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Estimation of Aquifer Parameters by Least-Squares Method under Linear Flow Conditions in Fractured Rocks

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Pumping and recovery test data in phyllite formations were analysed under linear flow conditions by incorporating modification in the method proposed by Şen (1986). Although the Şen (1986) method is developed for analysis of borewell test data, this method has been used for large-diameter well-test data by taking average inflow rate in the well. The results obtained were compared with Şen's graphical method. Lower values of root mean-square error were obtained by least-squares method. The estimated values of transmissivity and storage coefficient were acceptable at 1 per cent level of significance. An advantage of the least-squares method is the automization, which is lacking in the graphical method utilising curve-matching technique.

Introduction

About 2/3rd area in India is underlain by hard rocks (Rao 1979). The hard rocks are characterized by secondary porosity due to the presence of fractures, joints, fissures and foliation *etc.* Studies on evaluation of aquifer parameters in such aquifers are limited. Estimation of aquifer parameters is an important step in groundwater assessment and rational development. These parameters are also required for minimum spacing between two wells to avoid mutual interference. Pumping test is the main field test for determining aquifer parameters. Several methods have been developed for analyzing pumping test data based on radial and linear groundwater flow conditions.

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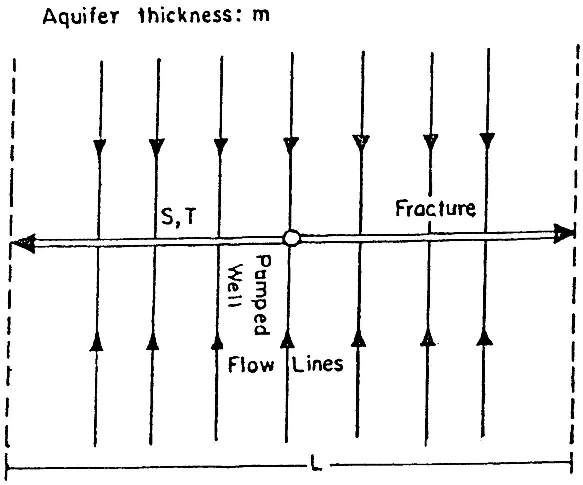

Fig. 1. Description of a vertical fracture in an aquifer.

Fig. 1 shows a conceptual model of a linear flow pattern. A homogeneous aquifer is transected by a single major fracture which may have a larger conductivity value than the surrounding medium and which has been penetrated by a well. If the well is pumped, the water level in the fracture declines, inducing flow into the fracture from the aquifer. The open fracture is a planar production surface that is an extension of the well itself. The well and its hydraulically connected production surface resemple a collector well (Campbell and Lehr 1973) except that the gallery is natural and its dimensions are unknown. The flow lines are perpendicular to the main fracture plane in the medium adjacent to the main fracture. Thus, the flow in the aquifer is linear and laminar toward the extended well.

The linear flow concept was first introduced in groundwater terminology by Muskat (1937) for limestone aquifers. Many years later, Ferris *et.al* (1962) presented a drain solution under linear flow in the form of a planar sink or source. Jenkins and Prentice (1982) presented aquifer test analysis in fractured rocks under linear flow conditions. They observed linear flow conditions in fractured rocks at three locations for small time of pumping and small distance from extended well. A graphical method for analysis of pumping test data has been developed by Şen (1986) under linear flow conditions in fractured-rock areas. However, graphical methods require either curve-matching or finding inflection points or, in special cases fitting a straight line to pumping test data. All these methods require considerable judgement on the part of investigator and there is room for error in the individual judgement. Also, it becomes tedious and time consuming when analysis of several sets of pumping test data is done. In this paper an attempt has been made for estimation of aquifer parameters by least-squares method under linear flow conditions in fractured rock with pumping and recovery test data.

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Theory

Pumping Phase

The nonsteady state hydraulic response in fractured rocks with linear flow pattern resulting from a constant discharge in a pumping well according to Şen (1986) is

$$s = \frac{Q}{2TL} \sqrt{4\pi Tt/S}\{1-\mathrm{erf}\ (x\sqrt{S/4Tt})\} \qquad (1)$$

Rewriting Eq. (1) by putting $u = \dfrac{x^2S}{4\,Tt}$

$$u = \frac{x^2S}{4Tt} \qquad s \equiv \frac{\sqrt{\pi}QX}{2TL}\ \{\frac{1-\mathrm{erf}(\sqrt{u})}{\sqrt{u}}\} \qquad (2)$$

On expansion of Eq. (2), we get

$$s \equiv \frac{\sqrt{\pi}QX}{2TL}\frac{1}{\sqrt{u}}\ (1-\frac{2\sqrt{u}}{\sqrt{\pi}} + \frac{2u^{3/2}}{3\sqrt{\pi}1!} - \frac{2u^{5/2}}{5\sqrt{\pi}2!} + \ldots + \ldots) \qquad (3)$$

where

T	–	transmissivity, (L^2/T),
S	–	storage coefficient, (fraction),
s	–	drawdown measured in a pumped well due to constant discharge, (L),
Q	–	constant discharge of pumping well, (L^3/T),
L	–	length of fracture, (L),
t	–	time since pumping started, (T),
X	–	perpendicular distance from the fracture, (L) and
erf()	–	error function, which is given as

$$\mathrm{erf}(a) \equiv \frac{2}{\sqrt{\pi}} \int_0^a e^{-y^2} dy$$

Assumptions in the derivation of the equation are:

a) The fracture is isotropic, homogeneous and is bounded on both sides by an impervious layer,
b) The fracture is planar, vertical and fully penetrating the aquifer and has no storage capacity,
c) The flow is assumed to be laminar with a linear flow pattern toward the pumping well,
d) The water level in the fracture at any time during pumping is assumed to be at uniform level along the entire length of the fracture, and
e) The pumped discharge, Q, is constant during the whole pumping phase.

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Modification of Şen (1986) Equation

For small values of $u (u \le 0.089)$ or large values of time $(t > \frac{r^2 S}{0.356T})$ the series of Eq. (3) can be approximated by the first two terms as

$$s \equiv \frac{\sqrt{\pi}QX}{2TL} \{ \frac{1}{\sqrt{u}} (1 - \frac{2\sqrt{u}}{\sqrt{\pi}}) \} \quad \text{or} \quad s = \frac{\sqrt{\pi}QX}{2TL} (\frac{1}{\sqrt{u}} - \frac{2}{\sqrt{\pi}}) \tag{4}$$

on putting $u = \frac{X^2}{4} \frac{S}{Tt}$, we get

$$s = -\frac{QX}{TL} + \frac{Q}{L} \sqrt{\pi/TS} \sqrt{t} \tag{5}$$

At the outer limit of the trough of the depression (Jenkins and Prentice 1982) where drawdown $s \equiv 0$, Eq. (5) yields

$$0 = -\frac{QX_e}{TL} + \frac{Q}{L} \sqrt{\pi/TS} \sqrt{t}$$

$$X_e = \sqrt{\pi Tt/S} \quad \text{or} \quad X_e = \sqrt{\pi T_g t/S_g} \tag{6}$$

The term X_e is known as the conditional radius of influence (Bindemann 1963); which differs from radius of influence (R_e) in steady state flow condition by its dependance on time. Also, $T_g \equiv T L$ is global transmissivity and $S_g = S L$, is a global storage coefficient.

Also, Eq. (5) may be abbreviated as

$$s = \alpha + \beta\sqrt{t} \tag{7}$$

where

$$\alpha \equiv -\frac{QX}{TL} \tag{8}$$

is entrance loss (Jenkins and Prentice 1982), and

$$\beta = \frac{Q}{L} \sqrt{\pi/TS} \tag{9}$$

Eq. (7) can be fitted as a straight line to a set of n points (s_i, $\sqrt{t_i}$, i = 1, 2, ..., n). The line of "best fit" of Eq. (7) is obtained by least-squares method which requires minimizing the sum of squares of the deviation of observed and predicted drawdowns.

Objective function F is given as

$$F = \sum_{i=1}^{n} (s_i - \alpha - \beta\sqrt{t_i})^2$$

According to the principle of least-squares F should be minimum. For F to be mini-

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mum, the partial derivatives of F, with respect to α, and β should vanish separately, *i.e.*

$$\frac{\partial F}{\partial \alpha} \equiv -2 \sum_{i=1}^{n} (s_i - \alpha - \beta\sqrt{t_i}) \equiv 0 \text{ and } \frac{\partial F}{\partial \beta} \equiv -2 \sum_{i=2}^{n} (s_i - \alpha - \beta\sqrt{t_i})\sqrt{t_i} = 0$$

On rearranging we get

$$\sum_{i=1}^{n} s_i = n\alpha + \beta \sum_{i=1}^{n} \sqrt{t_i} \tag{10}$$

and

$$\sum_{i=1}^{n} s_i\sqrt{t_i} = \alpha \sum_{i=1}^{n} \sqrt{t_i} + \beta \sum_{i=1}^{n} t_i \tag{11}$$

Eqs. (10) and (11) are known as normal equations for estimation of α and β.

Once α and β are known the values of T and S can be calculated by Eqs. (8) and (9) if the length of the fracture is measured exactly. But measurement of length of fracture is very difficult in the field tests. In this paper we take lenght of fracture as twice the conditional radius of influence ($2X_e$).

$$T = \frac{QX}{L\alpha} \tag{12}$$

$$S = \frac{Q^2\pi}{\beta^2 L^2 T} \tag{13}$$

Partially Penetrating Aquifer

The drawdown in a partially penetrating aquifer is converted into an equivalent drawdown that would occur in a fully penetrating aquifer as suggested by Hantush (1964)

$$s_f = s - \frac{s^2}{2H} \tag{14}$$

where

s – drawdown in a partially penetrating aquifer, (L),
s_f – equivalent drawdown in a fully penetrating aquifer, (L), and,
H – penetration depth of pumped well (extended well), (L).

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Seepage Face

When water is withdrawn from an unconfined aquifer, a seepage face occurs between the well-water level and the phreatic surface of the aquifer at the well face. The drawdown s in this case is replaced by s_o as suggested by Ehrenberger (1928)

$$s_0 = s - \frac{s^2}{2m} \tag{15}$$

where

s_o – Phreatic surface – static water level, (L),
s – well water level- static water level, (L),
$s^2/2m$ – Length of the seepage face, and
m – initial saturated thickness of the aquifer, (L).

The initial saturated thickness of the aquifer can be calculated as suggested by Acharya (1988) based on tests in the phyllite formation in Udaipur, which is:

Initial saturated thickness (m) of the aquifer = water column depth before test + average depth of impervious layer below the bottom of the well.

Average depth of impervious layer below the bottom of the well. = Kh/Kv × average depth of water column.

The term Kh/Kv is the ratio of the horizontal hydraulic conductivity to the vertical hydraulic conductivity which has been reported to be 2.2 for hard-rock areas of Udaipur (India).

Recovery Phase

As suggested by Jenkins and Prentice (1982) the equation for residual drawdown during recovery phase can be found similar to radial flow conditions. The residual drawdown s' can be written from Eq. (5) as

$$s' = -\frac{QX}{TL} + \frac{Q}{L}\sqrt{\pi/TS}\sqrt{t'} + \frac{QX}{TL} - \frac{Q}{L}\sqrt{\pi/TS}\sqrt{t_r} \quad \text{or} \quad s' = \frac{Q}{L}\sqrt{\pi/TS}\left(\sqrt{t'} - \sqrt{t_r}\right) \tag{16}$$

where

t' – $t_p + t_r$
t_r – time since pumping stopped, (T) and
t_p – pumping time, (T)

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During the recovery period the entrance loss into the well must be considered. This problem is of great significance in large diameter wells, particularly in older dug wells where flow velocities may be limited by low hydraulic conductivity and due to the storage effect in the well. Hence, Eq. (16) is corrected by adding the entrance loss to the residual drawdown.

$$s' \equiv -\frac{QX}{TL} + \frac{Q}{L}\sqrt{\pi/TS}\,(\sqrt{t'} - \sqrt{t_r}) \tag{17}$$

Eq. (17) may be abbreviated as

$$s' = a + b\,(\sqrt{t'} - \sqrt{t_r}) \tag{18}$$

where, $a \equiv -QX/TL$ and $b \equiv Q/L\sqrt{\pi/TS}$

Eq. (18) is fitted to a straight line by method of least squares as was done with Eq. (7). Once values of a and b have been determined then transmissivity and storage coefficient during recovery phase may be calculated as

$$T = \frac{QX}{La} \tag{19}$$

and

$$S = \frac{Q^2\pi}{b^2L^2T} \tag{20}$$

Application of the Method to Large-Diameter Wells

Large-diameter wells are of great importance in hard-rock areas of the world. A "large-diameter" well is defined as a well in which storage is large enough to produce significant errors when aquifer test data are analysed by methods which neglect well storage (Sammel 1974).

For complete recovery,

Volume of water pumped from well	=	Volume of water pumped from storage + volume of water contributed by aquifer.

$$Q_p \times t_p = Q_i \times t_p + Q_i \times t_r$$

$$= Q_i\,(t_p + t_r)$$

$$\frac{Q_i}{Q_p} = \frac{t_p}{t_p + t_r} \tag{21}$$

where

Q_i – average aquifer inflow rate, (L^3/T), and

Q_p – constant discharge pumped from the well, (L^3/T)

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Eq. (21) gives average inflow rate which includes well storage and fracture storage, and also the variation due to the irregular shape of the well. The estimated values of the transmissivity and the storage coefficient obtained by average inflow rate will be average values,since under actual field conditions the inflow rate into the large-diameter well is not constant during the pumping and the recovery phase respectively. For partial recovery, right-hand side of Eq. (21) must be multiplied by the fraction of recovery accomplished.

Validity of the Method

Since there are many methods to estimate aquifer parameters a least root-mean-square error criterion may be used to assess the accuracy of the different methods. The root-mean-square error (RMSE) of an estimate is defined as

$$\mathrm{RMSE} \equiv \sqrt{\frac{1}{n} \sum_{n=1}^{n} e_i^2}$$

where

e_i – difference between corrected and predicted drawdowns, and
n – number of observations.

The value of RMSE should be close to zero for better estimation of aquifer parameters. To test the significance of the difference between observed and predicted drawdowns, student's t-test was used. The value of t was calculated by the following relationship

$$t = \frac{\bar{d}\sqrt{n}}{\mathrm{S.D.}}$$

where

$\bar{d}$ – mean of the difference between observed and predicted drawdowns,
S.D. – standard deviation of the difference,
n – number of observations and
υ – degree of freedom, n-1

The value of S.D. was calculated by

$$\mathrm{S.D.} = \sqrt{\frac{(d-\bar{d})^2}{n-1}}$$

Field Testing of the Method

This method was field tested for pumping and recovery test data from two wells of the instructional farm of College of Tech. & Agril. Engg., Udaipur (India). The test-

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Table 1 – Details of wells tested at instructional farm of College of Tech. & Agril. Engg., Udaipur (INDIA)

Well No.	Areal Cross section, m^2	Depth of the well, m (b.g.l.)	S.W.L., m (b.g.l.)	Penetration depth of the aquifer, m	Initial saturated thickness of the aquifer, m	Constant discharge rate, m^3/min.	Average aquifer inflow rate, m^3/min.	Duration of pumping, min.	Duration of Recovery, min.
3	15.60	21.25	6.45	14.80	48.07	0.2617	0.0906	509	960
5	32.69	21.50	5.85	15.65	44.39	0.3713	0.1091	357	857

S.W.L. ≡ Static water level
b.g.l. ≡ below ground level

ed wells are large-diameter wells. The aquifer tapped is unconfined and comprised the phyllite of Aravali Super Group. These wells are partially penetrating as inflow from bottom of the wells was observed. During the tests, seepage of water through the walls of the wells was observed. The depth, areal cross section and other details of these wells are summarised in Table 1. Pumping and recovery tests were conducted during post monsoon season. A device, suggested by Athwale *et. al* (1983), was used for maintaining constant discharge from the pumped wells. Amount of recirculation was varied by manipulation of gate valve in the return pipe for constant discharge. During the tests, well water levels were recorded by a measuring tap from a fixed point. The duration of tests were kept short to avoid large drawdowns in the wells. Also low yielding aquifer and use of centrifugal pumps necessiated such durations as wells would otherwise become dry in 5-6 hours of pumping.

Analysis of pumping and recovery test data of large diameter wells was performed in the following manner:

1) Drawdowns and residual drawdowns are corrected by Eqs. (14) and (15) for each observation.
2) Calculate average inflow rate Q_i into the well from Eq. (21)
3) Calculate $\sqrt{t}$, $s\sqrt{t}$ for pumping phase and $(\sqrt{t'} - \sqrt{t_r})$, $s'(\sqrt{t'} - \sqrt{t_r})$ for recovery phase for each observation.
4) Determine $\sum\sqrt{t}$, $\sum t$, $\sum s$ and $\sum s\sqrt{t}$ (for pumping phase) and $\sum(\sqrt{t'} - \sqrt{t_r})$, $\sum(\sqrt{t'} - \sqrt{t_r})^2$, $\sum s'$ and $\sum s'(\sqrt{t'} - \sqrt{t_r})$ (for recovery phase) by summing the respective columns.
5) Count the number of observations.
6) Calculate global transmissivity ($T_g \equiv TL$) and global storage coefficient ($S_g = SL$) by using Eqs. (12) and (13) for pumping phase and similarly for recovery phase by Eqs. (19) and (20).
7) Finally calculate T and S for pumping and recovery phase after determining conditional radius of influence by using Eq. (6).

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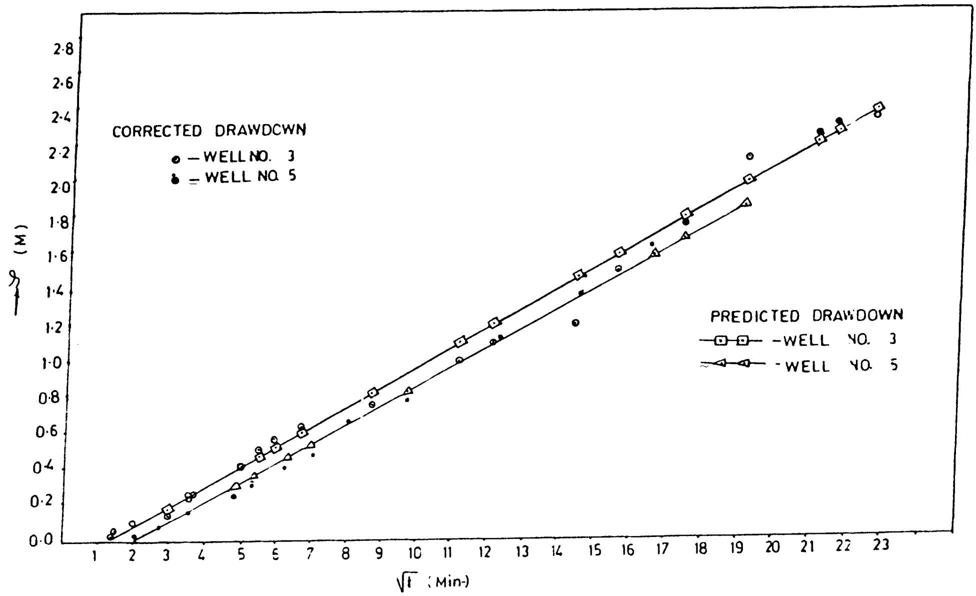

Fig. 2. Comparison of corrected and predicted drawdown by least-squares method.

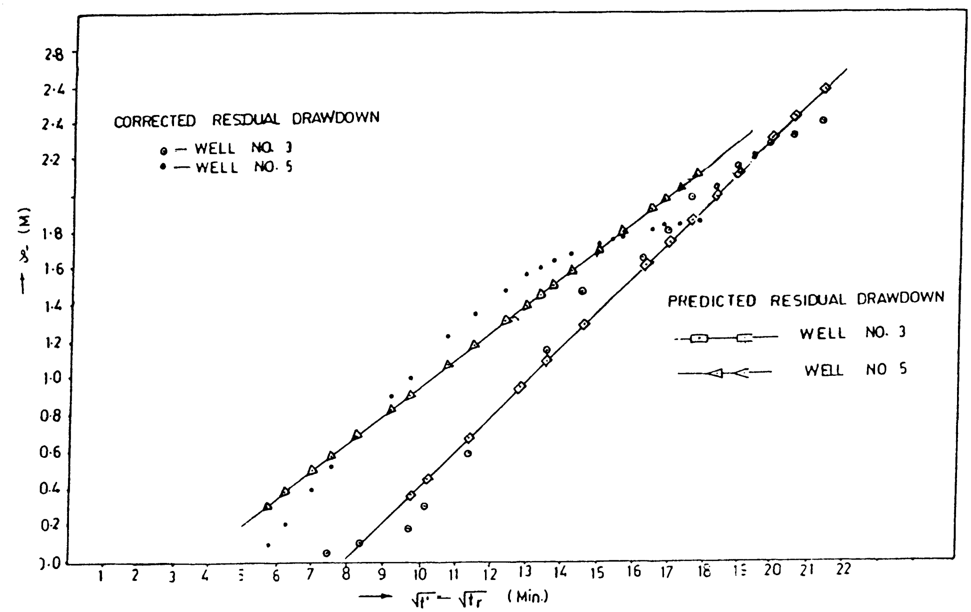

Fig. 3. Comparison of corrected and predicted residual drawdown by least-squares method.

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Table 2 – Estimated values of global transmissivity (T_g), global storage coefficient (S_g) and conditional radius of influence (X_e)

Method	Well No. 3			Well No. 5		
	T_g m³/min	S_g m	X_e m	T_g m³/min	S_g m	X_e m
1. Graphical						
Şen (1986)	0.952	1.532	-	1.450	2.506	-
2. Least-squares						
a) Pumping	1.364	1.456	38.69	1.595	1.915	30.55
b) Recovery	0.1375	5.250	-	0.651	2.569	-

($T_g = T \times L$ and $S_g = S \times L$)

Corrected and predicted drawdowns are shown in Fig. 2. It can be seen that predicted drawdowns during early periods deviate from the corrected drawdowns which may be due to storage effect in the wells. The values of u, also, exeeded 0.089 for the timeless that 15 minutes and 35 minutes for well Nos. 3 og 5 respectively. This indicates that the method of least squares must be used with caution if the basic criterion of u being less than 0.089 and exactly linear flow conditions are not met. However, in both wells duration of the tests were long enough which did not pose any problem in analysis. Fig. 2 depicts corrected and predicted residual drawdowns. Greater deviations were observed in the recovery phase than the pumping phase which probably may be due to the fact that the flow during the early recovery periods tended to be radial but for late recovery periods this was due to storage effect in the wells. Figs. 2 and 3 show that flow conditions were different during pumping and recovery phases, specially during early recovery periods. It is interesting to note from Fig. 3 that if the straight lines are extended they do not pass through the origin. This suggests that entrance losses during recovery phase should be considered. Addition of entrance losses term in Eq. (16), therefore, is justified. The data in Table 2 show that global transmissivity T_g and global storage coefficient S_g calculated by graphical and least-squares methods agree closely for both the wells during pumping phase but differ slightly in recovery phase which may be due to deviations in the flow conditions from linear to radial in early recovery periods. Table 3 depicts variations in estimated values of transmissivity T and storage coefficient S by graphical and least-squares methods. This is due to the fact that authors have taken the length of the fracture as twice the radius of influence (L=2 X_e) which is different for both the wells. This table also shows that the proposed method gives lower root-mean-square errors for pumping test over graphical method. But slightly higher values of root-mean-square error was obtained for well. No. 5 in recovery test, this may be due to change in flow conditions. This indicates superiority of the proposed method for estimation of aquifer parameters in both pumping and recovery phases to Şen (1986) method.

The proposed method gives approximate values of aquifer parameters since for

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Table 3 – Comparison of aquifer parameters (T and S) by graphical and least-squares method

Method	Well No. 3			Well No. 5		
	T m²/day	$S \times 10^{-2}$	RMSE $\times 10^{-2}$	T m²/day	$S \times 10^{-2}$	RMSE $\times 10^{-2}$
1. Graphical						
Şen (1986)	17.71	1.97	22.50	34.17	4.10	12.44
2. Least-squares						
a) Pumping Phase	25.38	1.88	8.43	37.59	3.13	4.13
b) Recovery Phase	2.56	7.06	9.48	15.34	4.20	13.69

the sake of simplicity, average aquifer inflow rate is taken. But in real field conditions aquifer inflow rate decreases with increased recovery period.

The values of aquifer parameters obtained by the method of least squares were tested statistically by student's t-test. The null hypothesis of no significant difference between corrected and predicted drawdowns and between corrected and predicted residual drawdowns was considered. Table 4 reveals that calculated values of t are less than the tabulated values and hence the hypothesis is accepted. This leads to the conclusion that corrected and predicted drawdowns and corrected and predicted residual drawdowns match fairly well. Therefore, values of T and S obtained by the proposed method may be accepted for pumping and recovery phases at 1 per cent level of significance. Negative values of t indicate that the drawdowns and residual drawdowns are overestimated.

Table 4 – Application of Student's t test to pumping and recovery test-data

Well No.	Pumping Phase				Recovery Phase			
	t calculated	t tabulated $t_{0.05}$	t tabulated $t_{0.01}$	Degree of freedom (ν=n-1)	t calculated	t tabulated $t_{0.05}$	t tabulated $t_{0.01}$	Degree of freedom (ν=n-1)
3	-0.1452	2.1009	2.8784	18	-0.650	2.1199	2.9208	16
5	-0.3751	2.1448	2.9763	14	-0.0119	2.0860	2.3453	20

Conclusions

It can be concluded from the results of the study that the method of least squares can be used for estimation fo aquifer parameters of large-diameter wells in fractured rocks under the following limitations:

1) The flow must be linear.
2) The values of u must be small analysis holds good for $u \leq 0.089$ *i.e.* for large values of time and small distance from the extended well.

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Although the method was developed for borewell pumping and recovery test-data under linear flow conditions, its suitability in large-diameter wells was established even though average aquifer inflow rates were taken. Estimated values of aquifer parameters were acceptable at 1 per cent level of significance. Therefore, the suggested method may be useful in preliminary estimation of aquifer parameters. Although the method has been derived for $u \leq 0.089$, the periods of occurrence of greater value of u were very short for the tested wells. So it can be used for larger value of u without producing appreciable error. The method has advantages over Şen's method (1986) as it eliminates the problem of subjectivity associated with curve-matching technique. The other advantage of the method is that no graphs are drawn or tables or charts are consulted. The procedure is simple and can be performed with commonly available electronic calculator.

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