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Introducing an Approach to Draw a Groundwater Levels Map in a n Aquifer, Including Qanats

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Abstract

In this research, a method of drawing groundwater levels maps is developed considering the active Qanats in the Gonabad Plain, Iran. The common approach for drawing the groundwater levels map, is interpolating the groundwater level elevation data obtained from observation wells. Qanat has been ignored for drawing the groundwater levels map in the most of time. However, it is one of the main structures that should be considered in this analysis. In the introduced approach, the groundwater surface levels map of the Gonabad Plain was drawn using the groundwater level elevation data obtained from observation wells and mother well of Qanats located in the aquifer and also considering that water bearing zone of Qanats drain groundwater, therefore groundwater levels is parallel and groundwater flow line is perpendicular to it. Results lead to preparation of an accurate groundwater levels map that is important for the maintenance of groundwater resources and also helping to reveal the secret of the method of drilling deep Qanats in the plain in several thousand years ago. By using this map, the aquifer transmissivity in water bearing zone of each Qanat and the capture zone of each Qanat were estimated. The results indicated that the aquifer transmissivity in water bearing zone of Qanats varies from 23 to 77 square meters per day.
Keywords: Groundwater, Levels map, Mother well, Qanat, Water bearing zone.

1. Introduction

The accurate prediction of groundwater levels maps (GLM) is an important issue for the sustainable management of groundwater resources (Todd and Mays 2005; Ghandehary et al., 2014; Nassery et al., 2017; Koohbanani et al., 2017; Barati 2020 a&b; Maghrebi et al., 2021, 2023; Mirani Moghadam et al., 2021; Oftadeh et al., 2021; Bahraseman et al., 2024; Mirboluki et al., 2024; Yeganeh et al., 2024; Salehi et al., 2024). Groundwater levels maps provide important information such as groundwater flow directions, recharge and discharge areas and estimation of flow rate and transmissivity of regional aquifer.

Groundwater levels mapping has been extensively considered in the previous studies (Kumar 2007; Varouchakis and Hristopulos 2013; Hosseini and Kerachian 2017; Ohmer et al., 2017; Ruybal et al., 2019; Celicourt et al., 2020; Li et al., 2020). However, the main focus of these researches was on the comparison of the performance of different methods for spatial interpolation, optimal levels mapping of groundwater levels and optimal groundwater monitoring networks.

In dry territories (e.g. Iran, Algeria, Egypt, and Syria), Qanats, as eco-friendly structures, have been widely used for exploiting groundwater as discussed in previous studies such as Khaneiki, (2007); Yazdi and Khaneiki, (2017), Ghasemi et al., (2021), Tabatabaei and Khozeymehnezhad (2022), Masoudi Ashtiani et al., (2023), Yousefian et al., (2023), Tabatabaei (2024) and Yousefian et al., (2025).

There are several ancient Qanats (from 2700 years ago) in the Gonabad arid region,

their flow rates vary from 15 to 125 lit/s, and annually 20 Mm^3 of groundwater have been exploited through these Qanats. In drawing the groundwater levels map, structures located in the aquifer such as faults, impermeable rock masses, lacks and Qanats should be considered.

For example, Bi-xin (2009) presented a drawing method for irregular scatter data field with faults. However, to the best of the author's knowledge, there is no approach to consider the effects of a Qanat to draw the GLM in an aquifer, which is the innovation and purpose of the present study.

2. Materials and Methods

2.1. Site description

The Gonabad Catchment is located in the east of Iran as it can be seen in Fig. 1. The Gonabad Catchment area is 1870 km^2 of which 940 km^2 is highland and 930 km^2 is flat. The highest and lowest altitude in this catchment is 2770 and 990 m a.s.l. respectively. The Gonabad Plain is surrounded by high mounts from the east, west, and south. The climate is semi-arid to arid and the wet period is from December to May. The annual precipitation amount is 145 mm in the desert and 264 mm in the mountains. Temperature increases from a mean of 18°C on the mountains to 24°C on the desert.

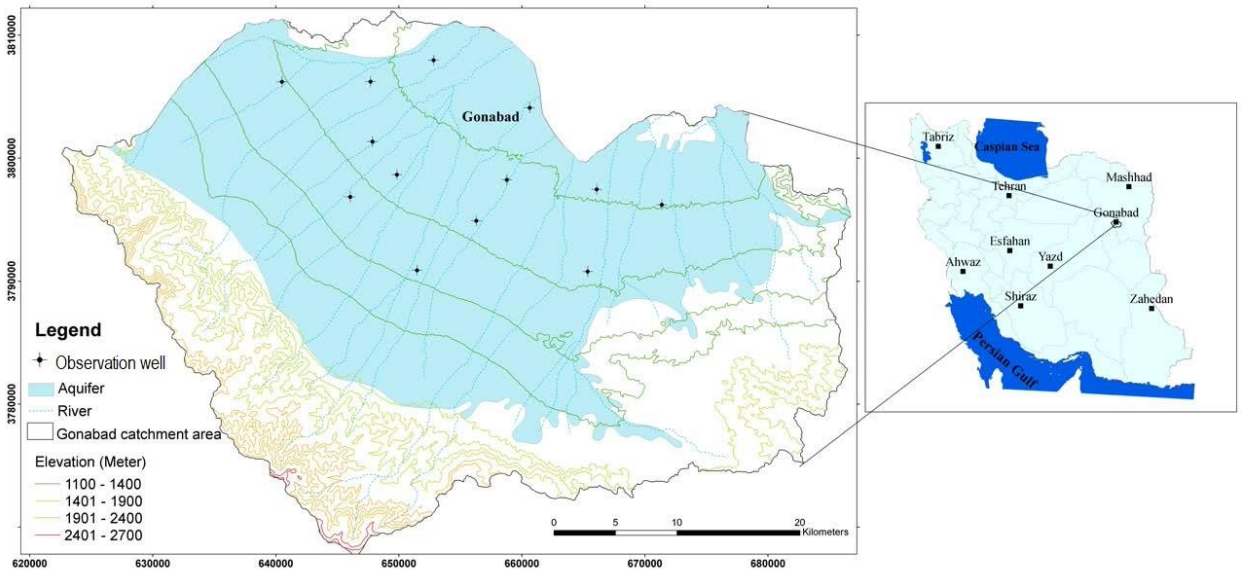

Fig. 1. Gonabad Catchment situation in Iran

2.2. Geological and hydrogeological settings

The geological map of the Gonabad Catchment is illustrated in Fig. 2 (Geological Organization of Iran). The oldest rocks in the region are carbonate Jamal formation (Permian and Lower Triassic) formed eastern highlands of the district. The silica-clastic Shemshak Formation (Jurassic) is vastly extended in the south of the district. The Badamu limestone (Upper Jurassic) is expanded slightly in the southwest of the catchment. Cretaceous limestone is outcropped slightly in the northeastern, eastern, and southern parts of the region. Volcanic rocks (Paleogene period) expanded in the southeast, west and northwest of the catchment. The Neogene formations scattered in the southern border of the plain, consist of conglomerates (old sediments) and clay and marl (younger sediments). Alluvial cones (Quaternary period) are widely exposed in the plain and formed alluvial aquifer. These sediments are coarse grain in the edge of the highlands and in the plain's outlet become fine grain and forms clay flat. The thickness of this alluvial sediment varies from at least 20 meters in the eastern part to a maximum of 300 meters in the southern part of the plain. The regional groundwater flow is from south and southwest toward the north and northeast and is drained in the direction of the northeast. The depth to groundwater surface ranges from 200 meters at the south to less than 50 meters at the north of plain.

As it was shown in Fig. 3, a Qanat consists of, a chain of vertical wells connected by a mildly sloping gallery and groundwater is

extracted via it by the gravity force (Behnia 2000; Karami 2008; Kuros and Khaneiki, 2007; Yazdi and Khaneiki, 2017; Khaneiki, 2018; Azari Rad et al., 2018; Khaneiki, 2020; Naghedifar et al., 2020).

As it can be seen from Fig. 4, the Qanat tunnel consists of two parts, water bearing zone and water carrying zone. In water bearing zone, Qanat tunnel enter the saturated zone of aquifer and groundwater is drained. Through water carrying zone, drained groundwater is transmitted to the Qanat outlet. The last and deepest well of a Qanat called mother well. In mother well, the groundwater level is about 0.5 meter above the bottom of mother well.

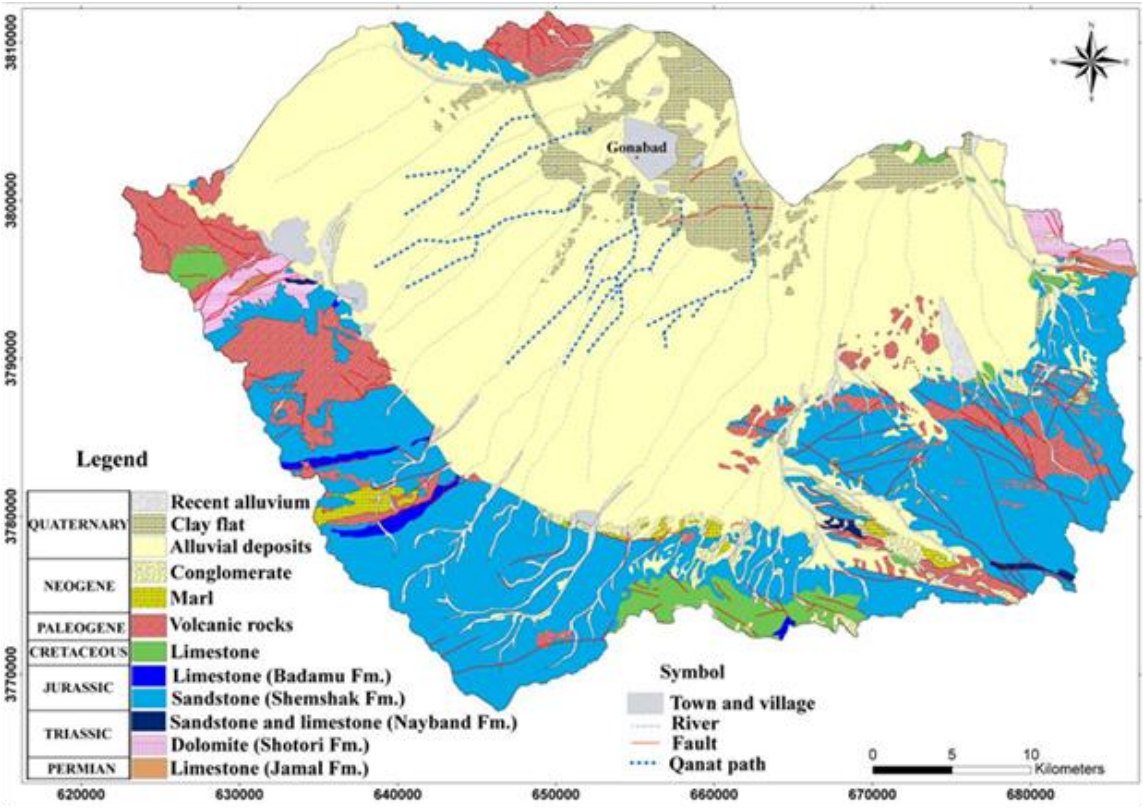

Fig. 2. Geological map of the Gonabad Catchment (Geological Organization of Iran)

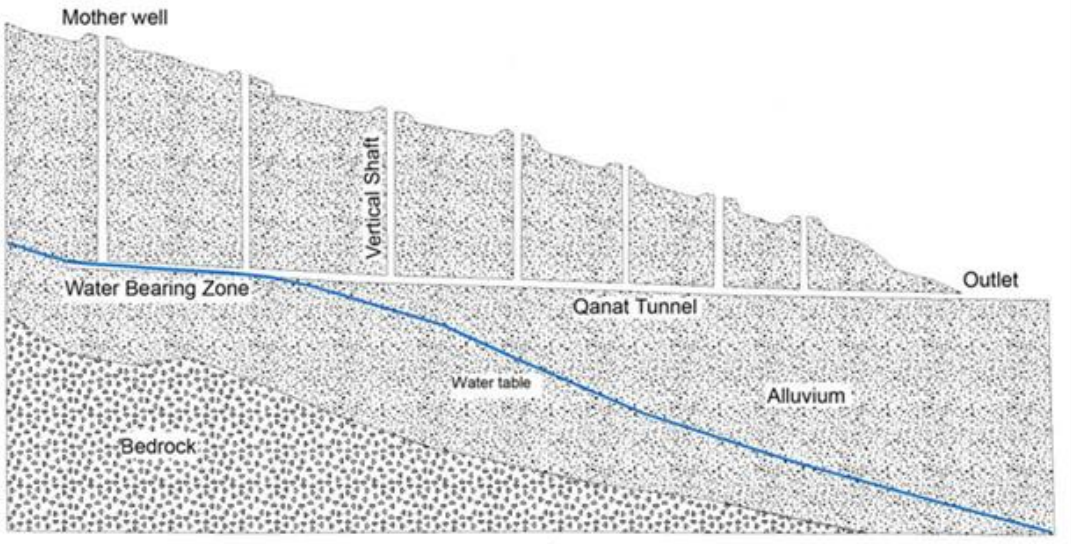

Fig. 3. Schematic of the longitudinal cross section of the Qanat system

In order to draw the groundwater level map in the Gonabad Plain, groundwater depth in the observation wells located in the plain was measured and by using the top elevation of the observation wells obtained by the mapping operation, groundwater level elevation was calculated. The Qanat paths were identified in the plain. The length of water bearing zone of Qanats was calculated, using the groundwater depth in the plain and the depth of the tunnel of Qanats along the path of Qanats, where the depth of groundwater and the depth of the tunnel are equal is the beginning of the water bearing zone of Qanats that continues to the end of the Qanats.

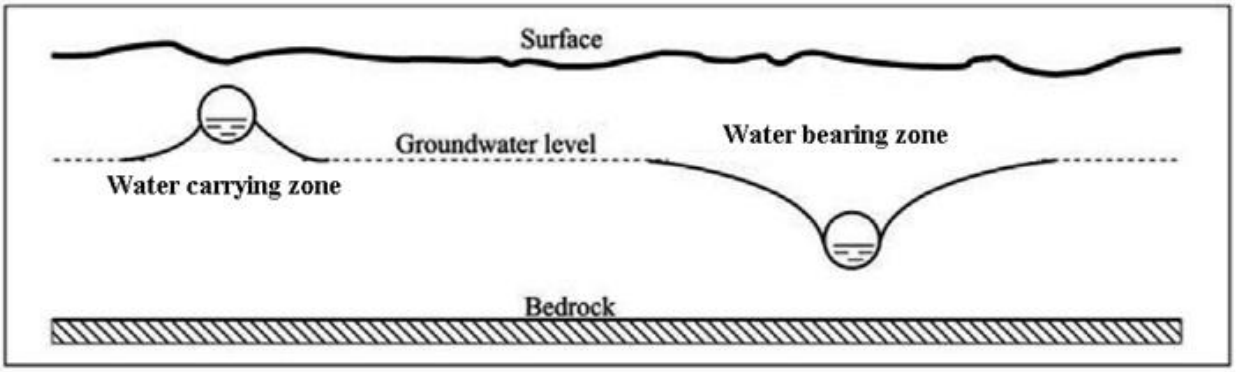

Fig. 4. Schematic of the transverse cross section of the Qanat system (Ahmadi et al., 2010, Quoted from Nazari Samani and Farzadmehr, 2006, with corrections)

The depth of mother well of Qanats and groundwater level elevation in mother well was calculated. Finally, the groundwater levels map in the Gonabad Plain was drawn, using the groundwater level elevation in observation wells and in mother well of Qanats and considering the fact that water bearing zone of Qanat drains groundwater therefore groundwater levels is parallel and groundwater flow line is perpendicular to it. Figure 5 presents the proposed methodology to draw groundwater levels map in an aquifer including Qanats.

3. Results and Discussion

3.1. Depth of mother well of Qanats and groundwater level elevation in mother well

The elevations of the outlet and top of the mother well of Qanats were obtained from the topographic map of region. The slope of the tunnel of the Qanats is mild and is on average about 0.001. Therefore, the floor elevation of the mother well of Qanats should be one meter above the elevation of the Qanat outlet per kilometer Qanats length. Also, the groundwater level elevation in the mother well is about 0.5 meter above the floor elevation of the mother well. For instance, in Kalat branch of Qasabeh Qanat, mother well is located 15 km southwest of Qasabeh Qanat's outlet. The slope of the tunnel of the Qanat is mild and is on average about 0.001 and the Qanat's outlet elevation is 1102 m a.s.l. Therefore, the elevation of the floor of the mother well of the Qanat should be 15 meters above the outlet elevation and equal to 1117 meters (Fig. 6). The groundwater level in mother well of Qasabeh Qanat is about 1117.5 m a.s.l.

3.2. Groundwater levels map of Gonabad Plain

The path of six Qanats in the Gonabad Plain was identified and the water bearing zone of Qanats was determined. The groundwater level map in the plain was drawn by interpolating groundwater level elevation in observation wells and in mother well of Qanats located in the plain also considering that water bearing zone of Qanats act as a drain as it can be seen in Fig. 7. In the water bearing zone of Qanat, groundwater is drained therefore groundwater level should be parallel and groundwater flow direction perpendicular to it. The general ground water flow is from south to the north of the aquifer, but because of the presence of Qanats, local groundwater flows occur around the water bearing zone of Qanats and there are depressions (sinks) in GLM around the water bearing zone of Qanats.

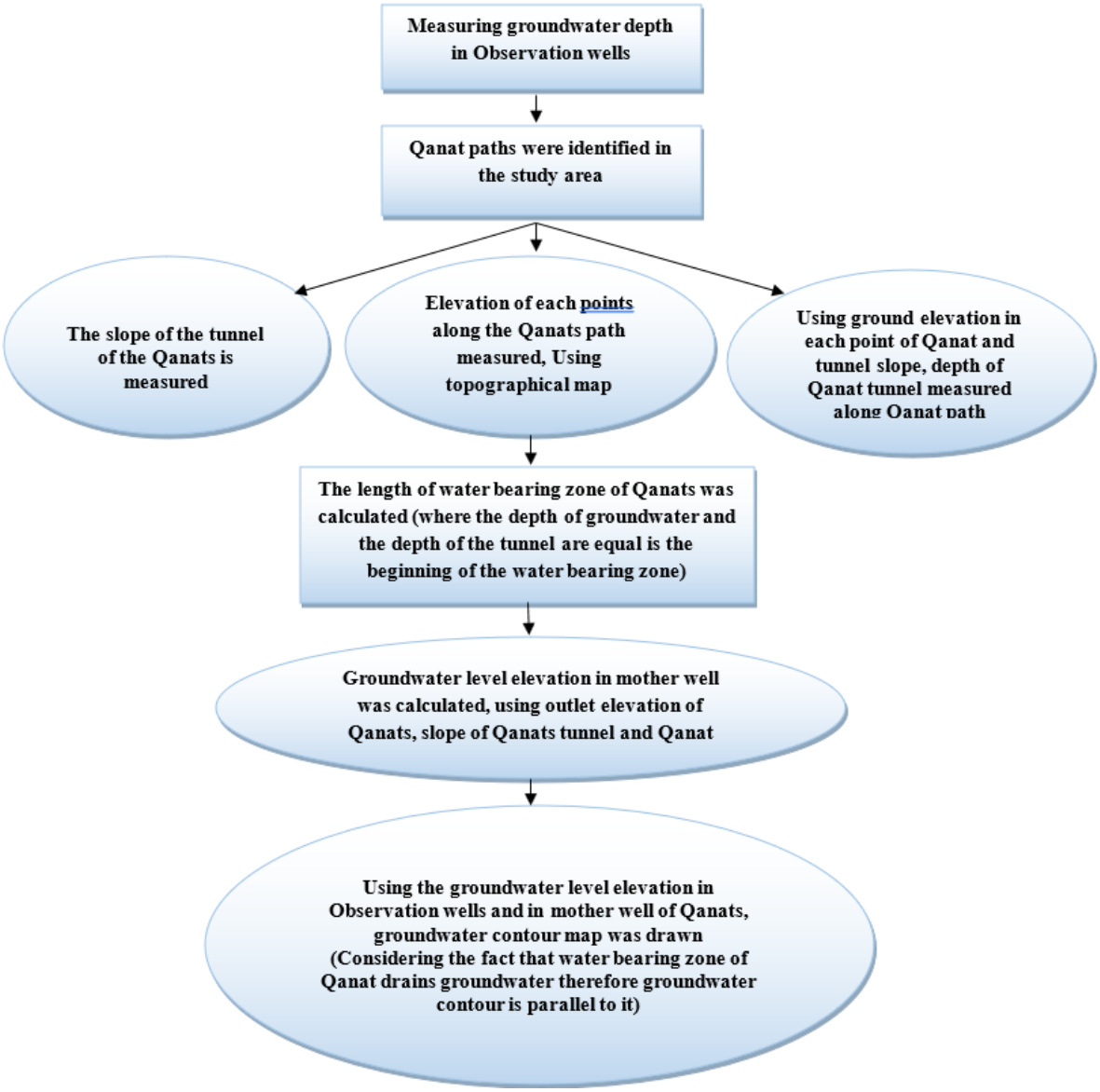

Fig. 5. Flowchart of the proposed methodology

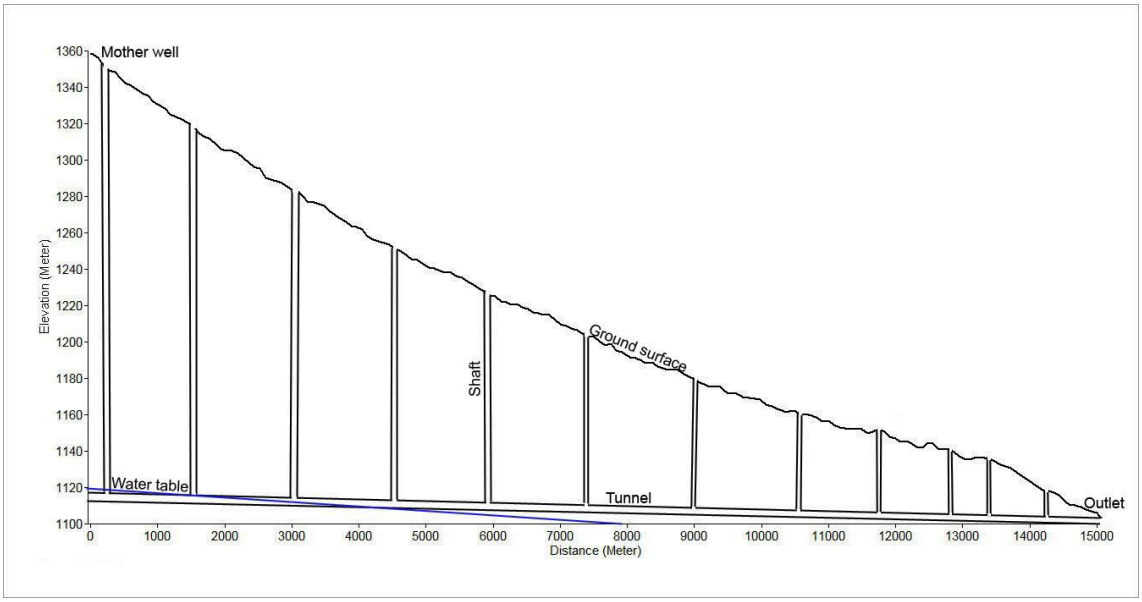

Fig. 6. Schematic cross section of Qasabeh Qanat along its Kalat branch.

Therefore, the GLM pattern becomes complicated and groundwater level is shown exactly and really in the new map (Fig. 7).

This GLM is practical for determining the catchment area and capture zone of Qanats, which is important for protection and `management of these valuable water heritages. Also, for the comparison purposes, the groundwater levels map was drawn in the Gonabad Plain using only groundwater elevation in observation wells and without considering Qanats as it can be seen in Fig. 8. As shown in this figure, the GLM pattern is simple and only shows the general groundwater flow direction without details.

3.3. The secret of digging deep and long Qanats in Gonabad

In a number of Qanats of Gonabad Plain the depth of mother well exceed 250 meters while groundwater depth is 200 meters. Digging of deep wells 50 meters below groundwater level had been a mystery for several years. Reverse digging of a well in saturated area, is one of the assumptions which was expressed for this by Yazdi and Khaneiki (2017) as presented. In our opinion, reverse digging of a well below groundwater level seems difficult and impossible, but old Qanat diggers knew fundamentals of groundwater drainage. They dug the last well a few meters under saturated zone, and then waited for the short time to Qanat drained the upstream area and when groundwater level fell down, drilling continued upstream gradually. Therefore, digging a long, deep Qanat has taken several years. This discussion can approve water bearing zones of Qanats act similar to drain.

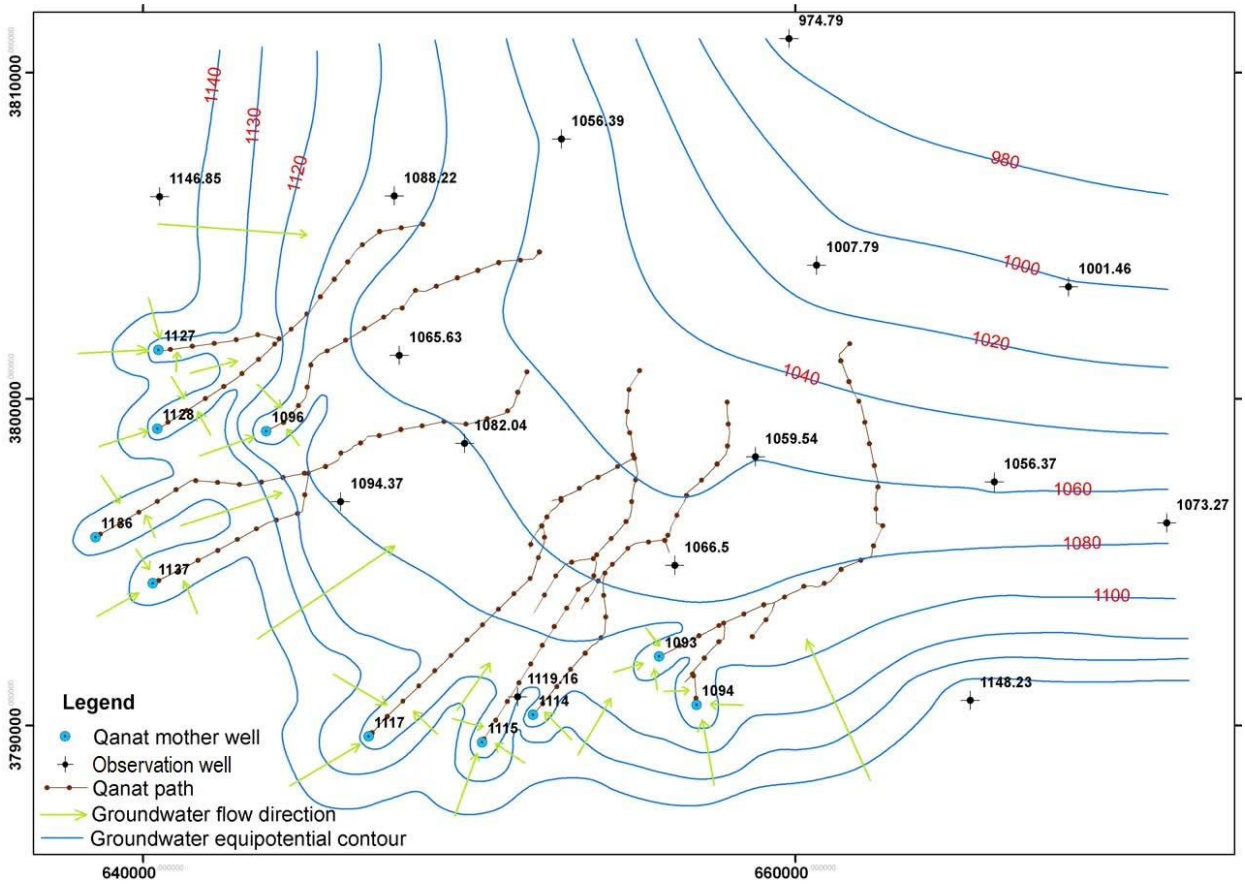

Fig.7. Groundwater levels map in the Gonabad Plain regarding Qanats

3.4. Discussion

The presented methodology to draw groundwater levels map in an aquifer including Qanats is important for hydrogeology calculations. Capture zone of Qanats of Gonabad Catchment was illustrated in Figure 9. By using this map, and construction of flow net, the flow directions, groundwater divide and aquifer transmissivity in water bearing zone of each Qanat were specified. Also capture zone of each Qanat was determined. The capture zone area of each Qanat was presented in Table 1. Water yield per one km^2 of capture zone for each

Qanats was also calculated. The maximum water yield is related to Dizagh and Bahabad Qanats, which indicates high aquifer storage in the water bearing zones of these Qanats. Table 2 listed transmissivity of water bearing zone of Qanats. Transmissivity of aquifer material in water bearing zone of Qanats estimated using flow net of Fig. 9 and following equation (Darcy's low):

$$Q=Twi \quad (1)$$

Where T is transmissivity of aquifer materials, W is average flow width and i is hydraulic gradient.

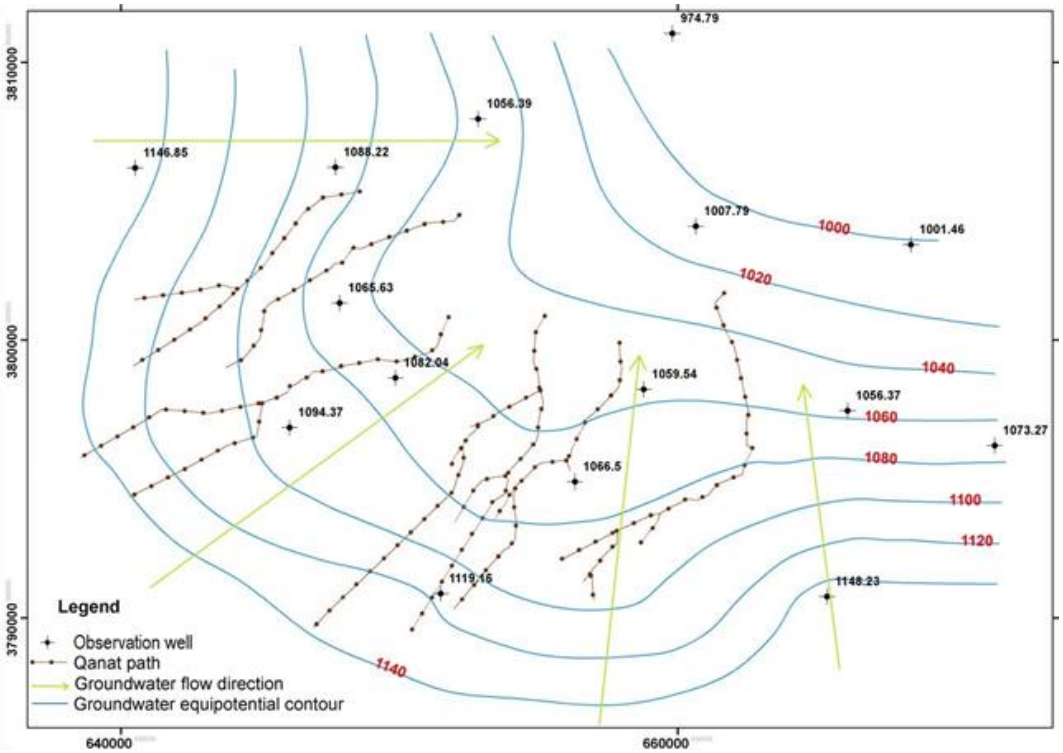

Fig. 8. Groundwater levels map in the Gonabad Plain ignoring Qanats

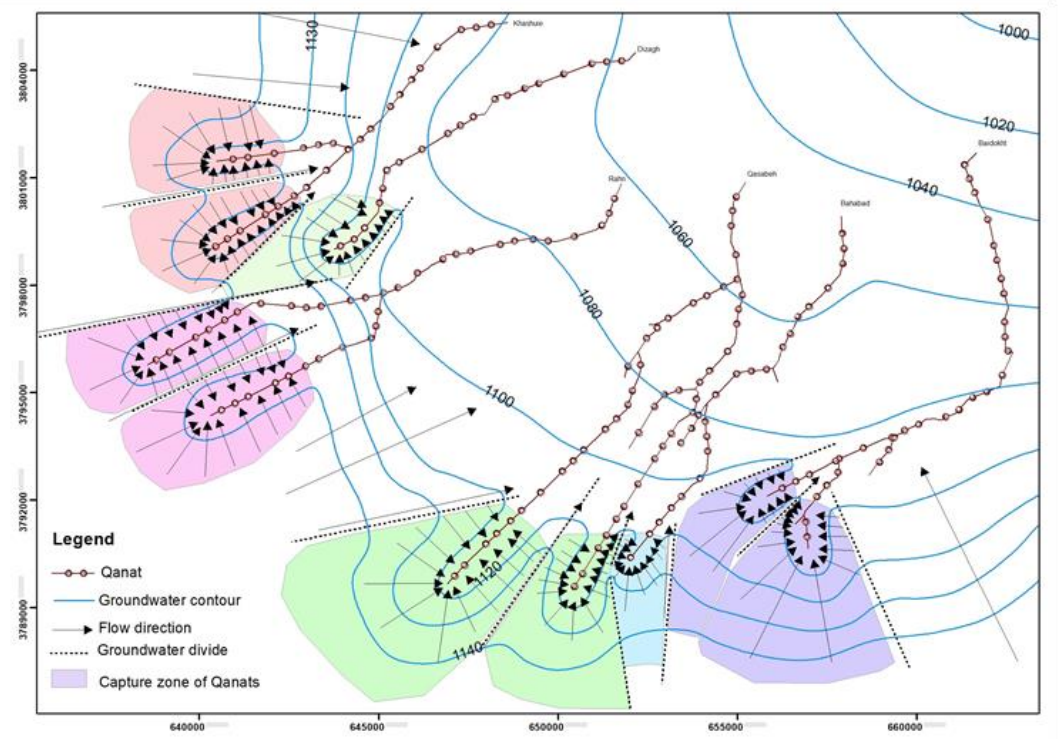

Fig. 9. Consideration of capture zone of Qanats for hydrogeology calculations

Table 1. Capture zone area, discharge and water yield for Qanats of Gonabad Catchment

Qanat	Capture zone (km^2)	Discharge (l/s)	Water yield per one km^2 of capture zone (l/s)
Qasabeh	39.9	100	2.51
Rahn	23.5	14	0.60
Baidokht	26.3	27	1.03
Khashuie	18.8	35	1.86
Dizagh	7.7	55	7.14
Bahabad	4.9	25	5.10

Table 2. Transmissivity calculation for Qanats of Gonabad Catchment

Qanat	Discharge (l/s)	Flow width (m)	Hydraulic gradient	Transmissivity (kb) (m^2/d)
Qasabeh	100	9386	0.012	77
Rahn	14	12184	0.003	33
Baidokht	27	2392	0.02	49
Khashuie	35	9480	0.014	23
Dizagh	55	3894	0.04	31
Bahabad	25	2000	0.019	57

The aquifer transmissivity in water bearing zone of Qanats varies from 23 to 77 square meters per day. The maximum transmissivity of aquifer materials is related to the water bearing zone of Qasabeh and Bahabad Qanat.

4. Conclusion

One of the most important structures should be considered in drawing the groundwater level map is Qanats. The water bearing zone of Qanats located inside saturated zone of aquifer and drained groundwater, therefore groundwater level contours don't cross it. The floor elevation of mother well of Qanat is calculated regarding the elevation of Qanat outlet and the slope of Qanat tunnel. Groundwater level elevation in mother well is about 0.5 meter above the floor elevation of the mother well. On this basis, to the best of author's knowledge, for the first time, groundwater levels map was drawn considering the active Qanats in the Gonabad Plain. The results indicated that the consideration of Qantas has important effects on the GLM of the aquifer, and it can present flow direction with more details. The resulted GLM is applicable for determination underground catchment area of Qanats and its transmissivity which is important for sustainable management and maintenance of these valuable groundwater resources in Gonabad arid region. Also, the secret of digging deep and long Qanats in Gonabad was discovered with the fundamentals of groundwater drainage that this map was prepared based on it.

5. Conflict of Interest

No potential conflict of interest was reported by the authors.

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