

Assessment of Transmissivity from Specific Capacity Data of the Fractured Basalt Aquifers in North-Northeastern Part of Jordan

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ABSTRACT. Transmissivity of aquifers is usually calculated by evaluating pumping test data. But due to the difficulty of carrying out such tests in addition to their relatively high costs, it is oftenly estimated from specific capacity data. In this article, an empirical relationship is derived using 116 pairs of transmissivity and specific capacity values which are obtained from pumping test analyses of groundwater wells penetrating a fractured Basalt Aquifer Systems in two main groundwater basins in Jordan (Azraq and Zarqa Basins). Linear and logarithmic regression functions have been performed and has been found that the logarithmic relationship predicting transmissivity from specific capacity values data has a better correlation ($r = 0.94$) than the linear relationship ($r = 0.85$). This relationship can be justified because transmissivity and specific capacity are lognormally distributed. The spatial distribution of transmissivity is affected only by the structural elements dominating the north-eastern part of Jordan as influenced by the rift formation since other hydrogeologic phenomena (such as karstification) similar to fractured carbonate rocks are not usually present in basalt.

There is no doubt that the most reliable method to estimate the aquifer hydraulic characteristics is to perform the pumping test analysis. But from practical point of view, the cost of performing a large number of these tests is relatively expensive. In groundwater mathematical models, however, the main problem which faces the modeler is the limited number of transmissivity values due to the small number of aquifer tests. In this case, it is preferred to obtain transmissivity values indirectly by correlation analysis. Therefore, the transmissivity of the aquifer can be estimated

using the specific capacity data which is easily obtainable. The specific capacity (Q/s) of a well can be defined as the ratio between the pumping rate (Q) to the drawdown (s) of the well.

Several empirical relationships were derived for different aquifers. Razack and Huntley (1991) found that the log-log empirical relationship between transmissivity and specific capacity are better than linear one in a large and heterogeneous alluvial aquifer in the region of Marrakech city (Morocco). They found that the best-fit equation is $T = 0.36 * (Q/s)^{0.67}$ measured in m^2/s . Huntley *et al.* (1992) found that the analytical solutions used to predict transmissivity from specific capacity in alluvial aquifers do not agree well with the measured transmissivities in fractured rock aquifers. The empirical relations they derived, showed that a linear regression model more appropriate would be applied to the logs of transmissivity and specific ($r = 0.89$) rather the original transmissivity and specific capacity values ($r = 0.72$). FAO/UNDP (1970) in their report concerning the hydrogeology of the Mesozoic-Cainozoic aquifers of the western highlands and plateau of East Jordan derived a log-log relation between specific capacity (SC) versus transmissivity (T) of only 44 wells penetrating the carbonate aquifers in East Jordan for which the data were available. The derived equation was: $\log T = \log SC + 1.5$ which was approximated to the following straight line form: $T = 34 * SC$, where $T =$ transmissivity in m^2/d and $SC =$ specific capacity in m^2/hr . Generally, this equation (FAO/UNDP 1970) is not applicable for wells penetrating fractured basalts.

El-Naqa (1994) derived an empirical relations using 237 data set of transmissivity and specific capacity values in a fractured carbonate aquifer in Central Jordan. He found that the logarithmic relationship predicting transmissivity from specific capacity data has a better correlation ($r = 0.95$) than linear function ($r = 0.84$). The best-fit empirical relationship obtained from the available data set is: $T = 1.81 * (Q/s)^{0.917}$.

In this study the relation between the transmissivity and specific capacity has been examined using a data set of 116 wells obtained from the files of the Water Authority of Jordan (WAJ 1990). The study area is restricted to the wells penetrating the Basalt Aquifer Systems in two groundwater basins in northeastern part of Jordan, where basalt flows cover 11000 km^2 . These basins are the northern part of the Azraq-Basin and the north eastern part of Zarqa-Basin where more than 600 wells have been drilled during the last two decades. Some of them are governmental and are used for water supply to Amman, while the rest are used for irrigation purposes in private farms. The availability of the large set of data can facilitate the achievement of statistical analysis to obtain an empirical relation between the transmissivity and the specific capacity.

Theoretical Background

Theoretically, the transmissivity is linearly proportional to the specific capacity of a well and the constant of proportionality can be obtained by the Dupuit-Thiem equation (Thomasson *et al.* 1960, Theis 1963, Brown 1963, Bradbury and Rothschild 1985, and Razack and Huntley 1991).

The theoretical relations between transmissivity and specific capacity for both steady-state and transient conditions are summarized by Razack and Huntley (1991, 1992). For confined aquifer the relation between the pumping rate (Q) and drawdown of piezometric level (s) can be given by Dupuit-Thiem equation:

$$s = Q/[2\pi T \ln (R/r)] \dots\dots\dots(1)$$

where

Q = constant discharge rate from the well.

s = drawdown of the piezometric level in the well.

R = radius of influence.

r = radius of the well with 100% efficiency.

This equation was solved by Thomsson *et al.* (1960) and could be rewritten introducing the term specific capacity (Q/s) to calculate the transmissivity which should be linearly proportional to specific capacity as follows:

$$T = [1/2\pi \ln (R/r)] * (Q/s) \dots\dots\dots(2)$$

or

$$T = C * (Q/s) \dots\dots\dots(3)$$

where C is a constant depends on the aquifer type. Razack and Huntley (1991) showed that the constant (C) could be 0.9, 1.2, 1.5 for consistent units of specific capacity.

The above equation (1,2 and 3) do not take into consideration the effect of the turbulent well loss. Therefore, the total drawdown in the well is given by Jacob (1947) as:

$$s = BQ + CQ^2 \dots\dots\dots(4)$$

where B = laminar well loss coefficient and C = turbulent well loss coefficient, other symbols were defined before. Equations 1 and 2 can then be rewritten as:

$$s = Q/[2\pi T \ln (R/r)] + CQ^2 \dots\dots\dots(5)$$

$$T = 1/[2\pi[s/Q]-CQ].\ln (R/r) \dots\dots\dots(6)$$

In the case of unconfined aquifer (phreatic aquifer), the Dupuit-Forchheimer assumption can be used to derive the relation between transmissivity and specific capacity as:

$$H^2-h^2 = Q/[\pi K*\ln (R/r)] \dots\dots\dots(7)$$

where H and h are the water heights at the radius of influence (R) and at the effective well radius (r) respectively; K is the hydraulic conductivity of the aquifer. The corrected value of drawdown s_c as suggested by Jacob (1974) is:

$$s_c = s - s^2/H \dots\dots\dots(8)$$

Therefore, equation 8 can be rewritten in the form of Thiem equation similar to the case of the confined aquifer as:

$$s_c = Q/[2\pi T*\ln (R/r)] \dots\dots\dots(9)$$

Applying the same procedure, the relation between transmissivity and specific capacity can be obtained in the same manner as:

$$T = [1/(2\pi*\ln (R/r))]*(Q/s_c)\dots\dots\dots(10)$$

The theoretical relations between specific capacity and transmissivity for confined and unconfined aquifers under transient condition are derived by applying the Cooper-Jacob approximation to the Theis non-equilibrium equation (Razack and Huntly 1991) as:

$$s = (2.3 Q/4\pi T)* \log [2.25 Tt/r^2S] \dots\dots\dots(11)$$

where t = elapsed time since pumping is started, S = aquifer storage coefficient. Therefore, equation 11 can be rewritten in term of specific capacity:

$$Q/s = 1/[(2.3/4\pi T)* \log [2.25 Tt/r^2S] \dots\dots\dots(12)$$

In the leaky artesian aquifers which are also known as semi-confined aquifers, the transmissivity can be expressed using Hantush (1956) inflection point method as follows:

$$T = [Q*K_0(r/B)]/[2\pi* (h_0-h)_{max.}] \dots\dots\dots(13)$$

where K_0 is a Bessel function, known as zero-order modified Bessel function of the second kind; (h_0-h) is drawdown at the inflection point which is defined as being equal to one-half the maximum drawdown. Therefore, the relation between specific capacity and transmissivity can be written as:

$$T = [(1/2\pi) * K_0(r/B)] * (Q/s) \dots\dots\dots (14)$$

Study Area

The study area is located in the northern central part of Jordan (Fig. 1). It comprises the subdivisions which are covered by six basalt flows and in which the basalts represent the main upper aquifer systems in two catchment areas (Azraq and Zarqa Basins). The area is a part of the transition zone between the western highlands and the eastern desert and classified as a semi-arid region. Its aridity is characterized by a high mean annual temperature of 14-38 °C. During the coldest month of January it ranges from 1-14 °C. The long-term mean annual rainfall in the study area ranges from about 100 mm in the southern parts to more than 350 mm in northern part. In addition the area is also characterized by a high potential of evaporation which can reach 3000 mm/year (Ministry of Transport 1992). The climate features of the area are influenced by the north-south, and west-east air directions. The climate in northern and western mountains is Mediterranean, while the eastern and southern hills have an arid to semi-arid climate (desertic area).

Hydrogeology of the Shallow Aquifer System

Over the whole study area and extending as far as Jabal Al-Arab in Syria, the main aquifer consists of a succession of six lava flows lies unconformably on a sedimentary successions of Tertiary and Upper Cretaceous age (Bender 1968). The southern limit of the Basalt Aquifer System passes through the Azraq Druze. The eastern boundary near Al-Safawi (H5) of the aquifer have not been identified. The main western limit of the Basalt Aquifer System trends north-south through Mafraq but along a tongue of the aquifer extends westwards along the Wadi Dhuleil to Zarqa. The aquifer extends north of the borders to Syria into Jabal Al-Arab.

The lavas consist mainly of black olivine with intercalated beds of clay and zeolitic volcanic ashes. Only the two upper flows crop out in the Azraq-Basin where their combined thickness is about 50 m. The thickness of volcanic record in the Azraq-Basin is over 250 m and the thickness of the volcanics in the northern part of the study area is about 400 m as recorded in Sabha well (WAJ-Files 1990).

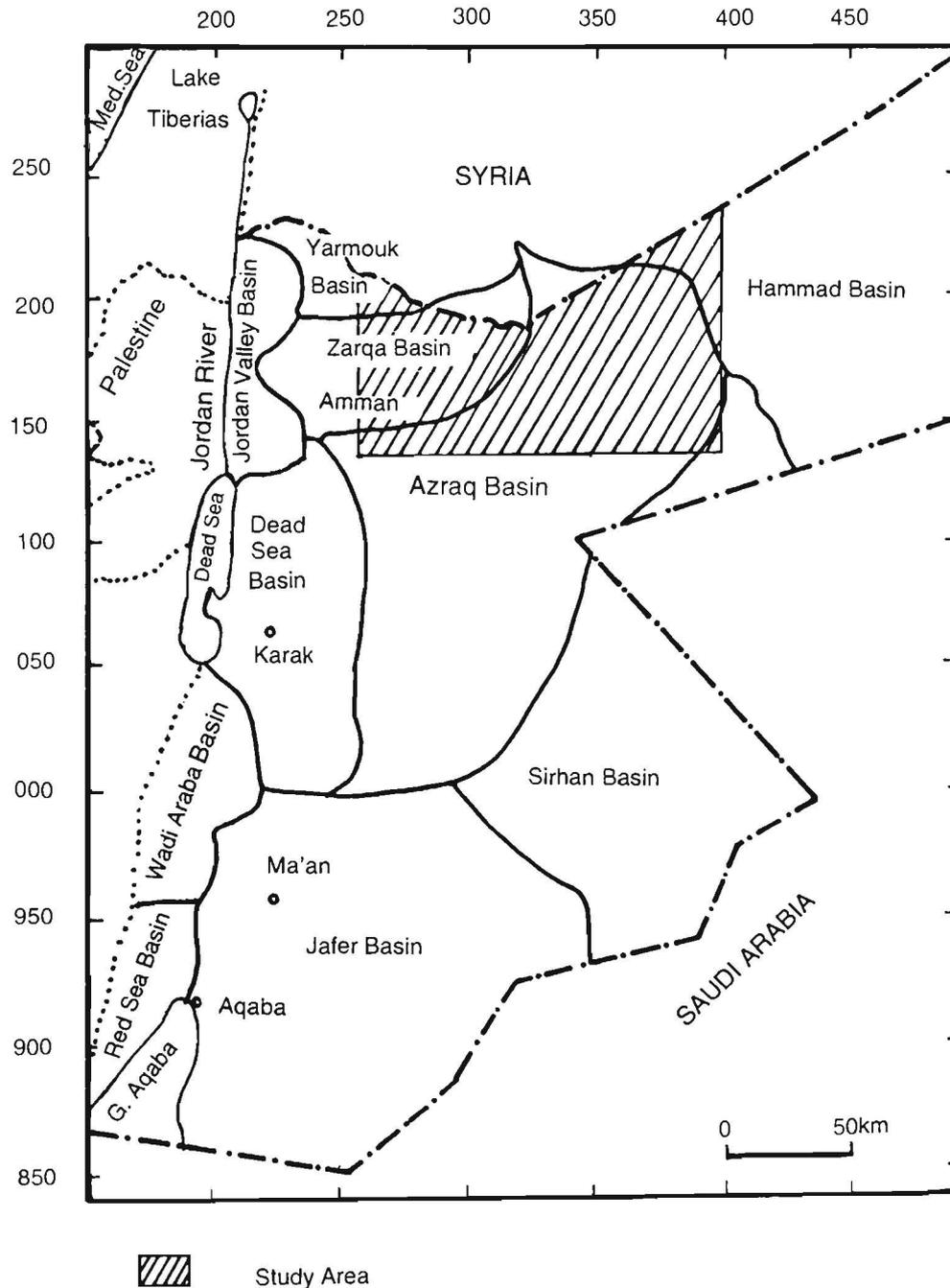


Fig. 1. Location map of the study area.

Generally, the Basalt Aquifer System forms together with the Rijam Formation (Tertiary age) at the southern rim of the basalt flows in the Azraq-Basin as well as at the western rim in the Dhuleil-Hallabat area with Amman/Wadi Sir Formations Shallow Aquifer Complexes (Rimawi 1992 and Abu Sharar and Rimawi 1993). These Shallow Aquifer Complexes have different hydraulic characteristics, which have been obtained from the lithologies of the Rijam and Amman/Wadi Sir Formations (El-Naser 1991 and Rimawi 1992).

The groundwater flow in the Basalt Aquifer System in the Azraq-Basin (closed basin) is directed north to south to the center of the basin (Fig. 2) whereas it flows from north to southwest in the upper part of the Zarqa-Basin and then it changes its direction in the Hallabat area to be from east to west (Abu Sharar and Rimawi 1993). The groundwater divide between the two basins coincides with the surface catchment area of the two basins.

The transmissivity of the Basalt Aquifer System in both basins varies in a very wide range between 1.362 m²/d to 78624 m²/d.

Methodology of study

Transmissivity and specific capacity data set were obtained from WAJ (1990) files. The pumping tests of 116 wells were verified in order to derive the empirical relation between transmissivity and specific capacity of the Basalt aquifer which can be considered as a fractured aquifer in many places and partially fractured basalt aquifer in some cases. The pumping test analysis of aquifer hydraulic characteristics were obtained using equilibrium equation and conventional non-equilibrium equation (Jacob 1947 and Theis 1963).

The data set consisting of 116 pairs of transmissivity and specific capacity which are obtained from pumping tests of 116 wells distributed in the two basins (Fig. 2).

Statistical analysis

Large set of data of transmissivity and specific capacity allowed for justified statistical analysis. The frequency distribution of both specific capacity and transmissivity indicate that both variables are lognormally distributed as shown in Fig. 3. The transmissivity and specific capacity are statistically homogeneous and of a random nature, thus the application of regression and correlation analysis can be easily achieved (Razack and Huntley 1991).

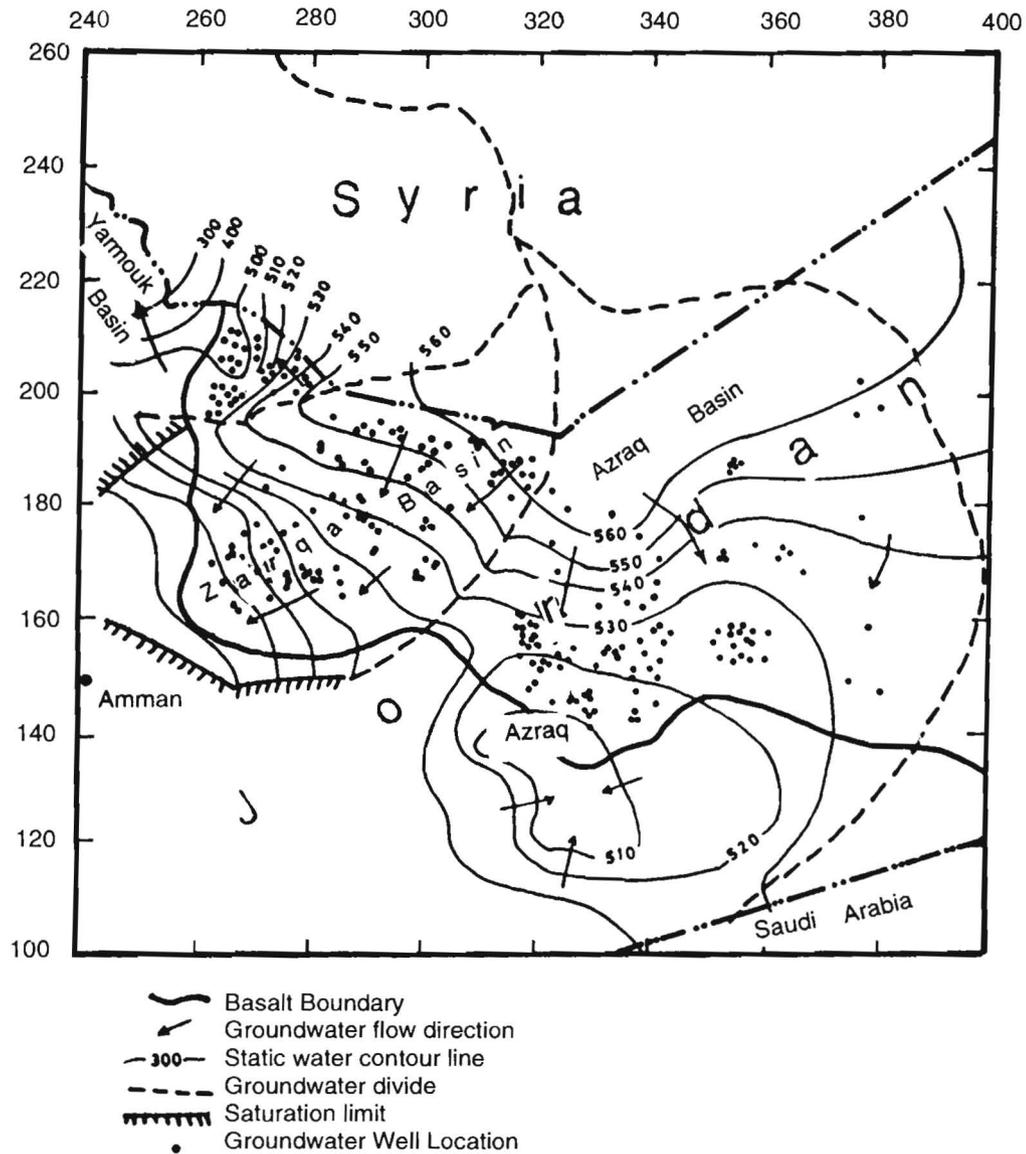


Fig. 2. Groundwater flow map of the Basalt Aquifer System.

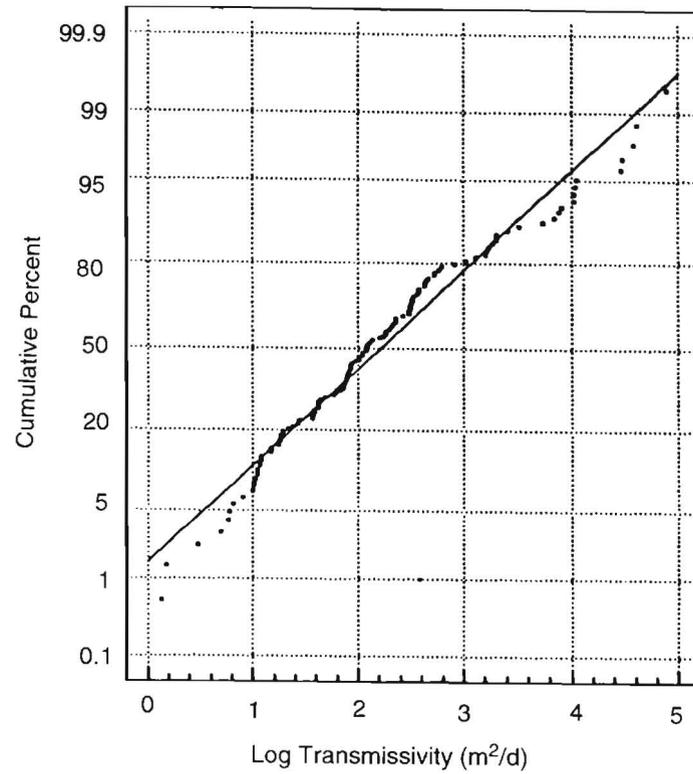
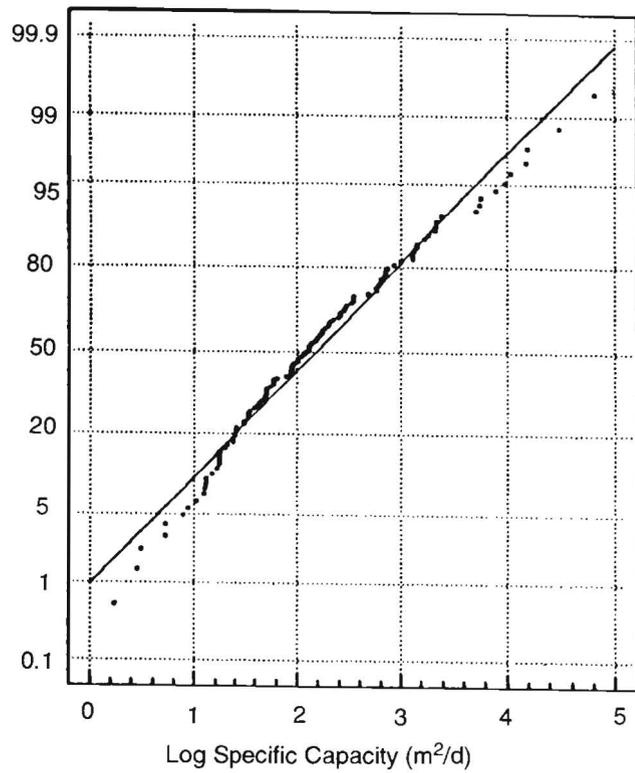
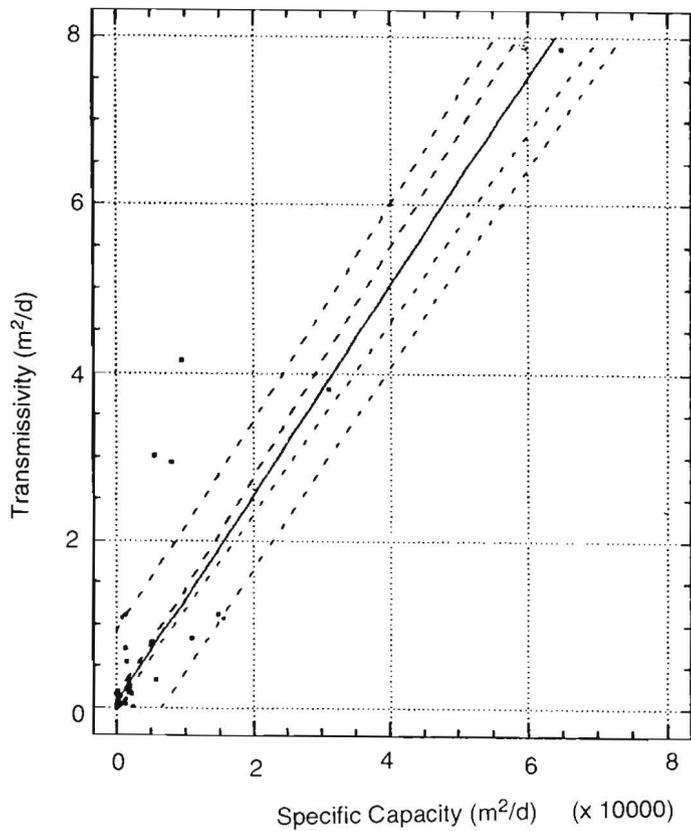


Fig. 3. Log-normal fitted distribution for both specific capacity and transmissivity data.

(x 10000)



(x 10000)

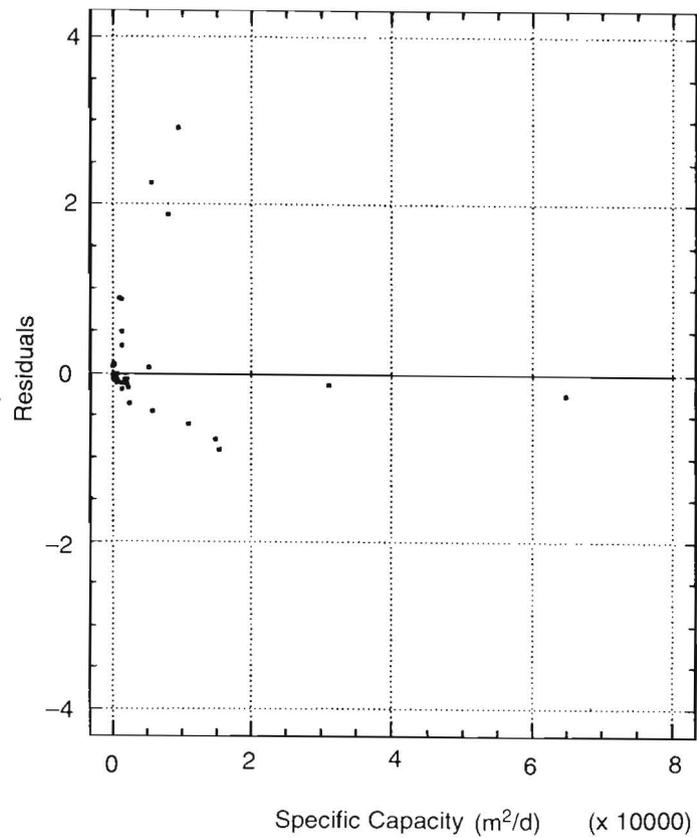


Fig. 4. (a) Linear relationship between transmissivity and specific capacity.
(b) Plot of residuals versus specific capacity.

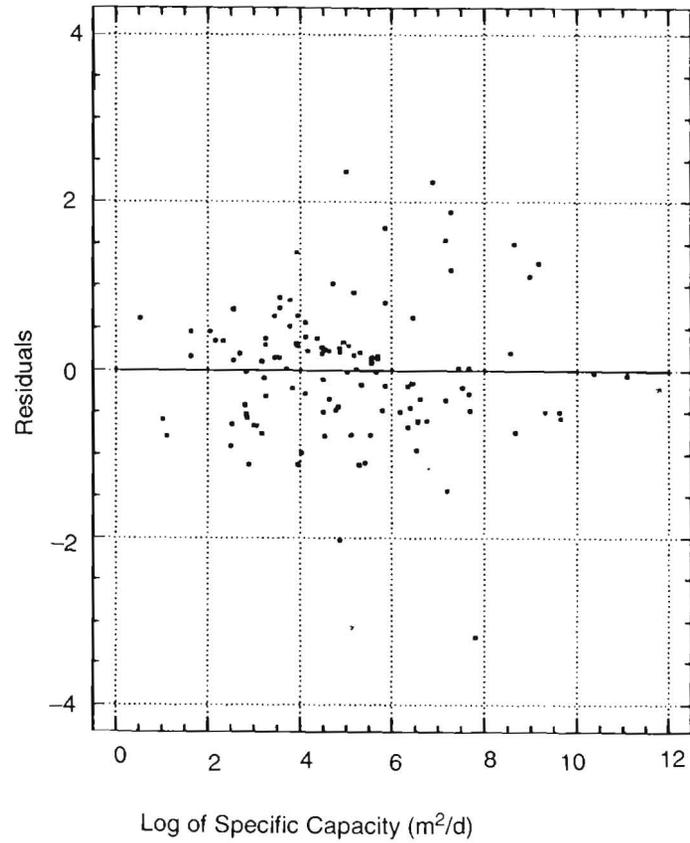
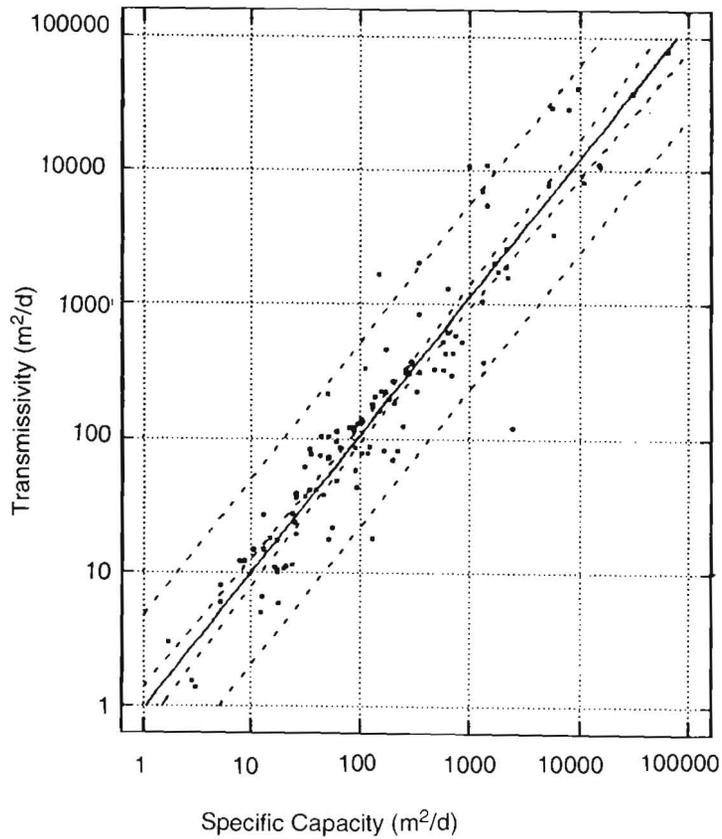


Fig. 5. (a) Log-log relationship between transmissivity and specific capacity.
 (b) Plot of residuals versus specific capacity.

The simple regression analysis has been applied to derive the empirical relationship between specific capacity and transmissivity. The transmissivity was plotted versus specific capacity using linear regression with 95% significant level as shown in Fig. 4a. Thus, the residuals which are the differences between the observed and predicted transmissivity values are plotted versus specific capacity on Fig. 4b. The following linear relation is obtained with correlation coefficient of 0.85:

$$T = 564.332 + 1.244 * (Q/s) \dots\dots\dots (15)$$

where T = estimated transmissivity in m²/day and Q/s = specific capacity in m²/day. It should be noted that the values of the regression constants are specific units of transmissivity and specific capacity applied in this study.

The standard error of estimation which is a measure of the scatter about the regression curve is calculated using the following equation (Spiegel 1975):

$$S_{y,x} = \sum(Y - Y_{est})^2/n \dots\dots\dots (16)$$

where $S_{y,x}$ = standard error of estimate of Y on X, where Y and X in this case the transmissivity and specific capacity respectively. Y_{est} = the estimated value of the transmissivity and n is the number of data set. However the standard error of estimate of transmissivity for linear regression is determined to be 4361.12.

On the other hand, the transmissivity was plotted versus specific capacity using a log-log regression with confidence limit of 95% as shown in Fig. 5a. In addition, the residuals of the transmissivity values versus specific capacity are plotted on Fig. 5b. A log-log relation is obtained (equation 17) with correlation coefficient of 0.95, however the standard error of estimate of transmissivity values is calculated to be 0.80.

$$T = 0.86 * (Q/s)^{1.029} \dots\dots\dots (17)$$

It is clearly noticed that the correlation coefficient obtained from linear regression ($r = 0.85$) is relatively lower than the correlation coefficient of logarithmic regression ($r = 0.94$). From statistical point view, the use of log-log relation improves the correlation coefficient significantly. This is logically right because the transmissivity and specific capacity data set are lognormally distributed. The best logarithmic relationship between the transmissivity and the specific capacity can also be explained as a function of the intensity of fractures and other structural elements which has affected the area since the rift formation. The fracture system of the aquifer is revealed by the presence of the fault zones which may affect the abrupt increase in the permeability.

In order to map the distribution of transmissivity values overall the basin geostatistical methods including spatial variability and kriging techniques (Clark 1979 and Davis 1986) can be used to extrapolate the transmissivity and specific capacity values particularly in the southern and eastern parts of the Azraq basin that have limited data points.

Conclusion

The transmissivity and specific capacity data set are obtained from 116 groundwater wells located in Azraq and Zarqa Basins. These wells produce water from the Basalt Aquifer System which is considered to be a highly fractured in some places where it is affected by fault systems passing through the area and partially fractured in the nearby areas of the fault systems. The data set of 116 pairs have been used to derive the empirical relationship to predict the transmissivity values from specific capacity data only with an acceptable accuracy. Linear and logarithmic regressions have been used to predict the transmissivity from specific capacity. The results obtained can be summarized as follows:

- 1) The theoretical equations which have been derived by different authors assumed that the transmissivity is linearly proportional to specific capacity. These relations however overestimate the transmissivity values with respect to the measured values in fractured rock aquifers.
- 2) The frequency distributions of transmissivity and specific capacity data indicate that there are lognormally distributed. Thus, this justify the necessity to use the logarithmic transformation function of the data set.
- 3) The prediction of transmissivity values from specific capacity values using linear regression function showed that the predicted transmissivity values from specific capacity data are generally greater than the measured values particularly at lower specific capacity. However at the higher values of specific capacity, T values are compared well with the measured ones. On the other hand, the predicted values of transmissivity using log-log regression function appear to be quite similar to the measured transmissivities.
- 4) The empirical relation between transmissivity and specific, obtained from the data set (116 pairs) applying log-log regression analysis showed a better correlation coefficient ($r = 0.94$) than the linear regression with correlation coefficient of ($r = 0.85$).

- 5) The best fit empirical relation obtained from the data set is $T = 0.86*(Q/s)^{1.029}$ for transmissivity and specific capacity which have units in (m²/day). Thus, the general form of this equation is $T = C*(Q/s)^{1.029}$ where C is a constant and is given in Table 1 for common units of transmissivity and specific capacity.

Table 1. Values of the coefficient C in the equation $T = C*(Q/s)^{1.029}$

T	(Q/s)					
	m ² /s	m ² /min	m ² /d	ft ² /s	ft ² /min	ft ² /d
m ² /s	1.196	0.018	0.95E-6	13.77	0.2	1.15E-4
m ² /min	71.76	1.08	5.97E-4	826.39	12.25	6.89E-3
m ² /d	1.033E+5	1.5552E+3	0.86	1.19E+6	17.634	9.917
m ² /yr	7.77E+7	5.68E+5	313.9	4.34E+8	6.4E+6	3,619.7
ft ² /s	12.86	0.19	1.07E-4	148.15	2.196	1.23E-3
ft ² /min	771.77	11.42	6.42E-3	8,888.9	131.75	0.074
ft ² /d	1.1E+6	16,451.75	9.25	1.28E+7	1.9E+5	106.69
ft ² /yr	4.02E+8	6.0E+6	3,376.25	44.67E+9	6.9E+7	3.89E+4

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تقييم الناقلية من معلومات السعة النوعية لخزانات البازلت المتشققة في منطقة شمال - شمال شرق الأردن

عمر الريموي و علي الناقة

قسم الجيولوجيا - كلية العلوم

الجامعة الأردنية - عمان - المملكة الأردنية الهاشمية

جرت عادة حساب الناقلية لخزانات المياه الجوفية من معلومات نتائج الضخ . ونظراً لصعوبة إجراء مثل هذه التجارب ذات التكلفة العالية ، فمن الممكن تحديد قيم الناقلية من معلومات السعة النوعية والتي من السهولة الحصول عليها .

في هذا البحث تم اشتقاق علاقة مبدئية ما بين ١١٦ زوج من معلومات الناقلية والسعة النوعية تم الحصول عليها من نتائج تجارب الضخ لأبار مياه تخترق الخزان الجوفي البازلتي المتشقق في حوضي الأزرق والزرقاء للمياه الجوفية . حيث تم تحديد معامل الارتباط الخطي واللوغارتمي ووجد أن العلاقة اللوغارتمية لتحديد قيم الناقلية من قيم السعة النوعية لها معامل ارتباط $(r = 0.94)$ أفضل من العلاقة الخطية والتي معامل ارتباطها $(r=0.84)$. ويمكن تفسير ذلك لأن قيم الناقلية والسعة النوعية تتبع التوزيع اللوغارتمي الطبيعي .

ان التوزيع المكاني لقيم الناقلية يتأثر بعناصر الجيولوجيا التركيبية السائدة في الجزء الشمالي الشرقي من الاردن والتي ترتبط ارتباطاً وثيقاً بتكوين حفرة الانهدام ، علماً بأن الظواهر الهيدروجيولوجية الأخرى مثل الفجوات الكارستية والتي تشابه مع الصخور الجيرية المتشققة فهي غير موجودة في البازلت .