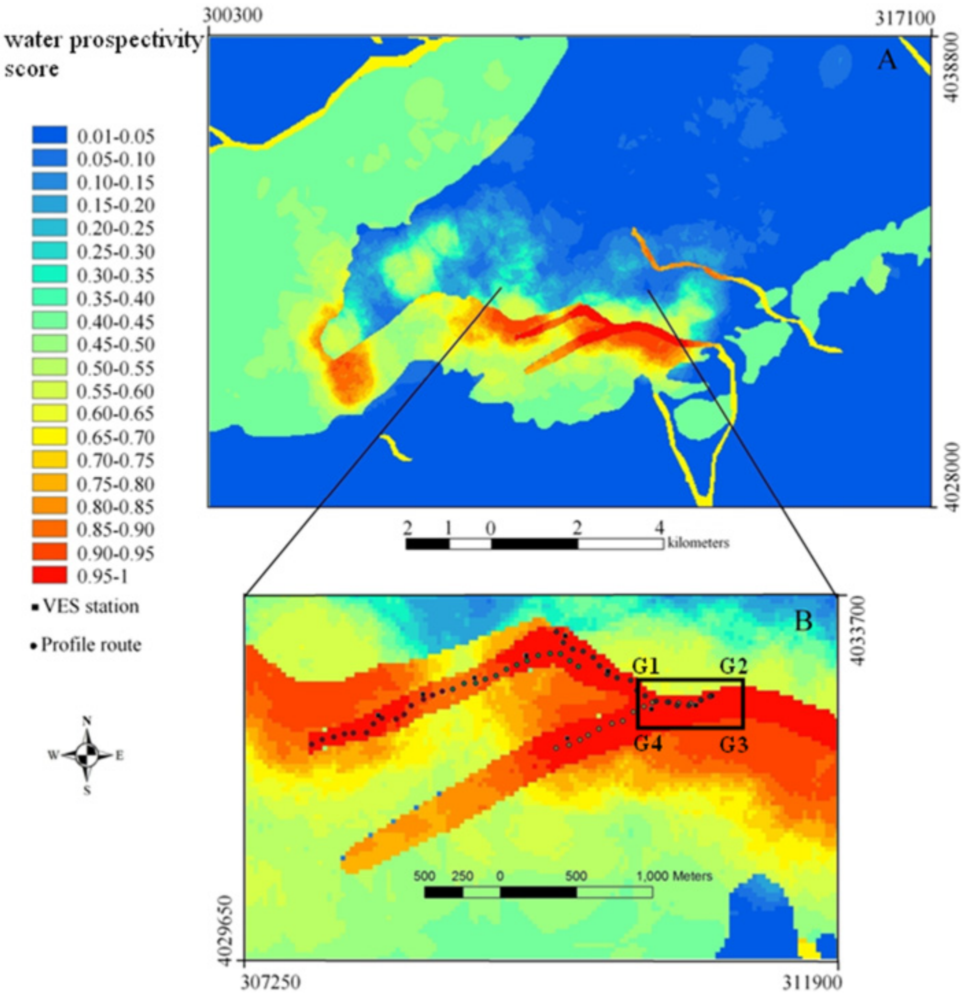

Fig. 7. A) Fuzzy score of water prospectivity in Tepal area, obtained based on fuzzy 'gamma' operator, B) Sketch map of Fuzzy score of water prospectivity in Tepal area, the position of gravimetry (G1G2G3G4) and geophysical data surveys are presented

investigations have been shown in Figure 8. Furthermore, gravimetry and Schlumberger VES and dipole-dipole electrical resistivity profiling surveys have been carried out in July 2011 using CG-5 AUTOGRAV gravity meter and Swedish ABEM Company resistivity meter (Terrameter SAS-4000), respectively (data source of local scale).

2.3.1. Gravity

The gravity data have been acquired using Scintrex CG-5 AUTOGRAV gravity meter on the delineated $G_1G_2G_3G_4$ quadrangle network (Fig. 7) and the resulting Bouguer gravity anomaly has been interpreted in order to validate the fuzzy WP model. The residual Bouguer gravity

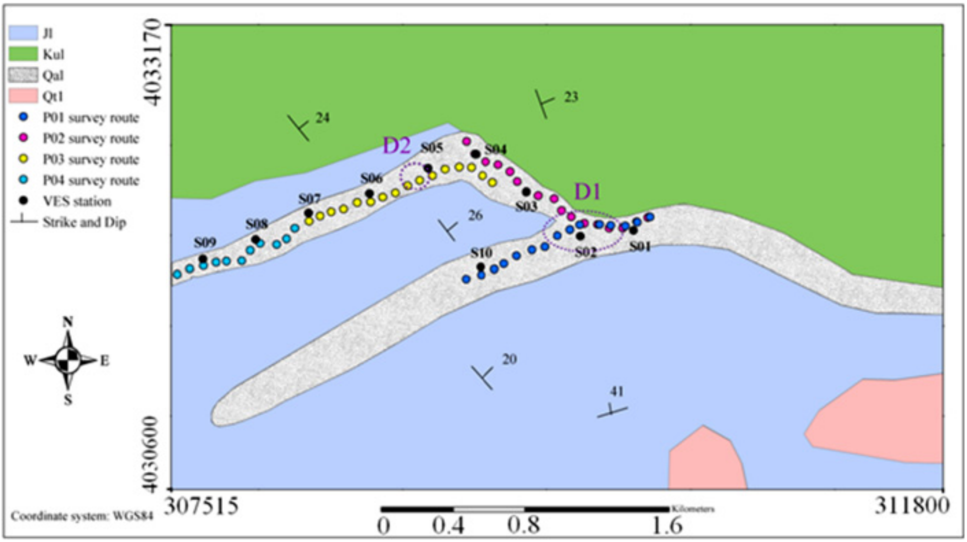

Fig. 8. The geological map of the study area, in which the locations of 10 resistivity sounding points S01 to S10 and 4 resistivity profiling survey lines are also denoted. D1 and D2 are the recognized suitable locations for drilling to access and extract karstic groundwater

anomaly, obtained as a result of applying Griffin method or filter on the gravity data, is shown in Figure 9. The negative anomalies could be relative to the cavities or sinkholes developing in the karstic terrain.

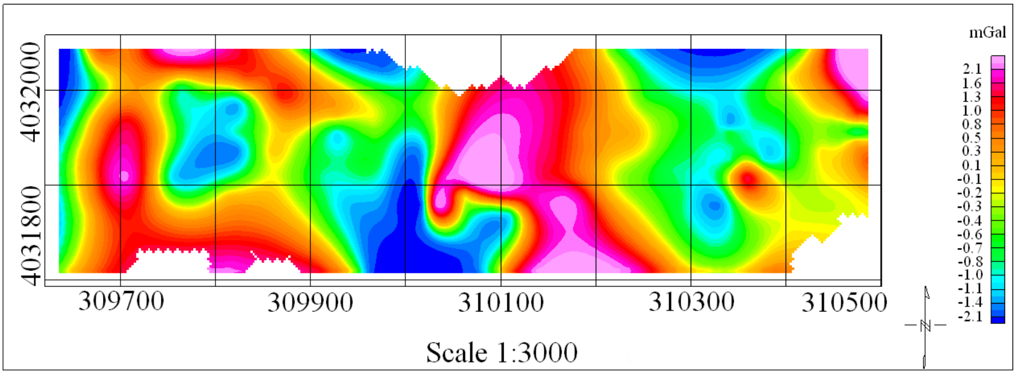

Fig. 9. Residual Bouguer anomaly map obtained by Griffin filtering

2.3.2. Geoelectrical resistivity VES and profiling

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

For direct current (DC) electrical resistivity surveys, common configurations are the Schlumberger, Wenner and dipole-dipole spreads (Kirsch, 2006). 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 (Reynolds, 2011).

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

On the high fuzzy score of WP area, which 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. 8), the water table (Fig. 10 and Table 2) is determined as a result of performing VES surveys using Schlumberger array. Because of the presence of essential inhomogeneities in such karstified areas, it is normally required to use supplementary methods for obtaining enough information from the subsurface ground. Due to low sensitivity of the Schlumberger array to lateral inhomogeneities, and also good characteristics of 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 (Loke, 2001), 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, the VES surveys have been carried out in 10 resistivity sounding points S01 to S10 (Figs. 7 and 8) using the Schlumberger array with electrode separations of maximum 1000 meters. In addition, the resistivity profiling surveys have been carried out along 4 lines (Figs. 7 and 8) of more than 4 kilometers long using 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 have been made. The resistivity modeling and interpretation results of the VES and resistivity profiling data are demonstrated in Figures 10 and 11. Besides, Tables 2 and 3 clarify the explanation of VES results. The root mean square error (RMSE) is used in this software to explain the amount of error of modeling.

The use of RMSE is very common and it makes an excellent general purpose error metric for numerical predictions. So it is a frequently used measure of the difference between values predicted by a model and the values actually observed from the environment that is being modelled. The RMSE of a model prediction with respect to the estimated variable X_{model} is defined as the square root of the mean squared error in equation 4.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_{obs,i} - X_{model,i})^2}{n}} \quad (4)$$

where X_{obs} is observed values and X_{model} is modelled values at time/place i.

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

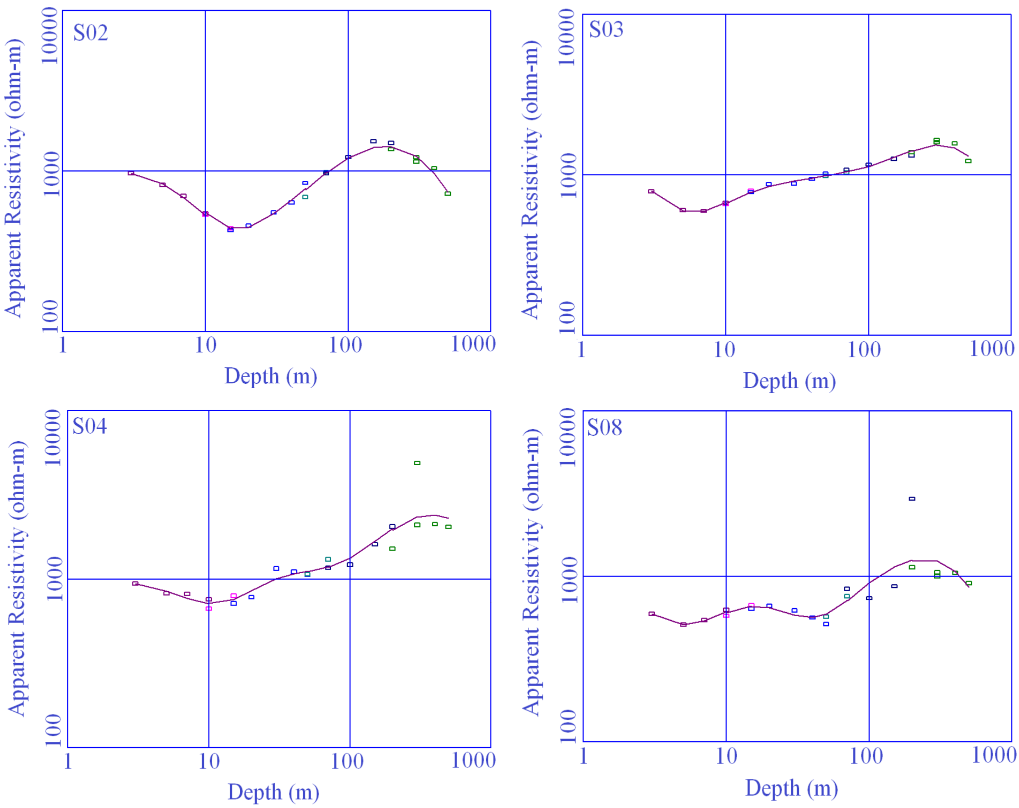

Fig. 10. 1-D modeling and interpretation results of the VES, obtained using IX1D software

The interpretation of four soundings, S02, S03 S04 and S08, suggest 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, and thus, no water-bearing zones could be found in these relative high resistivity subsurface layers.

Furthermore, the inversion modeling results of the resistivity profiling data along 4 lines P01, P02, P03 and P04, shown by 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 favorite karstic water zones.

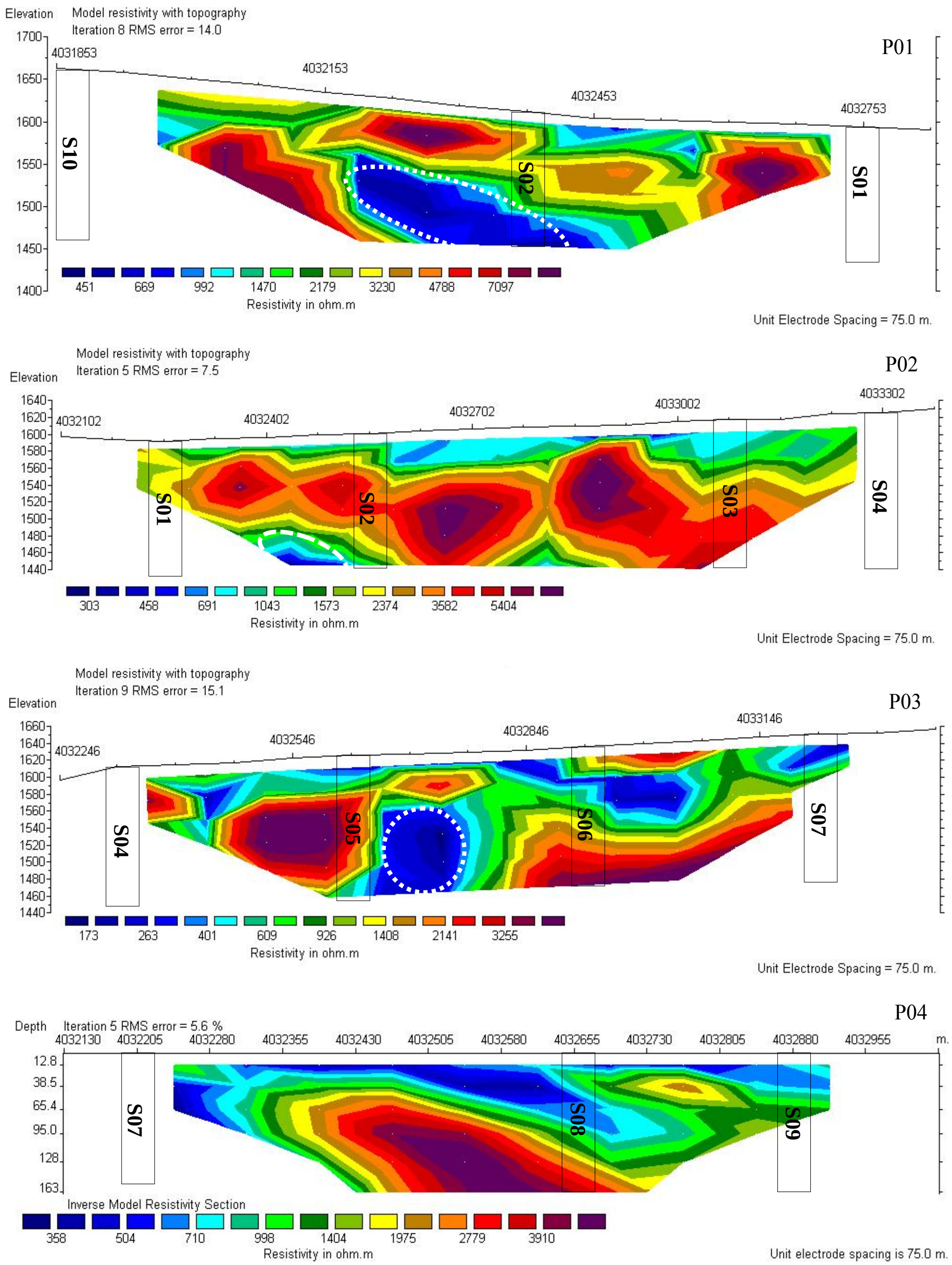

Fig. 11. The 2-D modeling and interpretation results of the resistivity profiling data along 4 lines P01-P04, obtained using RES2DINV Software. The VES locations or points S01 to S10 across these resistivity profiling sections are also shown

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%**		**23.62%**	
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	818.62	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 W.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 W.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 W.m shows a poor potential of water resource.
S08	Possible existence of a water-bearing zone with a resistivity of 118 W.m in the depth of more than 105 m.
Other VES	Absence of water-bearing zone

3. Discussion

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

Lithology, faulted zones and influence of synclinal fold system around the study area are the favorite criteria which control karstification. The geological map of the study area (Fig. 2) that illustrates limestone formations without of marl sequences and development of mainstream implies favorite lithology, and LID map (Fig. 5) implies favorite structural criteria for karstification and occurrence of karstic terrain development in the subsurface; moreover, presence of low dip bedding (Fig. 8) and mean annual rainfall of 130 mm in the Shahrood region, provides favorite conditions in the study area. Therefore, based on 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 LID evidences have been integrated using fuzzy 'gamma' operator, and as a result, WP model of the study area has been provided for the first phase of groundwater exploration performance in the area.

Sequentially, in the second exploration phase, as it can be seen in figures 7 and 8, geophysical investigations are focused on locations that WP values are fairly high. The geophysical investigations, carried out in the study area, include gravity and electrical resistivity methods comprising of VES (using the Schlumberger array) and resistivity profiling (using dipole-dipole array). Because of significant contrast in density and resistivity between water-bearing fractured zones and compact bedrock, gravity and electrical resistivity methods are considered as suitable geophysical techniques for detection of water-bearing fractured zones in the area. At the end, the measured geophysical data have been modeled and interpreted in order to determine high potential location to supply large and reliable quantities of karstic water.

As a result of gravity data interpretation, the negative anomalies have been considered to be relative to the development of cavities or sinkholes in the karstic terrain, and this result confirms the result of WP modeling in the first phase of groundwater exploration in the study area. Furthermore, the interpretation of resistivity data shows that 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 zone.

4. Conclusions

The present study highlights the following findings for karstic water prospectivity mapping:

1. Sequential approach, including regional scale and local scale exploration phases, could be used for investigating sustainable groundwater supplies in the terrain underlying by crystalline basement rocks.
2. For karstic water potential modeling, geological evidences such limestone unites, drainage, Quaternary gravels and marls and LID could be utilized, efficiently, in the regional scale.
3. The negative residual Bouguer anomalies confirm the presence of sinkholes and cavities in the WP model.
4. Based on 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 amount of necessity of deep investigation, sensitivity to horizontal changes in resistivity and time and fund consuming.
5. The obtained section of P01 resistivity profiling survey, conducted on favorite geological and structural situation with regard to high LID, has been integrated with favorite lithology units, and as a result, the presumable water bearing zones have been recognized thor-

oughly on 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 P02 line confirm 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 8), and thus, it is proposed as the first priority for drilling water well to access karstic groundwater. Based on the interpretation of S05 VES and P03 profiling section, the district D2 in Figure 8 is also introduced as the second priority and proper location for drilling water well to access karstic groundwater.

Acknowledgments

Authors wish to thank Dr. M. H. Loke for his guidance in modeling resistivity data using RES-2DINV software, Mr. Mehdi zarei, the Head of Geophysical Laboratory of Shahrood University of Technology for his assistance in geophysical surveys and use of the Laboratory facilities, Mr. Seyed Ali Hossinizadeh and Mr. Ali Akbar Frootan for their assistance in geophysical surveys, Mr. Meysam Davoodabady-Farahani for giving us permission to use the gravity data of the study area, Finally, Water Administration and Dispatching Company of Shahrood city is also greatly appreciated for their financial support and permission to use the required information from the area.

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