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Optimisation of aquifer parameters: a case study from Bheri Terai area, mid western Nepal

Moti Bahadur Kunwor
Department of Irrigation

ABSTRACT

For the study of groundwater potential in any area, it is necessary to determine aquifer parameters as correctly as possible. The most effectively and popularly used tools in the field by groundwater geologists and engineers till today is old conventional curve techniques. A new approach is given to refine the aquifer characteristics by computer-assisted numerical techniques.

The computer-assisted techniques were used in the Bheri Terai area (Banke/Bardiya), mid western Nepal with an objective of studying the aquifer parameters more accurately with reference to the prevailing hydrogeological condition. Keeping in view of the nature and types of aquifer, an optimisation based model developed by Jageshwar (1985) has been adopted for estimation of aquifer parameters. The aquifer parameters in the study area have been evaluated by using both curve procedure and computer assisted numerical techniques. Parameters are optimised by minimisation of sum of the square of residues between computed and observed drawdown. The starting values of parameter for optimisation were generally assigned as per the available graphical procedures. The applicability of the model to the field data has been demonstrated by using the existing test pumping data of Bheri Terai area (GWRDB, 1979). The purposed model for the analysis of test pumping data yields significantly better reproduction of time drawdowns. The results of analysis of test pumping data indicate confined and leaky confined nature of deep aquifer. Majority of leaky aquifers show a declining nature of piezometric head in the overlying aquifer while, some of the confined aquifer shows finite nature in areal extent due to the presence of barrier boundary (most probably impervious clay?).

INTRODUCTION

This paper deals with the computer-assisted geohydrological studies carried out in the Bheri Terai area, Nepal using available data. The study is mainly directed to evaluation of hydraulic parameters of Deep Confined and Leaky Confined types of aquifers using optimisation techniques.

A significant study of groundwater in the Bheri Terai area (Fig. 1) was carried out jointly by HMG/ Nepal and USAID with technical assistance of USGS during the year 1972 to 1973 (GWRDB, 1979). During ground water exploration program, 45 test wells were drilled with a depth of 152 m to a maximum of 457 m. The test wells were drilled on a grid spaced at roughly 9-10 km in east-west and 5 to 6 km in north-south (Fig. 1). In addition to the drilling, test pumping was also carried out in 9 wells. The remaining wells were incorporated into the observation well net work.

Geologically, Bheri Terai is a fringe area of the Gangetic alluvial plain composed of porous and permeable sand and gravel layers alternating with clay horizons. The study area occupying about 1800 km^2 is demarcated by the Rapti River in the east, Karnali River in the west, Siwalik foothills in the north and Indo-Nepal border in the south. Rainfall and existing perennial rivers in the area seem to contribute substantial recharge to groundwater reservoir. The lithological logs of bore hole and lithological sections (Fig. 2 and 3) reveal that water table aquifers are generally found in shallower depth, whereas, the confined and leaky confined aquifers are mainly restricted to deeper depths. The piezometric surface control map (Fig. 4) shows that the general direction of ground water flow is towards south.

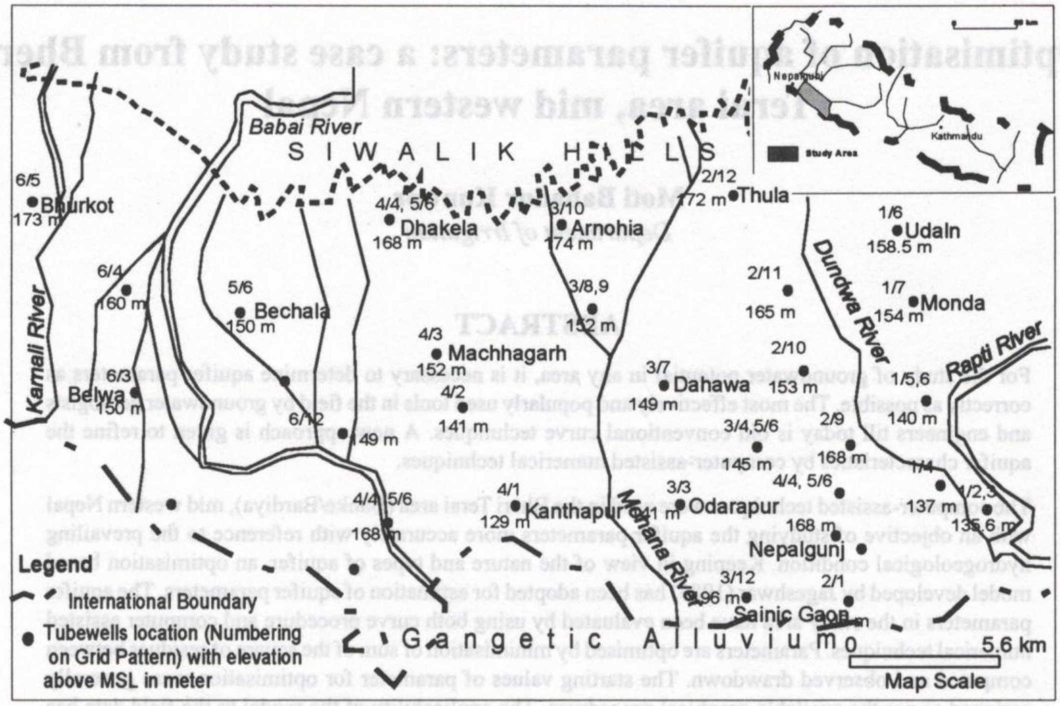

Fig. 1: Tubewell location map of Bheri Terai area, Nepal. Location map of the study area on inset.

The most difficult task in groundwater resource evaluation is the collection of reliable data relating to the spatial distribution of storage coefficient and transmissiivity. The difficulty arises in a number of ways, since these are not physically measurable quantities. These parameters appear in differential equations governing the aquifer response (piezometric head fluctuation) to the aquifer excitation (pumpage, recharge, or change in boundary conditions). The inclusion of transmissivity and storage coefficient in these differential equations is based upon the Darcy's law and the continuity equation for unsteady state flow in porous media.

Test pumping is the most popular method used for the estimation of aquifer parameters. In this method, the aquifer is excited under controlled conditions in the form of pumpage from a single well. The aquifer response generated in the form of drawdowns in the observation wells is recorded carefully. The generated data are then employed for the estimation of parameters based on the idea of closest match between the recorded or observed response and the response given by the governing equation of groundwater flow. The procedure of analysing test pumping data involves the estimation of such parameter value, which minimise the deviations of the computed drawdowns from the corresponding observed drawdowns. The overall procedure of analysis comprises of the following two components:

(i) Computation of drawdowns for a given set of parameter values. These computations can be carried out either using analytical equations or by numerical procedures.

(ii) Arriving at the closest match between the observed and computed drawdowns. This can be accomplished either by subjective or visual inspection (Curve Procedures) or by objective optimisation procedures.

GRAPHICAL ANALYSIS OF TEST PUMPING DATA

Theis (1935) introduced first the non-steady-state solution, which takes into account of the related parameters: time and aquifer storage. This method

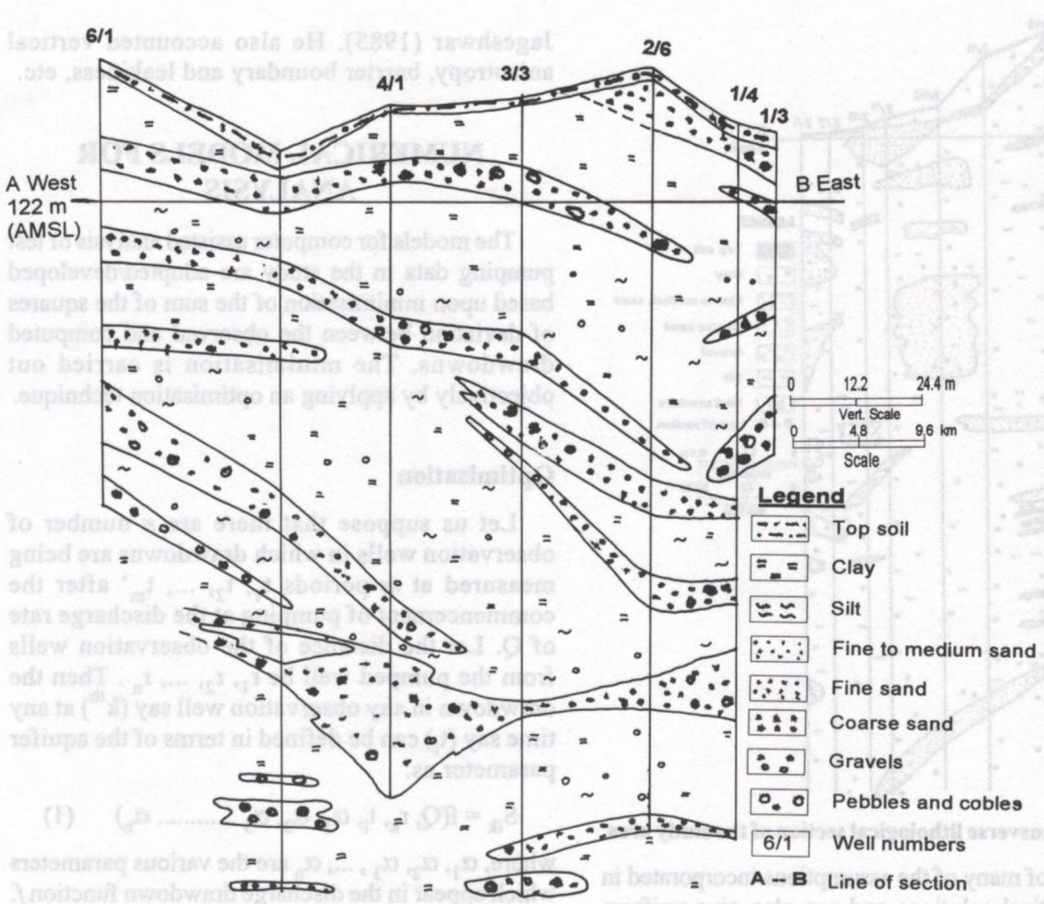

Fig. 2: Longitudinal lithological section of the study area.

is applicable only for confined aquifer. For the evaluation of leaky confined aquifer, Hantush and Jacob (1955) introduced a solution which accounted for the condition in which overlying aquitard has negligible storage. Hantush (1964) modified his earlier concept considering the appreciable amount of water released from the storage in aquitard. This is applicable for the condition $t \leq m's'/10p'$, where aquitard is thick and relatively impermeable. For the condition $t \geq 2m's'/p'$, where aquitard is thin and relatively permeable, plot of field data are superimposed on the type curve $w(u'', r/L)$ and values of L,T and S are determined. Stallman (1963) introduced a family of logarithmic type curve of $w(u_r)$ Vs l/u_r for many values of $R_i = r_i / r_r$, where R_i = distance ratio, r_i = distance from observation to image well and r_r = radial distance of the observation well. Ferris et al. (1962) applied the method of images. His method can be applied to any number of barrier or recharge boundaries.

NUMERICAL ANALYSIS OF TEST PUMPING DATA

Varden Berg (1971) proposed technique of non-linear regression to overcome the problem of subjective bias. The technique involves analytical differentiation of drawdowns. Rushton and Chan (1976) proposed an alternative method in which numerically computed drawdowns corresponding to different feasible sets of parameter values, are compared with the observed data. Out of these, the set of parameters, which yield the closest reproduction of the observed drawdowns, are picked up. This approach can account for the

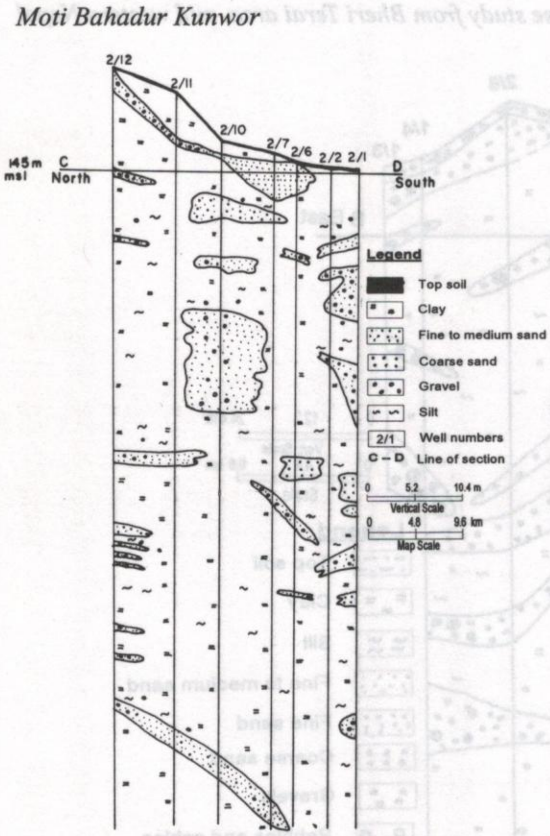

Fig. 3: Transverse lithological section of the study area.

violation of many of the assumptions incorporated in the analytical solutions and can also give uniform emphasis to the entire data set, apart from eliminating the necessity of type curves altogether.

Mania and Sucche (1978) proposed the use of sensitivity coefficient for on objective least square estimation. This was followed by a large number of authors (McElewee, 1980; Chander et al., 1981; Cobb et al., 1982). This technique may offer a substantial reduction in computer time requirement over classical non-linear optimisation techniques provided the drawdown can be analytically differentiated.

Daccadesh (1984), developed a numerical scheme for computer assisted analysis of test pumping data for confined and leaky confined aquifer. In addition, he accounted the effect of partial penetration for confined aquifers.

A comprehensive study for the estimation of aquifer parameter for confined, leaky confined and unconfined aquifer was carried out by Jageshwar (1985). He also accounted vertical anisotropy, barrier boundary and leakiness, etc.

NUMERICAL MODELS FOR ANALYSIS

The models for computer assisted analysis of test pumping data in the study are adopted/developed based upon minimisation of the sum of the squares of deviation between the observed and computed drawdowns. The minimisation is carried out objectively by applying an optimisation technique.

Optimisation

Let us suppose that there are *n* number of observation wells in which drawdowns are being measured at *m* periods $t_1, t_2, ..., t_m$' after the commencement of pumping at the discharge rate of Q. Let the distance of the observation wells from the pumped well be $r_1, r_2, ..., r_n$. Then the drawdown in any observation well say (k^{th}) at any time say (t_i) can be defined in terms of the aquifer parameter as:

$$S_{ik} = f(Q, r_k, t_i, \alpha_1, \alpha_2, \alpha_3 .... \alpha_n) \qquad (1)$$

where, $\alpha_1, \alpha_2, \alpha_3, ..., \alpha_n$ are the various parameters which appear in the discharge drawdown function *f*. This function can be explicit or implicit depending upon the nature and type of aquifer and other physical features.

Confined aquifer (S_{ik}) can be expressed from the Theis' equation:

$$S_{ik} = (Q / 4T) * w(u) \qquad (2)$$

While, for leaky confined aquifer (S_{ik}) can be written from Hantush's equation:

$$S_{ik} = (Q / 4T) * w(u, r_k / L) \qquad (3)$$

Similarly, for the leaky confined aquifer with water released form the storage in aquitard with declining piezometric head in the overlying unpumped aquifer S_{ik} can be written from the modified Hantush equation as:

$$S_{ik} = (Q / 4T) * w(u) \qquad (4)$$

Now, if the observed drawdown in kth well at the ith time is S_{ik}, then the deviation of the simulated

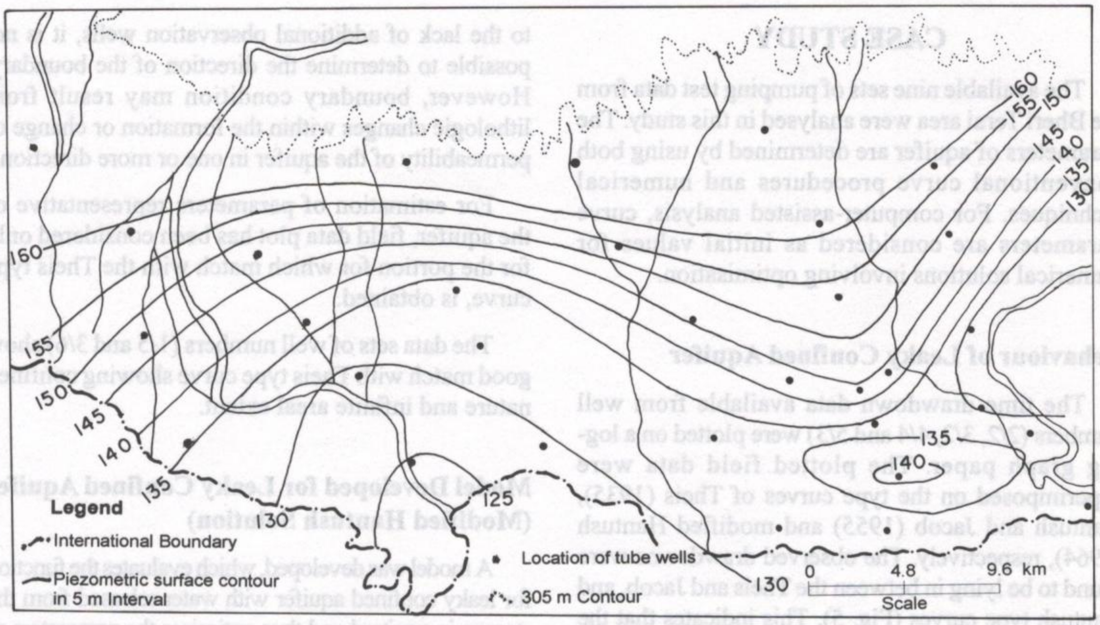

Fig. 4: Pre-monsoon piezometric surface contour map (May-June, 1975).

drawdown (S_{ik}) from the observed drawdown is given by:

$$e_{ik} = S_{ik} - s^{+}_{ik} \quad (5)$$

Thus, the sum of the squares of deviation or differences in the drawdowns can be written as:

$$Z= \underset{ki}{\Sigma\Sigma} (e_{ik})^2 \quad (6)$$

In case of the confined aquifer, Z is a function of S and T, whereas in case of leaky confined, Z is a function of S, T and L or.

i.e., $Z = z(S,T)$ for confined (7)

or $Z = z(S,T.L/\text{or } \psi)$ for leaky confined

Therefore, the parameter can be estimated as follows:

Minimise Z with respect to the parameters (S, T, L or ψ) subject to the constraints derived from the physics of parameters as well as from the subjective knowledge of aquifer system. This is achieved by using an appropriate non-linear optimisation technique.

Dacadesh's model (1984) was based upon the constrained minimisation of the sum of the squares of deviation of computed drawdowns from the observed drawdowns. The model calculates the drawdowns by numerical evaluation of well function. For confined aquifers, he has employed the approximate finite series solution for well function given by Abromowitz and Stegun (1970) for different ranges of U which requires less computer time than the numerical integration.

Hence, the approximate solution for estimating the well function for confined aquifer is given as:

when $0 \leq x \leq 1$

$$w(x) = -\ln(x) + a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 \quad (8)$$

and when $0 \leq x \leq 1$

$$w(x) = \left[\frac{X^4+a_1X^3+a_2X^2+a_3X+a_4}{X^4+b_1X^3+b_2X^2+b_3X+b_4}\right]\frac{1}{xe^x} \quad (9)$$

Where, a_o, a_1, a_3, a_4, b_1, b_2, b_3 and b_4 are constant values, given by Abromowitz and Stegun (1970, p. 231) at different ranges of x.

For the confined aquifer, well function can also be evaluated by the summation of an infinite series in term of u (Walton, 1970). But the infinite series tend to oscillate at larger value of u. For leaky confined aquifers, well function need to be calculated numerically, since no approximate solution could be found.

CASE STUDY

The available nine sets of pumping test data from the Bheri Terai area were analysed in this study. The parameters of aquifer are determined by using both conventional curve procedures and numerical techniques. For computer-assisted analysis, curve parameters are considered as initial values for numerical solutions involving optimisation.

Behaviour of Leaky Confined Aquifer

The time drawdown data available from well numbers (2/2, 3/2, 4/4 and 5/3) were plotted on a log-log graph paper. The plotted field data were superimposed on the type curves of Theis (1935), Hantush and Jacob (1955) and modified Hantush (1964), respectively. The observed drawdowns were found to be lying in between the Theis and Jacob, and Hantush type curves (Fig. 5). This indicates that the pumped aquifer is receiving certain vertical recharge from the overlying aquifer. However, the rate of recharge is lower than the one assumed to occur in Jacob and Hantush solution (i.e., the hydraulic head in unpumped aquifer remains constant). This is more pronounced at higher time ordinates. This pattern of lower rate of recharge could be because of a decline in hydraulic head of overlying aquifer. This conclusion was further corroborated by the lithology of sites. This implies that even a small leakage can cause significant fluctuations in the piezometric head of overlying aquifer because of lower values of S resulting from the confined nature. Therefore, an attempt was made to match the data with the type curve of modified Hantush solution. The match was found to be quite satisfactory (Fig. 5). Field data sets of well number 6/1 show a best possible fit with Hantush and Jacob (1955) rather than Theis and modified Hantush.

Behaviour of Confined Aquifer

Plotting of the time drawdown data of well number (3/9) shows a sudden departure after a pumping period of 120 minutes (Fig. 5). This departure representing the increase of drawdowns indicates the presence of a hydrologic boundary nearby, which violates the assumption of Theis solution about infinite areal extent of the aquifer.

As there is no surface indication of boundary due to the lack of additional observation wells, it is not possible to determine the direction of the boundary. However, boundary condition may result from lithologic changes within the formation or change of permeability of the aquifer in one or more direction.

For estimation of parameters representative of the aquifer, field data plot has been considered only for the portion for which match with the Theis type curve, is obtained.

The data sets of well numbers (1/5 and 3/6) show good match with Theis type curve showing confined nature and infinite areal extent.

Model Developed for Leaky Confined Aquifer (Modified Hantush Solution)

A model was developed, which evaluates the function for leaky confined aquifer with water released from the storage in aquitard and thus optimises the parameters as explained earlier. Hantush (1964) introduced the modified solution for leaky confined aquifer by assuming the aquifer to be homogeneous, isotropic, infinite in areal extent, fully penetrating with axis symmetrical radial flow, and using the following equation:

$$\frac{\delta^2 s}{\delta r^2} + \frac{1}{r} - \frac{\delta s}{\delta r} + \frac{p'}{T} - \frac{\delta s_c}{\delta z} = \frac{S}{T} - \frac{\delta s}{\delta t} \quad (10)$$

where s_c is the drawdown in the aquitard (L). By imposing the boundary conditions s(r,o) = o, s, t = o and the initial condition s_c (r, z, o) = o, s_c(r, m, t) = s (r,t), s_c(r, m+m', t) = o, the drawdown(s) for the condition $t \leq m's' / 10p'$ is given as:

$$s = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-y}}{y} \operatorname{erfc}\left[\frac{\psi\sqrt{u}}{\sqrt{[y(y-u)]}}\right] dy \quad (11)$$

where, $u = r^2 s / 4Tt$ and $\psi = (r / 4) * \sqrt{(s'p' / TSm')}$

It can also be expressed as:

$$\psi = (r / 4L) * (s' / S) \quad (12)$$

where s' is the storage coefficient of aquitard, m' is the thickness of aquitard (L) and p' is the hydraulic conductivity of aquitard (LT^{-1}).

Since erfc(x) is the complementary error function defined by

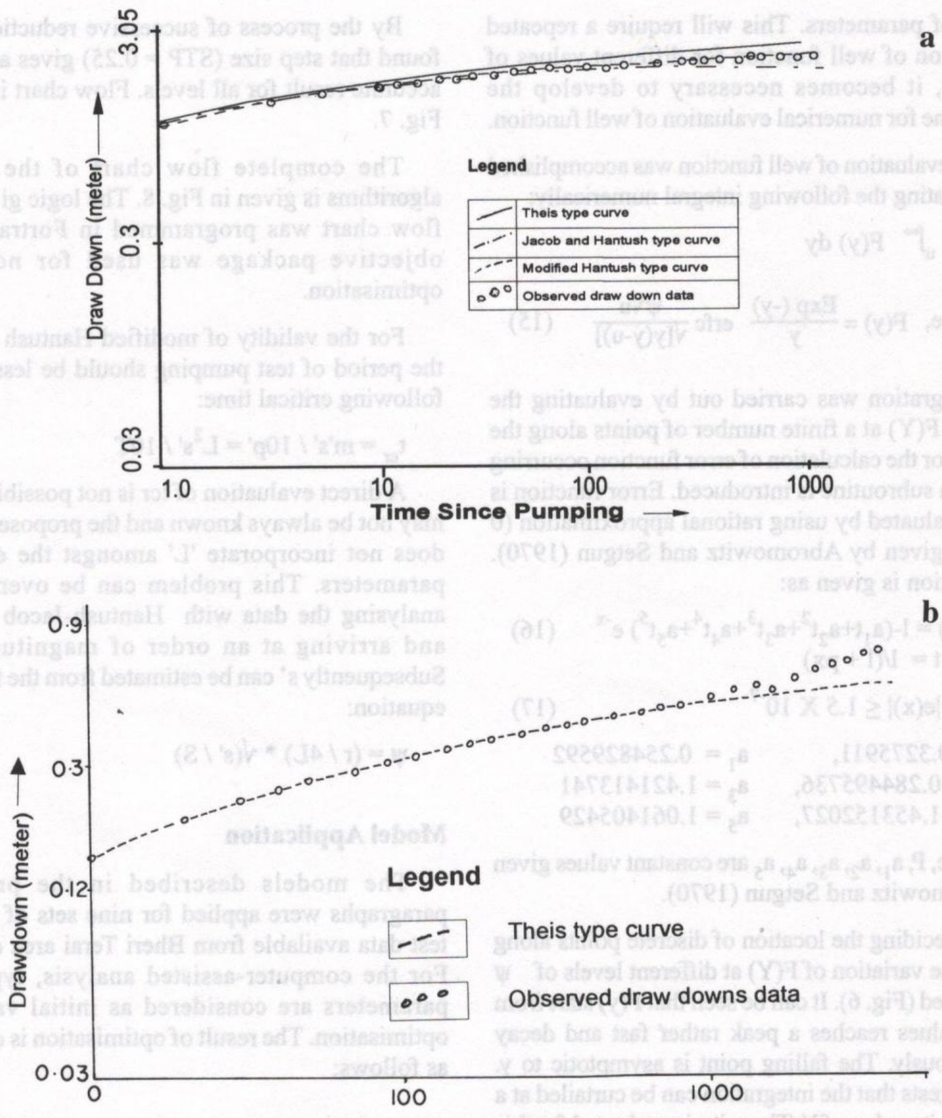

Fig. 5: (a) Response of a leaky confined aquifer (well No. 4/4), (b) Response of a finite confined aquifer (well No. 3/9).

$$\mathrm{erf}(X) = 1-\mathrm{erfc}(X) = (2/\pi) * \int_0^x \exp(-y^2)\, dy \quad (13)$$

With the integral expressed symbolically as $w(u,\Psi)$, i.e.,

$$w(u,\psi) = \int_u^\infty \frac{e^{-y}}{y}\ \mathrm{erfc}\ \frac{\psi\sqrt{u}}{\sqrt{[y(y-u)]}}\ dy \quad (14)$$

The values of $w(u,\Psi)$ are given by Hantush (1964) in term of practical range of u and Here, the aquitard is considered to be thick and relatively impermeable.

For arriving at the optimal values of aquifer parameters, the objective function (Z) from equation (7) has to be evaluated for successively changing values of parameters. This will require a repeated calculation of well function for different values of u. Thus, it becomes necessary to develop the subroutine for numerical evaluation of well function.

The evaluation of well function was accomplished by evaluating the following integral numerically:

$$W = \int_{u}^{\infty} F(y)\, dy$$

$$\text{where, } F(y) = \frac{\text{Exp}(-y)}{y} \text{ erfc} \frac{\psi\sqrt{u}}{\sqrt{[y(y-u)]}} \qquad (15)$$

The integration was carried out by evaluating the function F(Y) at a finite number of points along the Y axis. For the calculation of error function occurring in F(y), a subroutine is introduced. Error function is being evaluated by using rational approximation ($0 \leq X \leq$) given by Abromowitz and Setgun (1970). The relation is given as:

$$\text{erf}(x) = 1-(a_1t+a_2t^2+a_3t^3+a_4t^4+a_5t^5)\, e^{-x} \qquad (16)$$

where $t = 1/(1 + px)$

$$|e(x)| \leq 1.5 \text{ X } 10^{-7} \qquad (17)$$

$p = 0.3275911$, $a_1 = 0.254829592$

$a_2 = -0.284495736$, $a_3 = 1.421413741$

$a_4 = -1.453152027$, $a_5 = 1.061405429$

where, P, a_1, a_2, a_3, a_4, a_5 are constant values given by Abromowitz and Setgun (1970).

For deciding the location of discrete points along Y-axis, the variation of F(Y) at different levels of ψ was studied (Fig. 6). It can be seen that F(y) start from a zero values reaches a peak rather fast and decay monotonously. The falling point is asymptotic to y. This suggests that the integration can be curtailed at a certain finite value of Y. The criterion adopted for this truncation was as follows;

$$|F(y)| \leq 10^{-5} \;;\; y > y^{+}$$

where, Y^{+} is the value of Y at which function F(y) assumes the maximum value.

It can be further concluded from the curves that a smaller step size is required in the lower range of Y. The step size can be increased with increasing Y. For the study, the following function for step size was adopted

$\Delta y = \theta y$, where θ = step size

By the process of successive reduction, it was found that step size (STP = 0.25) gives adequately accurate result for all levels. Flow chart is given in Fig. 7.

The complete flow chart of the adopted algorithms is given in Fig. 8. The logic given in the flow chart was programmed in Fortran IV. An objective package was used for non-linear optimisation.

For the validity of modified Hantush equation, the period of test pumping should be less than the following critical time:

$$t_{cr} = m's' / 10p' = L^2s' / 10T \qquad (18)$$

A direct evaluation of tcr is not possible since s' may not be always known and the proposed scheme does not incorporate 'L' amongst the estimated parameters. This problem can be overcome by analysing the data with Hantush-Jacob equation and arriving at an order of magnitude of L. Subsequently s' can be estimated from the following equation:

$$\psi = (r / 4L) * \sqrt{(s' / S)} \qquad (19)$$

Model Application

The models described in the preceding paragraphs were applied for nine sets of pumping test data available from Bheri Terai area of Nepal. For the computer-assisted analysis, type curve parameters are considered as initial values for optimisation. The result of optimisation is described as follows;

Well No. 4/4 Dhakela

Data

The well was pumped for 1440 minutes at a constant rate of 1.36 m^3/min. The observation well is located at a distance of 15.24 m from the pumped well. The maximum drawdowns recorded in the observation well is 2.58 m. Field data plots were matched by using Theis, Hantush and modified Hantush. Best fit was obtained with modified Hantush. S and T were considered intrinsic parameters. In order to get the idea of leakage, was introduced as tentative parameter.

The initial values were assigned as per the modified Hantush Type Curve technique as $S = 0.0099$. $T = 0.362\ m^2 / min = 0.01$. The limiting values were assigned $S_{max} = 0.099$, $S_{min} = 0.00099$, $T_{max} = 3.62\ m^2/min$, $T_{min} = 0.0362\ m^2/min$, $\psi_{min} = 0.001$.

Results

The proposed model was applied to estimate the intrinsic aquifer parameters (S and T) and to examine the effect of leakiness. The effectiveness of tentative parameter in influencing the drawdown has been tested by including amongst the decision variables (S and T).

Initially, the model was run considering only the intrinsic parameter (S and T) to be effective. The minimised SSR is $0.14607\ m^2$ form the starting value of $8.9148\ m^2$. In the subsequent run, the tentative parameter of leakage (ψ) was included. The minimised residual variance is $0.02548\ m^2$ from $0.2122\ m^2$. Here, it seems that the minimised SSR is considerably reduced through optimisation with the additional parameter ψ.

The improvement in the optimal match as a consequence of including the effect of leakiness is visually demonstrated in Fig. 9. Numerically, the improvement is indicated by a very high value of F statistics (+189.24). The fact that the computed value of F is much higher than the tabulated value of $F_{critical}$ at 95% level of confidence the effectiveness of the leakiness in influencing the drawdown is established beyond doubt. The result of analysis is presented in Table 1.

The maximum time up to which modified Hantush is applicable (tcr) was estimated using equations 18 and 19. The order of magnitude of L as obtained by Jacob Hantush solution comes to be 2337 m. Based upon this value of L, 's' was computed as 0.102×10^{-3} and t_{or} as 8852.5 min.

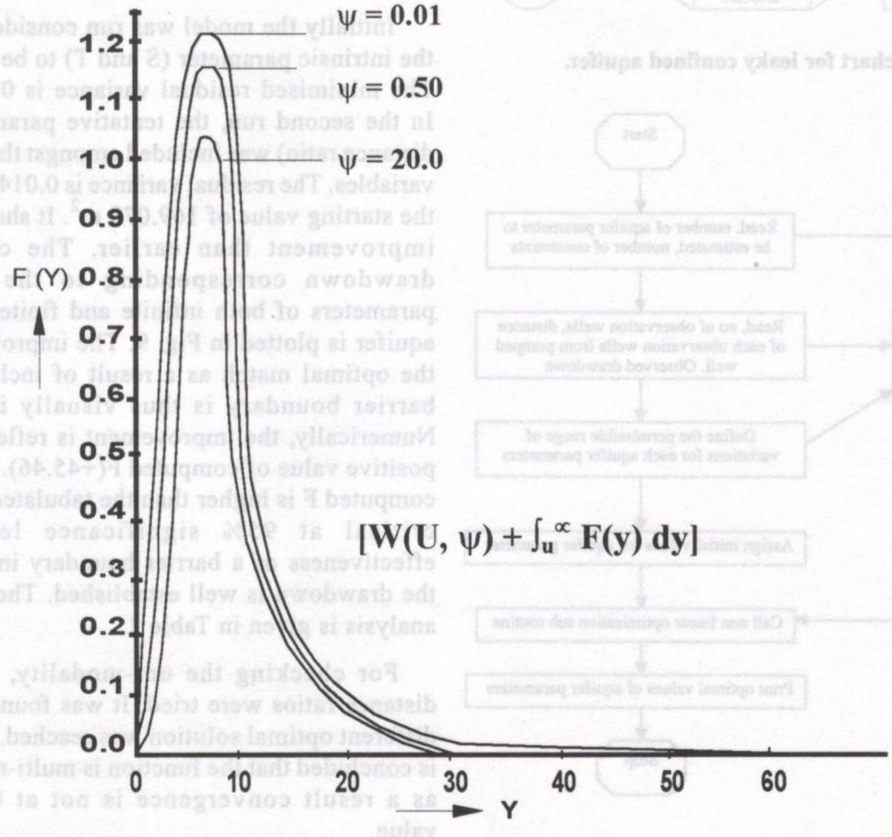

Fig. 6: Behaviour of F(Y) at different levels of ψ.

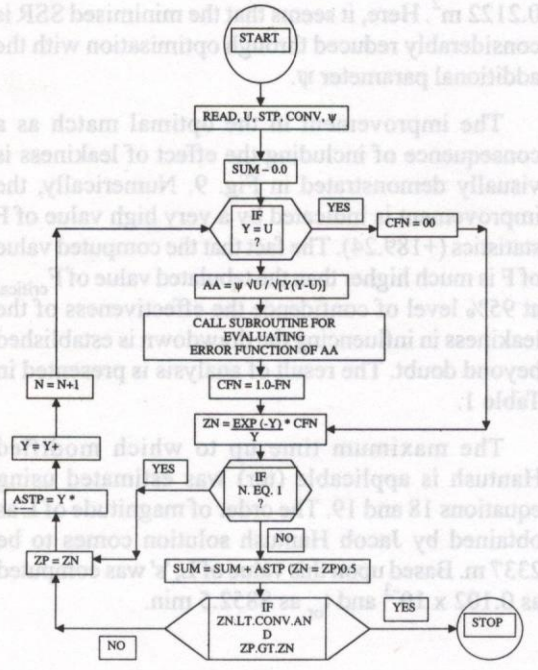

Fig. 7: Flow chart for leaky confined aquifer.

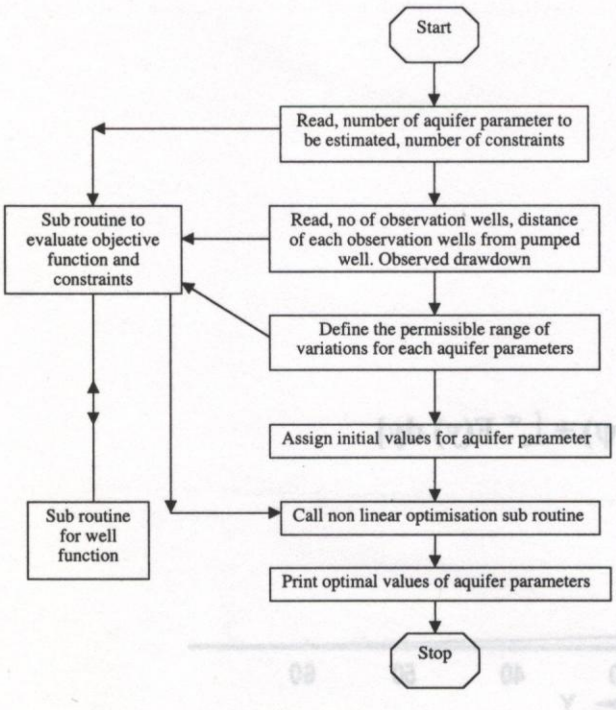

Fig. 8: Flow chart for optimising the aquifer parameter.

Well No. 3/9 Madaha

Data

The well was pumped up to 360 min at a constant rate of 0.201 m^3/min. The observation well is located at a distance of 15.24 m from the pumped well. The maximum drawdown recorded in the observation well is 0.72 m. The starting parameters evaluated as per Theis type curve procedure, were assigned as S = 0.0283, T = 0.219 m^2/min. The distance ratio ($R_i = r_i/r_r$) calculated approximately by using Stallman's method was 15.00. S and T were considered as intrinsic parameters. In order to get the idea of boundary effect, distance ratio (R_i) was introduced as a tentative parameter. The limiting values of S and T were assigned as S_{max} = 0.283, S_{min} = 0.00283, T_{max} = 2.19 m^2/min., T_{min} = 0.0219 m^2/min.

Results

Initially the model was run considering only the intrinsic parameter (S and T) to be effective. The minimised residual variance is 0.0391 m^2. In the second run, the tentative parameter (i.e. distance ratio) was included amongst the decision variables. The residual variance is 0.0142 m^2 form the starting value of 169.073 m^2. It shows better improvement than earlier. The computed drawdown corresponding to the optimal parameters of both infinite and finite confined aquifer is plotted in Fig. 9. The improvement in the optimal match as a result of including the barrier boundary is thus visually idealised. Numerically, the improvement is reflected by a positive value of computed F(+45.46). Since the computed F is higher than the tabulated value of critical at 95% significance level, the effectiveness of a barrier boundary influencing the drawdown is well established. The result of analysis is given in Table 2.

For checking the uni-modality, different distance ratios were tried. It was found that the different optimal solution was reached. Hence, it is concluded that the function is multi-model and as a result convergence is not at the same value.

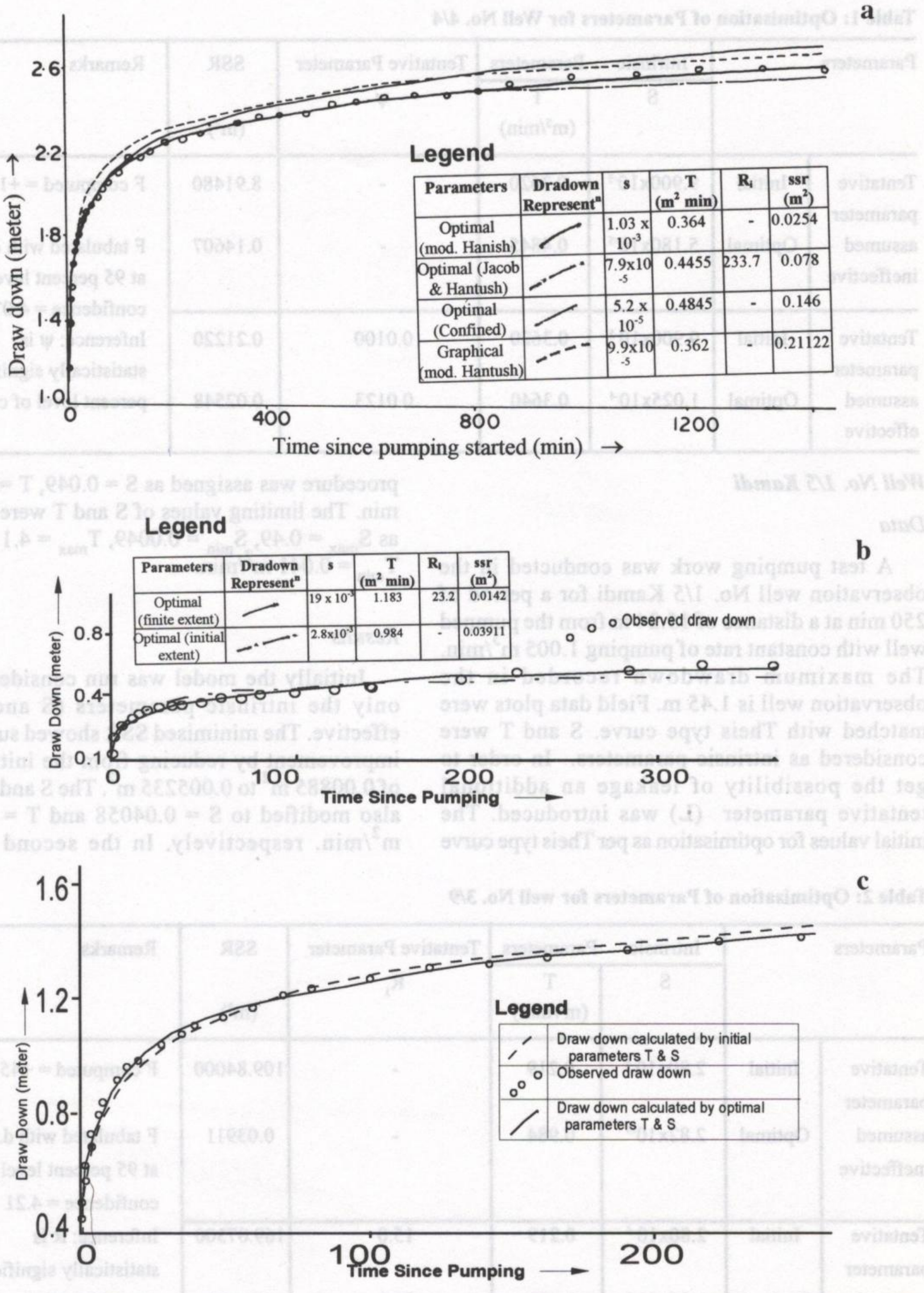

Fig. 9: (a) Reproduction of drawdown data (well No. 4/4), (b) Reproduction of drawdown data (well No. 3/9) and (c) Reproduction of drawdown data (well No. 1/5).

Table 1: Optimisation of Parameters for Well No. 4/4

Parameters		Intrinsic Parameters		Tentative Parameter	SSR	Remarks
		S	T (m²/min)	ψ	(m²)	
Tentative parameter assumed ineffective	Initial	9.900×10^{-5}	0.3620	-	8.91480	F computed = +189.24 F tabulated with d. f. (40,1) at 95 percent level of confidence = 4.078 Inference: ψ is statistically significant at 95 percent level of confidence
	Optimal	5.180×10^{-5}	0.4845	-	0.14607	
Tentative parameter assumed effective	Initial	9.900×10^{-5}	0.3620	0.0100	0.21220	
	Optimal	1.025×10^{-4}	0.3640	0.0123	0.02548	

Well No. 1/5 Kamdi

Data

A test pumping work was conducted in the observation well No. 1/5 Kamdi for a period of 250 min at a distance of 15.24 m from the pumped well with constant rate of pumping 1.005 m^3/min. The maximum drawdown recorded in the observation well is 1.45 m. Field data plots were matched with Theis type curve. S and T were considered as intrinsic parameters. In order to get the possibility of leakage an additional tentative parameter (L) was introduced. The initial values for optimisation as per Theis type curve procedure was assigned as S = 0.049, T = 0.41 m^2/min. The limiting values of S and T were assigned as S_{max} = 0.49, S_{min} = 0.0049, T_{max} = 4.1 m^2/min., T_{min} = 0.041 m^2/min.

Results

Initially the model was run considering that only the intrinsic parameters (S and T) are effective. The minimised SSR showed substantial improvement by reducing from the initial value of 0.00885 m^2 to 0.005235 m^2. The S and T values also modified to S = 0.04058 and T = 0.42627 m^2/min. respectively. In the second run the

Table 2: Optimisation of Parameters for well No. 3/9

Parameters		Intrinsic Parameters		Tentative Parameter	SSR	Remarks
		S	T (m²/min)	R_1	(m²)	
Tentative parameter assumed ineffective	Initial	2.80×10^{-4}	0.219	-	109.84000	F computed = +45.46 F tabulated with d. f. (26,1) at 95 percent level of confidence = 4.21 Inference: R is statistically significant at 95 percent level of confidence
	Optimal	2.82×10^{-3}	0.984	-	0.03911	
Tentative parameter assumed effective	Initial	2.80×10^{-4}	0.219	15.0	169.07300	
	Optimal	1.94×10^{-3}	1.183	23.2	0.01420	

tentative parameter (i.e., leakage factor L) was included amongst the decision variables and model was reoperated. However, the minimised (SSR) so obtained was higher as minimised (SSR) obtained earlier (i.e. without including the tentative parameter (L). This indicates that fit worsened by considering the additional parameter. This is numerically reflected in the negative value of F statistics (-0.5892). This indicates that tentative parameter was not effectively present and as a result leakiness is absent and the aquifer is fully confined. The result of analysis is presented in Table 3. The reproduction of drawdown is given in Fig. 9.

Well No. 6/1 Taratal

Data

The well was pumped for a period of 1440 min at a constant rate of 0.091 m^3/min. The observation well is located at a distance of 15.24 m from the pumped well. The maximum drawdown in the observation well is 0.109 m. Field data plots were matched with Theis, Hantush an modified Hantush type curve. Fit is bad with Theis and modified Hantush type curve while it is good with Hantush. S and T are considered as intrinsic parameters. In order to get the idea of leakage, an additional parameter (L) was introduced as tentative parameter. The initial parameters for optimisation were assigned as per the type curve procedure of Hantush and Jacob (1955) as S = 0.0124, T = 0.4827 m^2/min. and L = 305 m. The limiting values for S,T, and L were assigned as, $S_{max} = 0.124$, $S_{min} = 0.00124$, $T_{max} = 4.827\ m^2/min$, $T_{min} = 0.04827\ m^2/min$, and $L_{min} = 30.5$ m.

Results

To start with a partial model was run considering only the intrinsic parameters (S and T) to be effective. The optimal parameters are S = 0.00289, T= 0.8338 m^2/min and the mini SSR = 0.007423 m^2. In the subsequent run, the tentative parameter (L) was included amongst the decision variables. the optimal value are; S = 0.01497, T = 0.4832 m^2/min, L = 304.3 m. and the minimised SSR is 0.00392 m^2. With the additional parameter, improvement in the objective function is better than earlier. Numerically, improvement is indicated by high positive value of F statistics (+34.85). By the fact that computed F is greater than the tabulated F at 95% level of confidence, it is concluded that the aquifer is leaky confined. The result is given in Table 4.

DISCUSSION AND CONCLUSIONS

The results of optimal parameters are presented in Table 5. The plotting of time drawdown data shows

Table 3: Optimisation of parameters for well No. 1/5.

Parameters		Intrinsic	Parameters	Tentative Parameter	SSR	Remarks
		S	T (m^2/min)	L	(m^2)	
Tentative parameter assumed ineffective	Initial	4.90×10^{-4}	0.4100	-	0.00885	F computed = -0.5892
	Optimal	4.05×10^{-4}	0.4263	-	0.00523	F tabulated with d. f. (26,1) at 95 percent level of confidence = 4.26
Tentative parameter assumed effective	Initial	4.90×10^{-4}	0.4100	50.000	0.01812	Inference: L is statistically significant at 95 percent level of confidence
	Optimal	4.22×10^{-4}	0.4270	4.998	0.00540	

that optimal parameters represent a better reproduction of observed drawdown as compared to the type curve parameter (Fig. 9). Besides its limitation, the type curve parameters tend to give larger residues especially at higher time ordinates. This can be attributed to the dampening effect of log-log plot used in the type curve procedure. For the analysis of leaky confined aquifer, type curve procedure can be used for only one observation well (unless the observation well lie at the same distance from the pumped well), whereas the data of any number of observation wells lying at different distances and in different directions can be analysed by the proposed scheme. However the utility of graphical solution lies in providing appropriate starting solution which can be fine-tuned through optimisation.

The model apart from evaluating the aquifer parameters was able to confirm the presence or absence of certain hydrogeological features like leakiness, barrier boundary, nature and types of aquifer, groundwater potentiality etc. The optimised values of parameter show that eastern, western and northern part of the aquifer have high transmissivity (T) and storativity (S) as compared to the southern part of the study area. The majority of the leaky aquifer shows a declining nature of piezometric head

Table 4: Optimisation of parameters for well No. 6/1.

Parameters		Intrinsic Parameters S	T (m²/min)	Tentative Parameter L	SSR (m²)	Remarks
Tentative parameter assumed ineffective	Initial	1.24×10^{-4}	0.4827	-	0.06900	F computed = +34.85
	Optimal	2.89×10^{-5}	0.8338	-	0.00742	F tabulated with d. f. (39,1) at 95 percent level of confidence = +4.082.
Tentative parameter assumed effective	Initial	1.24×10^{-4}	0.4827	305.0	0.00340	Inference: L is statistically significant at 95 percent level of confidence
	Optimal	1.49×10^{-4}	0.4832	304.3	0.00392	

Table 5: Optimised aquifer parameters.

Well No.	Parameters			
	S	T(m²/min.)	L(m)	ψ
2/2	1.480×10^{-5}	0.1116	-	0.0498
3/2	2.600×10^{-4}	0.0865	-	0.0450
4/4	1.025×10^{-4}	0.3640	-	0.0123
5/3	8.900×10^{-5}	0.1414	-	0.0540
6/1	1.490×10^{-4}	0.4832	304.3	-
3/9	1.940×10^{-3}	1.1830	-	-
1/5	4.050×10^{-4}	0.4832	-	-
1/6	4.300×10^{-4}	0.4260	-	0.0107
3/6	4.430×10^{-4}	0.3082	-	-

in the overlying aquifer while, some of the confined aquifer show finite nature in areal extent.

It seems imperative to pursue more detailed geohydrological and hydrogeological investigation in the area to corroborate the present findings with additional data. Further, it is suggested that ground water modelling of the area is more essential since, it gives a better idea of groundwater development, management and utilisation. The proposed methodology is economically viable since the CPU time required does not exceed 2 minutes in any case unless the step seize is reduced

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