

# Comparative Study of Step Drawdown and Constant Discharge Tests to Determine the Aquifer Transmissivity: the Kangavar Aquifer Case Study, Iran

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**Abstract-** Evaluation of the hydraulic parameters of aquifers is essential for estimating and developing groundwater resources. Constant discharge pumping tests, monitoring the groundwater level variations in observation wells, can be expensive and time consuming. This paper introduces an approach that is efficient and economical and probably can replace the full pumping test. Well-choosing through field survey, constant discharge pumping tests and step drawdown tests are used in this study to determine the transmissivity (T) of the Kangavar aquifer, located in western Iran. To describe the geological characteristics of the subsurface formations, 16 vertical electrical soundings were performed and interpreted using Schlumberger array. To estimate the transmissivity by a step drawdown test, the aquifer coefficient (n) in well was computed by solving the Miller and Weber equation, through Fixed Point Iteration numerical method by using Visual Basic 6.5 programming. Contours of transmissivity attained through constant discharge and step drawdown tests were plotted for the study area, using kriging method. The results obtained were analyzed applying statistical comparisons, through which no significant difference was observed. Finally, it is concluded that step drawdown test can be used as an alternative to the expensive and time consuming constant discharge tests.

**Keywords-** Groundwater; Aquifer; Pumping Test; Step Drawdown Pumping Test; Transmissivity; Statistical Analysis

## I. INTRODUCTION

Various methods are available in groundwater hydrology for the assessment and estimation of the hydraulic characteristics of aquifers; these characteristics include transmissivity (T), hydraulic conductivity (K) and storage coefficient (S) [1,2]. Identification of hydrogeological parameters is an essential task for modelling a groundwater system [3]. Constant discharge test in existing or recently drilled wells is known as the most common method for determining hydraulic coefficients of an aquifer [4,5]. However, it is worth mentioning that using constant discharge test is a costly operation facing limitations such as numerous observation wells and equipment.

The step drawdown test has been experienced as an effective method to determine the relationship between head loss and discharge rate [6,7]. Although step drawdown test is usually used to determine well efficiency and well loss coefficient in a well, the results of step drawdown test can be slightly modified to be used in determining the hydraulic parameters of aquifers [4,8]. The methods introduced by Theis [9], Hantush [8], Birsoy and Summers [10] and other experts confirm the possibility of applying this test to determine aquifer's hydraulic parameters. It is necessary to determine and select a convenient pump for implementing step drawdown test. Consequently, applying the results of this test to determine hydraulic parameters saves both time and money.

In this study, estimation of the transmissivity of Kangavar unconfined alluvial aquifer was performed using two methods, constant discharge and step drawdown tests. The results of the step drawdown test were calculated through numerical methods.

## II. DESCRIPTION OF STUDY AREA

### A. Study area

Kangavar basin is located in Kermanshah province, Iran, and lies between latitudes 34 ° 12' and 34 ° 32' N and longitudes 47 ° 52' and 48 ° 06' E. The basin area is about 175 km<sup>2</sup>. The average altitude is 1430 m above mean sea level, as shown in Fig. 1. The minimum and maximum average temperature in a 15-year period (1995-2000) is 4.3 °C and 21.3 °C, respectively. The coldest month in this area is January, and July is known as the warmest month. The mean annual precipitation in the region is 375 mm from 20-year data (1990-2010). Also based on Thornthwaite classification [11], the climate of the region is semiarid. The main rivers in the study area are known as Khoram Rood, Ghare Chay, Sarab Kangavar and Gamasiab. The highest point (level) of the region is the summit of Amrollah Mountain at 3187 m above mean sea level. The lowest point is located in the southern part of region at 1400 m above mean sea level.

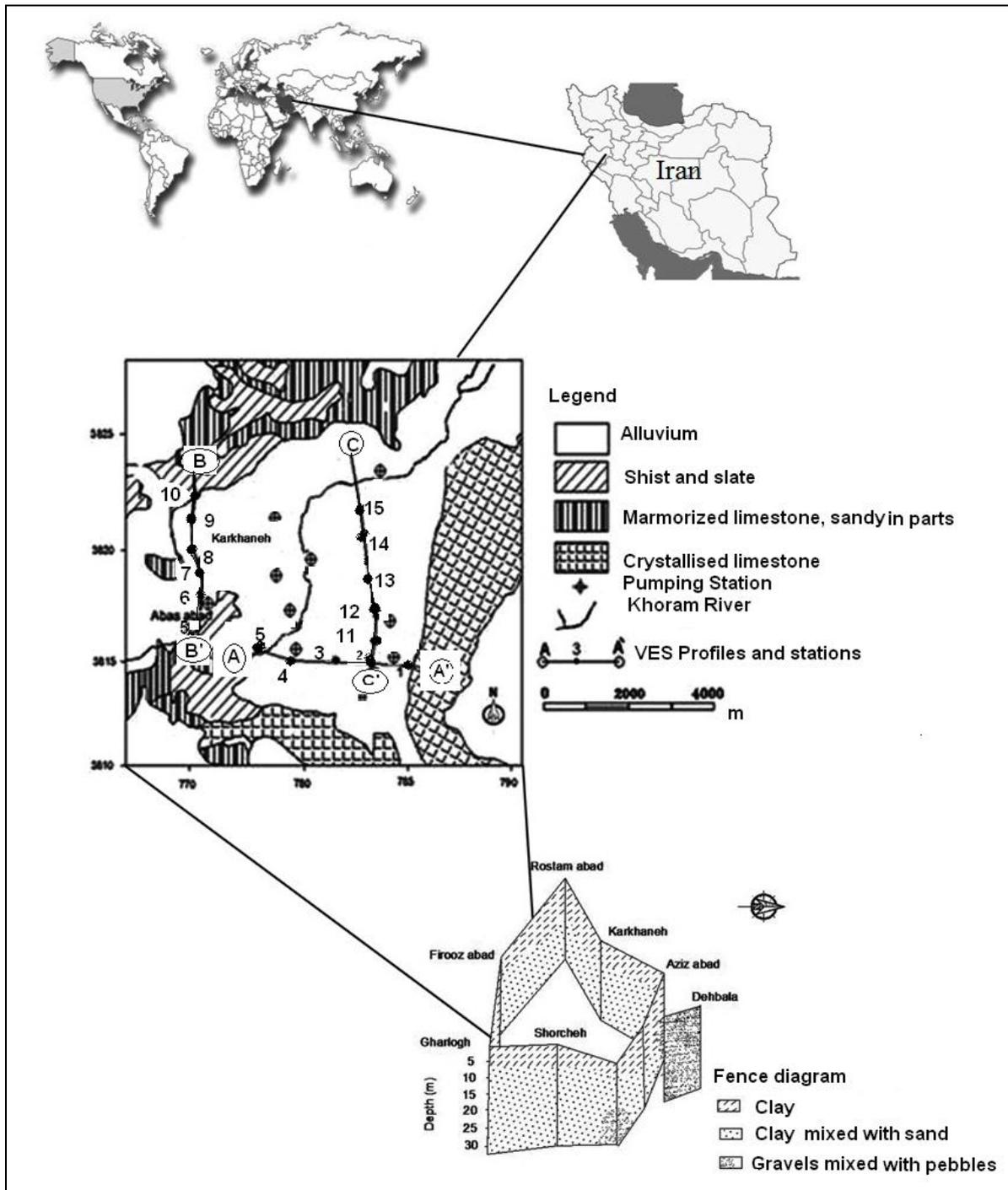


Fig. 1 Hydrogeological map of the study area representing fence diagram, test wells and lines, along which electrical sounding profiles were performed

### B. Geological and Hydrogeological conditions

The region is located between Zagros and Sanandaj-Sirjan zones and regarded active in terms of tectonic activities [12]. The brief explanation about the geology of the region merely focuses on hydrogeological features. Unconsolidated alluvial sediments (deposits), lying under the thick consequent Mesozoic and Cenozoic formations, represent the characteristics of the basin. Alluvial deposits cover sediments of flood plains, which consist of sand and clay intermediate layers and lens-shaped clay layers. Lithological data obtained from productive wells show that the thickness of the aquifer increases in the middle part of the basin, reaching the value of 110 m, while it varies between 5 and 10 m in the aquifer fringe. A fence diagram was used to illustrate a 3D image of aquifer conditions (Fig. 1) using regional lithological data. Standard methods determined by Moore [13] and Freeze and Cherry [14] were used to provide the diagram. Fence diagram shows the presence of clay in most points of the region, however, it seems that sands are predominant in the N-W part of the region.

The occurrence of groundwater in the region is controlled by various factors such as structure, geological sequence and stratigraphic disturbances [15]. Groundwater recharge of the region occurs through direct rainfall infiltration, floods and riverbed as well as the lateral subsurface flow [16]. Also, the irrigation return flow can result in recharge. In the recharge area, groundwater originates from upper hills to the central part of basin, and eventually enters Khoram Rood River. The main spring of the region is known as Kabootar Laneh with minimum and maximum recharges of 76 L/s and 80.3 L/s, respectively. The depth of static water level is highly variable so that it is shallow in the eastern part in spite of that the static water level in the central part reaches 30 m and even deeper. The Kangavar aquifer is in unconfined conditions; therefore the specific yield ranges between 0.02 (2%) in the SW parts and 0.11 (11%) in the NW parts.

### C. Geophysical data

Investigating the digging log of piezometric wells, the size, material, penetrability and alluvium yield were found. Special attention was paid to analyzing materials of different grain sizes. The data were used to describe the hydraulic conductivity of the aquifer. It was pointed out that, Kangavar aquifer is an unconfined aquifer consisting of clay-sand gravels where hydraulic conductivity varies between 4.1 and 12.6 m/day.

Sixteen vertical electrical soundings were used to determine the parameters such as layering, depth, resistance and geological formation in the plain [15]. Interpretation of the data was carried out using quantitative and geological methods. In Fig.1, the sounding positions are shown in three directions of profiles, including AA', BB' and CC'. The transverse profiles of sections are presented in Figs. 2, 3 and 4.

The results obtained from the analysis of electrical soundings show that transverse profiles of section AA' is located on soundings 1-5. The upper layers with electrical resistance of 20-35  $\Omega$ .m and thickness of 70-250 m are consisted of sand and alluvium. Hard rocks are located under this layer. Within the region of sounding 2, there is a reduction in electrical resistance up to 38  $\Omega$ .m at the depth of 250 m. Presence of fault and fracture in deeper layers is obvious (Fig. 2). Transverse profiles of section BB' are consisted of five electrical soundings. The first upper layer is constructed from alternate alluvial layers. The second layer is a transformed hard formation, the salient of which is observed in northern part of the plain. This layer is highly dense and shows resistivity of 150- 350  $\Omega$ .m (Fig. 3). Transverse profiles of section CC' lie north-south. There is a saturated layer, 200 m in depth, in sounding 12. The reduction of electrical resistance in the region is 12-13  $\Omega$ .m due to the presence of fault or fracture under the surface layer (Fig. 4).

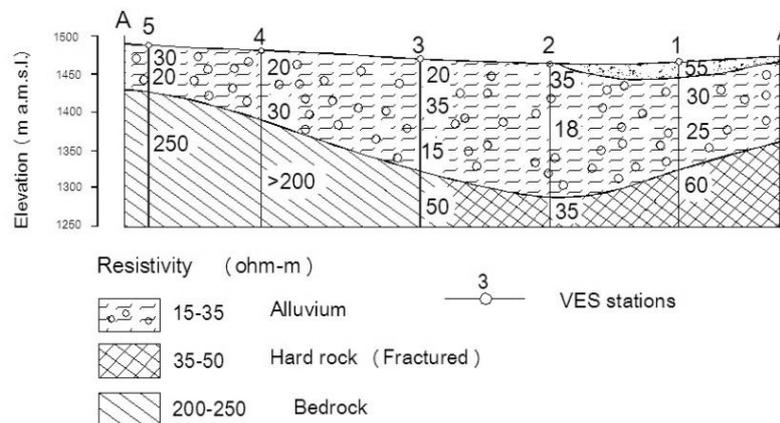


Fig. 2 Schematic geoelectrical section AA'

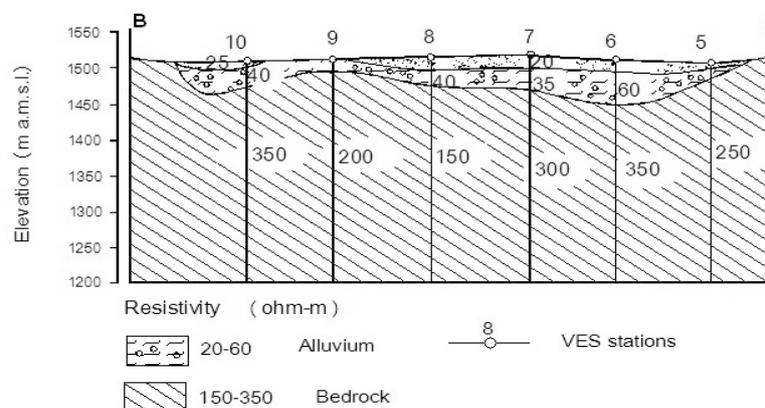


Fig. 3 Schematic geoelectrical section BB'

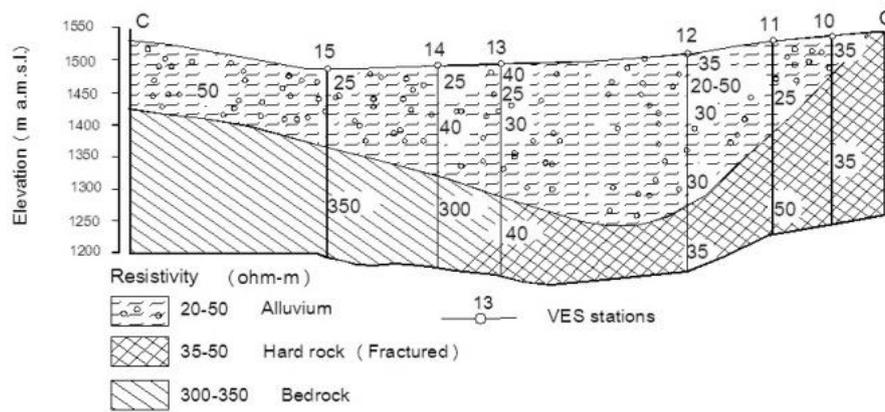


Fig. 4 Schematic geoelectrical section CC'

### III. MATERIALS AND METHODS

#### A. Constant discharge test

Constant rate test is used to assess an aquifer through constant discharge and observing aquifer response in observation wells. The water level must be measured accurately several times in pumping well and observation wells, due to rapid drawdown of water level in the first (and second) hours of the test [4]. Hence, the monitoring of water level was performed in short time intervals. Then, the time intervals increased gradually as pumping continued (Fig. 5).

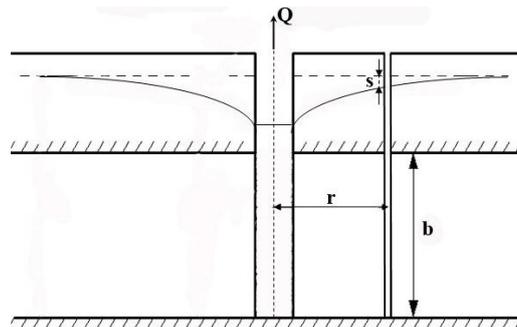


Fig. 5 Loss in observation well during the pumping

Measuring the water level decline (drawdown), Theis [9], Cooper and Jacob [17] and Chow [18] proposed methods for pumping test analyses leading to the calculation of hydraulic parameters. Theis [9] presented a drawing method to determine hydraulic coefficients based on the following relationships:

$$T = (Q/4\pi s)W(u) \quad \text{and} \quad S = (4uTt/r^2), \quad (1)$$

where  $s$  is the loss of water level (drawdown) in observation well (m),  $Q$  is the pumping rate ( $\text{m}^3/\text{min}$ ),  $r$  is the distance of the observation well to pumping well (m),  $t$  is the pumping time in minutes,  $\pi=3.14$ ,  $T$  is the transmissivity of the aquifer ( $\text{m}^2/\text{min}$ ) and  $S$  is the storage coefficient of the aquifer (dimensionless).  $W(u)$  is generally read 'well function of  $u$ ' or 'Theis well function'. Cooper and Jacob [17] applied Theis's method for small values of ' $r$ ' and large values of ' $t$ '. They used graphical methods to solve the following equation:

$$s = (2.3Q/4\pi T) \log(2.25Tt/r^2S). \quad (2)$$

The data obtained from constant discharge test were analyzed using Theis's method. Finally, the transmissivity ( $T$ ) was determined for Kangavar aquifer and contours map was illustrated using kriging method (Fig. 8).

#### B. Step drawdown pumping test

Three-step drawdown pumping test is used to determine the efficiency of a well [19]. The durations of the steps are: 100 min, 60 min and 60 min, respectively. Some methods have been presented by specialists to obtain hydraulic properties of an aquifer. A single well is required in step drawdown test, resulting in reduced cost and time in comparison with constant discharge test. In this test, each selected well was pumped at a constant discharge rate for a fixed period of time. Then the discharge rate was increased for the next pumping step [17,20,21]. The time interval in the new step was the same as that of the previous step to remove the effect of time on loss and specific capacity of the well [7]. The mechanism of discharge rate ( $Q$ ) and drawdown ( $s_w$ ) measuring was discussed by Johnson [22]. The water level decline was measured at the end of each

pumping step. Three equations are required to estimate the parameters B, C and n (see the following paragraphs), and consequently at least three time intervals are needed.

As the main focus of this study is to investigate the possibility of replacing constant discharge test with step drawdown test to reduce cost and time, the relationships and equations related to the step drawdown proposed by aquifer hydraulics experts are first introduced in this paper, and the numerical method and algorithm to obtain the transmissivity is then expressed. Generally, the total drawdown in wells can be associated with two factors: first is the drawdown originated from aquifer characteristics (aquifer drawdown), and the second drawdown element is due to the flow through the well screen and flow inside of the well to the pump intake (well losses) (Fig. 6). As well loss is related to turbulent flow, a powerful relationship is mathematically described by n degree, which varies within a range according to various researchers. Therefore, the following equation is obtained for the calculation of drawdown in well:

$$s_w = BQ + CQ^n, \quad (3)$$

where BQ is the drawdown portion (aquifer or formation loss) relating to the aquifer hydraulic characteristics and can be predicted by the theoretical drawdown equations (Theis equation). The value B is defined by the formula:

$$B = \ln(r_0/r_w)/2\pi T, \quad (4)$$

where  $r_0$  and  $r_w$  are the effective outer radius and effective well radius, respectively [23].

C is a constant governed by the radius, construction and conditions of the well, "n" is a constant greater than one, and  $CQ^n$  expresses the loss in well (well loss). It is pointed out that clogging of well screens can increase well losses in old wells [6]. Therefore, the total loss (drawdown) of a well is:

$$s_w = (Q/2\pi T) \ln(r_0/r_w) + CQ^n, \quad (5)$$

and:

$$s_w/Q = \ln(r_0/r_w)/2\pi T + CQ^{n-1}. \quad (6)$$

And eventually, the transmissivity is obtained as:

$$T = \ln(r_0/r_w)/2\pi[(s_w/Q) - CQ^{n-1}]. \quad (7)$$

Using the transmissivity of each well produced from equation (7), a transmissivity contour map was plotted for the step drawdown tests in the region, using kriging method (Fig. 9).

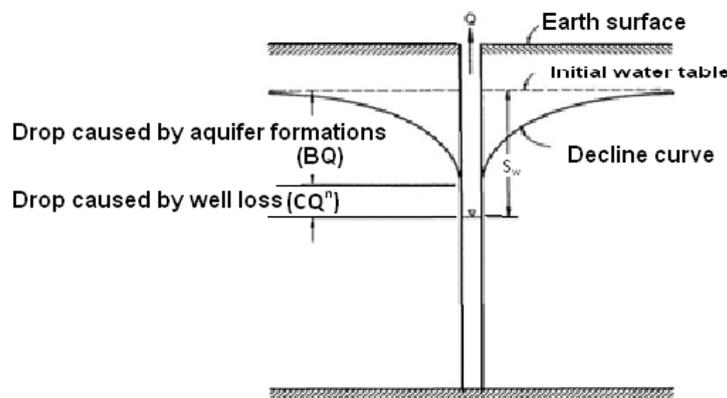


Fig. 6 Loss in well

As mentioned before, there is a relation of "n" degree between drawdown and discharge rate. Jacob [24] proposed a method in which the degree of "n" was supposed equal to 2, representing a relationship of square pumped discharge and well loss. Eq. (3) can be written as following:

$$s_w = BQ + CQ^2, \quad (8a)$$

$$s_w/Q = B + CQ. \quad (8b)$$

Drawing  $s_w/Q$  versus  $Q$ , parameters B and C are obtained, where C is the slope of the line and B is the intercept, and  $Q=0$ .

Rorabaugh [25] proposed a graphical method to solve Eq. (3) based on trial and error. According to this approach, both sides of Eq. (3) are divided by Q to obtain the Equation (10):

$$s_w/Q = B + CQ^{n-1}, \quad (9a)$$

Or

$$[s_w/(Q) - B] = CQ^{n-1}, \quad (9b)$$

then:

$$\log[(s_w/Q) - B] = (n-1) \log Q + \log C. \tag{10}$$

Plotting  $s_w/Q - B$  term versus  $Q$  in a logarithmic paper, a straight line is obtained. The slope equals to  $n-1$  and its intercept at  $Q=1$  identifies the value of  $C$ . As  $B$  value is not specified, different values for  $B$  are assumed and  $(s_w/Q) - B$  term is drawn versus  $Q$  in a double logarithmic paper. This is continued so that a line obtained from Eq. (10) becomes straight. The first value of  $B$  is generally supposed to be zero with a concave curve. Then, the  $B$  value is increased until an approximate straight line is formed. The larger value of  $B$ , the more convex the graph becomes.

Sheahan [21] presented a set of type curves through which the parameters of flows from step drawdown test can be obtained. Plotting  $s_w/Q$  versus  $Q$  values on a logarithmic paper for  $n$  between 0.4-1.7, type curves are provided. Using similar coefficients, field diagram of  $s_w/Q$  versus  $Q$  values is drawn on a transparent logarithmic paper and adapted with type curves to obtain  $B$ ,  $C$  and  $n$  values. Requiring a lot of field  $s_w/Q$  values to determine a field curve to be adjusted accurately is the main drawback of using type curves.

Miller and Weber [26] developed a method to determine  $n$  by trial and error method. Following equation is obtained thorough logarithmic transformation to determine the value of  $n$ :

$$n_i = \log[e_i + (Q_3/Q_2) - (K_2/K_1)(Q_1/Q_2)] / \log(Q_3/Q_2), \tag{11}$$

where:

$$e_i = (K_2/K_1)(Q_1/Q_2)^n.$$

$$K_1 = s_1 - (Q_1/Q_2) s_2,$$

$$K_2 = s_2 - (Q_3/Q_2) s_1.$$

Miller and Weber's method was used to calculate  $n$ ,  $C$ ,  $B$  and  $T$  in this study. Using Visual Basic 6.5 [27], Miller and Weber's equation was solved through iteration fixed point method. Visual basic is an Integrated Developing Environment (IDE) programming language of the third generation [28]. Visual Basic is developed for Rapid Application Development (RAD) based on Graphical User Interface (GUI). Calculating  $n$ ,  $B$  and  $C$  parameters, the transmissivity ( $T$ ) values were determined. Fig. 7 shows the flowchart used to obtain a value of  $n$  that is near to the real one. The “ $n$ ” is considered to be fixed in some methods such as Jacob [24], and this assumption is the basis for calculating hydraulic coefficients of aquifer software’s such as Aquifer Win and Aquifer Test. Considering a fixed value for  $n$ , in any situation, deviates the loss rate of well from the real value, consequently another error is introduced in addition to common errors of field measurements.

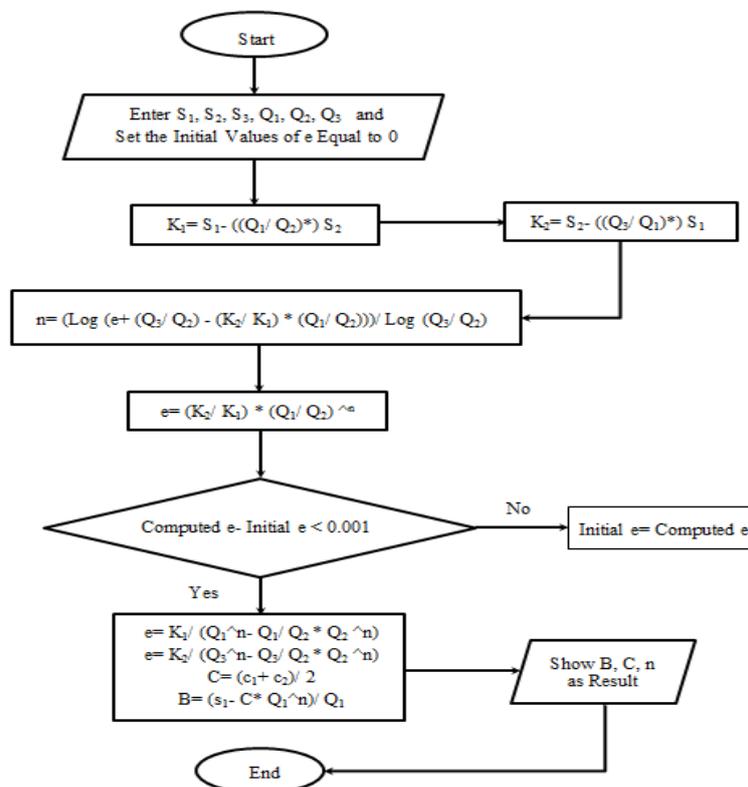


Fig. 7 Flowchart of the calculation of B, C and n coefficients

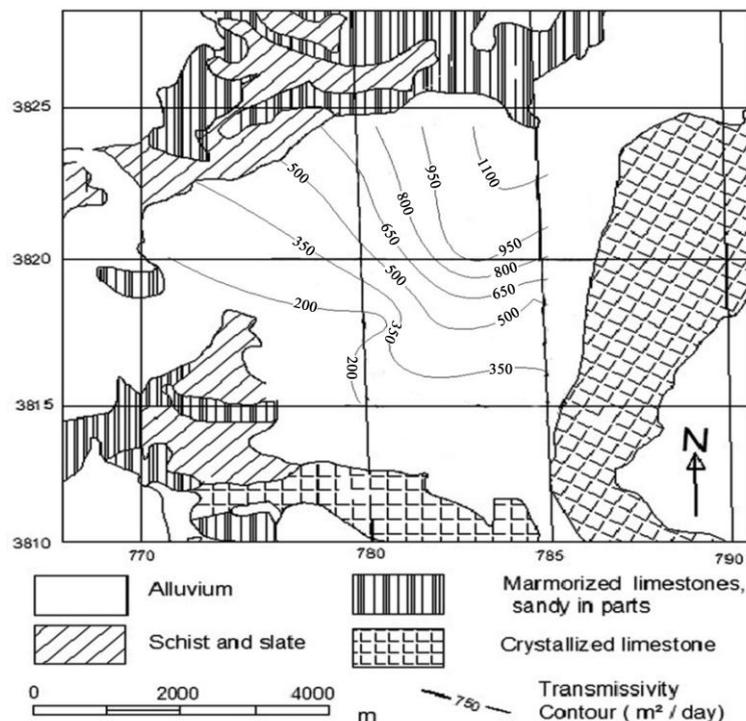
## IV. RESULTS AND DISCUSSION

Based on data obtained from constant rate tests, transmissivity (T) values (Table 1) and contours map were illustrated using kriging method (Fig. 8). Twelve wells were used in the kriging procedure. Furthermore, the transmissivity contour map was plotted for step drawdown method in the study area (Fig. 9). The calculated transmissivity (T) values show that in the north parts of the basin, T values are high ( $750 \text{ m}^2/\text{day}$ ), while those in the southern parts of the basin are low ( $<200 \text{ m}^2/\text{day}$ ). This observation was also confirmed by the analysis of the borehole and the soundings data, as illustrated in the fence diagram. After determining the values of transmissivity, step drawdown test was used instead of constant discharge test. Then, using statistical comparisons through SPSS software, the outputs from comparing two methods are presented in Table 3 and Fig. 10.

To examine and compare the results of those two tests, regression method and determined correlation coefficient ( $R^2$ ) examination were used. SPSS16.0 statistical package was used to analyse the data. Regression option was applied to analyze the data, and ANOVA and summary model were used to get the out point (Tables 2 and 3, Fig. 10). The significance of regression and the liner relationship between variables were calculated by F in ANOVA (Table 2). In Table 3, coefficient R represents the regression value, and  $R^2$  shows the determination coefficient and correlation of two variables. Adjusted  $R^2$  is the adjusted determination (explanation) coefficient.

TABLE 1 TRANSMISSIVITY COEFFICIENT OBTAINED FROM CONSTANT RATE AND STEP DRAWDOWN TESTS

Well location	Step drawdown test ( $\text{m}^2/\text{day}$ )	Constant discharge test ( $\text{m}^2/\text{day}$ )
Ali Abad	494.5	1100
Abbas Abad	135.6	150
Small Gharlogh	156.7	250
Large Gharlogh	446.8	500
New Gharlogh	256.8	400
Rostam Abad	487.2	210
Karkhane	464.1	600
Small Firooz Abad	439.7	450
Sultan Abad	121.4	140
Goodin	893.6	1200

Fig. 8 Transmissivity ( $\text{m}^2/\text{day}$ ) contour map based on constant discharge test for the study area

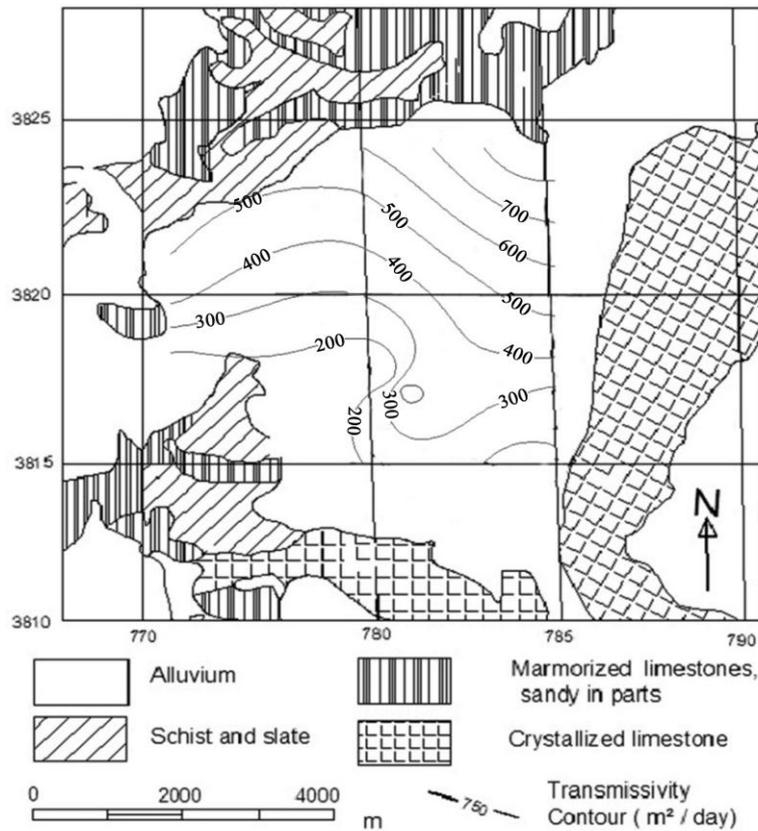


Fig. 9 Transmissivity coefficient contour map based on step drawdown test for the study area (m<sup>2</sup>/day)

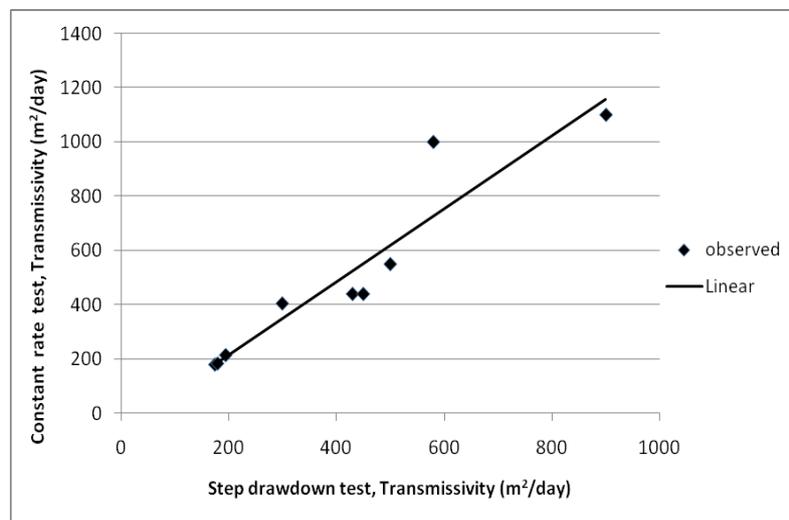


Fig. 10 The relationship between transmissivity values (T) obtained from step drawdown test and constant discharge (full pumping) test analyses

The discrepancies (Table 1, Ali Abad, Goodin and New Gharlogh sites) in the determined transmissivity (T) values, observed in three wells, can only be attributed to the insufficient development and clogging effects of the wells. Reasonable relationship between the step drawdown test and the constant discharge test was obtained as shown in Table 1. It should be emphasized that step drawdown test method can be used as an alternative method, when there are economic constraints, for determining hydraulic properties of aquifer.

Based on the ANOVA table and significance level (sig=0.4), the significance of transmissivity was confirmed at the level of 99% for both methods. As seen from the model summary in Table 3, the values of R, R<sup>2</sup> and Adjusted R<sup>2</sup> were 0.82, 0.67 and 0.63, respectively, showing no significant difference. Therefore, where applying constant discharge test is difficult, step drawdown test can be used as an alternative to determine the hydraulic properties of aquifer.

TABLE 2 ANOVA ANALYSIS RESULTS OBTAINED USING SPSS SOFTWARE

	Sum of Squares	df	Mean Square	F	Sig.
Regression	854262.84	1	854262.84	16.39	0.004
Residual	416937.16	8	52117.15		
Total	1271200	9			

TABLE 3 MODEL SUMMARY

R	R <sup>2</sup>	Adjusted R <sup>2</sup>
0.820	0.672	0.631

## V. CONCLUSIONS- DISCUSSION

Based on the results of pumping tests (constant discharge and step drawdown), which were carried out in Kangavar plain (Western Iran), the following conclusions can be drawn.

- The transmissivity, in step drawdown test, can be estimated by calculating the aquifer coefficient (n) solving Miller and Weber equation, through Fixed Point Iteration numerical method by using Visual Basic 6.5 programming.

- The data derived from mapping transmissivity values attained through constant discharge tests and step drawdown tests were analyzed applying statistical analysis, through which no significant difference was observed.

- Constant discharge tests accomplished by monitoring the groundwater level variations in observation wells can be expensive and time consuming. Hence, step drawdown test can be used as an alternative to the expensive and time-consuming constant discharge test. The duration of the constant discharge tests employed was about 240-300 min, and comparatively lesser in a few wells. The various formulae available for the calculation of aquifer characteristics from pumping test data are valid only if various assumptions about aquifer continuity, thickness, homogeneity, isotropy, well storage and the nature of the water flow are valid under field conditions. In addition, wells may pose critical problems in the analysis of the field pumping tests. In the presence of diverse field conditions, the various assumptions are seldom valid during pumping tests and thus the estimation of aquifer parameters may lead to erroneous values of the relevant parameters. At the same time, those procedures are time consuming and cost prohibitive if practiced indiscriminately.

- According to the above analysis, the required drawdown test includes three steps, of 100, 60 and 60 min durations, respectively. The step drawdown test can be a comparatively effective and economical method for determining hydraulic properties of aquifer. Consequently, this approach is safe for large-scale investments on aquifer exploitation projects.

The benefit of the proposed solution and estimation of transmissivity is that reliable results may be obtained quickly without long pumping tests. The application of the Miller and Weber method requires three-step drawdown pumping tests of short durations (30-100 min). It is pointed out that all these aforementioned procedures were applied to pumping tests in confined aquifers and can also be applied in the case of unconfined aquifers, assuming that the drawdown is small in relation to the saturated thickness. Todd [6] suggested that to adapt the equations to unconfined aquifers, the drawdown  $s$  should be replaced by using  $s \approx s - (s^2/H_s)$ , where  $H_s$  is the initial saturated aquifer thickness. Furthermore, the pumping test solutions given in this paper are based on some simplified assumptions that are invalid in certain circumstances [29]. For example, in many cases the wells are partially penetrating, thus affecting the drawdown. The effect of partial penetration is negligible on the flow pattern and the drawdown beyond a radial distance larger than 0.5 to 2 times the saturated thickness of the aquifer, depending on the amount of penetration [6]. The aquifer of the study area is unconfined but it meets the above criteria, thus those methods can be applied in the study area.

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