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HYDROGEOLOGICAL PARAMETERS IN HARD ROCK AREAS

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CONTENTS

LIST OF SYMBOLS

A - cross-sectional area of the well

A' - volume of the well per unit depth

B - a constant

C - specific capacity

D - depth of the water column in the well prior to pumping.

H - initial saturated thickness of the aquifer

H_a - average thickness of the aquifer

K - hydraulic conductivity

P_r - lateral permeability of the aquifer

Q, Q_p - steady pumping rates

Q_i - inflow discharge from the aquifer

Q_R - optimum yield

q - inflow discharge from the aquifer

R - conditional radius of influence of the well

r - radial distance

r_o - the distance at which the drawdown is negligible

r_w - radius of the well screen

r_c - radius of the well casing

S - storage coefficient

S_y - specific yield

s' - drawdown in the aquifer adjacent to the well face

Δs - incremental change in drawdown

T - transmissivity

T' - a constant.

t, t' - time

Δt - time interval

t_P - total time of pumping

t_R - time of recovery

U - drawdown function

W - a parameter (hard rock well permeability)

y - depth of water column in the well

β - a constant equal to T/S_y

SUMMARY

The wide use of large-diameter wells for groundwater abstraction especially in hard rock areas calls for a thorough understanding of the flow dynamics in these wells for better management and development of groundwater resources. For a quantitative understanding of the optimum yield and performance of large-diameter wells, pumping tests are carried out in these wells. The analysis of such test data pose a special problem because of the well storage, meagre groundwater flow due to low transmissivity of the aquifers etc. Over more than two decades, considerable work has been carried out on methodology relating to the analysis of pumping test data from large-diameter wells. In the present report, it is attempted to put together all the techniques related to pump test analysis, so that the report would help as a guide for the groundwater hydrologists dealing with large-diameter wells. The merits and limitations of individual techniques have been discussed in detail. The recommendations pertaining to future research activities for better management of groundwater resources in hard rock terrains have been made.

1.0 INTRODUCTION

Provision of adequate water supplies to meet established needs is a problem of major concern to communities located in semi-arid and arid-regions. The combined effects of steady population growth, competing demands of agricultural and industrial users, and the scarcity of available water resources have often resulted in imbalance between sustainable water supply and demand. The future possibility of meeting increased water requirements depends upon the technical and economic feasibility of developing potential supplies.

In India over 70 percent of population lives in villages whose main occupation is agriculture. Over 90 percent of the utilizable water resources are consumed by irrigation of which nearly 40 percent comes from groundwater. Today nearly 70 to 80 percent of the groundwater is extracted through dug wells of large-diameter. At present there are over 8 million dug wells in the country and 4 million shallow tubewells besides a large number of deep tubewells. In the sixth five year plan an addition of 1.2 million dug wells had been envisaged. From the above statistics it is obvious that the dug wells are the most common groundwater extraction structures in the country. Preliminary exploratory studies have indicated a possibility of more than 12 million dug wells in the country. Dug wells of large-diameter are the preliminary source of groundwater extraction not only in India but also in central and south east Asian countries where the crystalline rocks predominate. Hard rocks (crystalline rocks) such as granites, gneisses, schists, basalts, and indurated pre-Cambrian sediments cover approximately 75 percent of the total area of the Indian subcontinent.

The wide use of large-diameter wells is mainly due to the cheapness and simplicity of construction and operation. Besides, these type of wells are quite suitable for shallow aquifers with low transmissivity because the volume of water stored within the well acts as a reservoir from which a large proportion of the pump discharge is withdrawn.

It is necessary to have an accurate knowledge of the aquifer parameters for determination of yield of the well such as transmissivity (T) and coefficient of storage (S). Among the various methods available for the determination of the aquifer parameters pumping tests are most suitable as the insitu aquifer parameters can be determined by pumping test data. Over more than three decades, considerable work has been carried out on methodology relating to analysis of pumping test data from large-diameter wells. It is therefore worthwhile to recapitulate the more important methods that are available for analysing pumping test data from large-diameter wells.

The analyses of the test data from large-diameter wells pose special problems. These problems arise due to very low groundwater flow in the aquifer relative to the storage volume in the well during the abstraction phase, and significant inflow discharge from the aquifer during the recovery phase in contrast to near-zero inflow discharge in case of small diameter bore wells. Regime of groundwater flow into a large-diameter well therefore differs considerably from that of bore well of small diameter. Because of significant volume of water present in a large-diameter well, momentary withdrawal of groundwater from aquifer storage is always much smaller than that withdrawn from the well storage. Ground water flow discharge increases with drawdown and reaches the maximum rate at the moment of completion of pumping of the well. Besides these problems, are the problems of seepage face in large-diameter wells tapping unconfined aquifer, partial penetration, anisotropic nature of the aquifer and variable discharge rates.

Due to the very significant effect of the well storage on drawdown the conventional methods of pumping test analysis based on the Theis (1935) equation are not suitable for large-diameter wells. Analytical and numerical solutions of steady and unsteady flow to a well considering well storage have been developed by several researchers, and these analysis can be made use of for interpretation of pumping test data from large-diameter well.

2.0 REVIEW

The review of the techniques for analysis of flow to a large-diameter well is dealt under the following sub-heads:

2.1 Techniques Related to Confined Aquifer Case,
2.2 Techniques Related to Unconfined Aquifer Case,
2.3 Techniques Related to Semi-confined Aquifer Case,
2.4 Techniques Related to Bounded Aquifer Case,
2.5 Techniques Related to Recovery to Large-Diameter Wells, and
2.6 Miscellaneous Techniques.

2.1 Techniques Related to Confined Aquifer Case

2.1.1 Papadopulos and Cooper method

Papadopulos and Cooper (1967) presented a method which could predict the drawdown in a confined aquifer due to pumping from a large-diameter well. The analytical solution takes storage in the well into account and determines the drawdowns which will occur both in the well and in the aquifer while the well is pumped at a constant rate. The method requires that the time-drawdown curve be plotted on log-log scale. This plot is then compared with a family of type curves drawn on the same scale for evaluation of the aquifer parameters. The family of type curves given by Papadopulos and Cooper contains straight line portions which are parallel.

These straight line portions of the type curves correspond to the period when most of the water is pumped from the well storage. If a short duration pumping test is conducted in a large-diameter well, the time-drawdown curve matches with any of the straight line portions of the type curves. Although a unique value of transmissivity can be obtained, the evaluation of the storage coefficient using such short duration pump test data is questionable as the storage coefficient would change by an order of magnitude when the data plot is moved from one type curve to another. According to Papadopulos and Cooper, the well storage dominates the time-drawdown curve upto a time t given by:

$$t = \frac{25r_c^2}{T}$$

where r_c is the radius of the well casing and T is the transmissivity of the aquifer. For accurate determination of storage coefficient the well should be pumped beyond this time which is quite long for aquifer with low transmissivity. Since large-diameter wells are generally constructed in shallow aquifers with low transmissivity, long duration pumping test in such wells is therefore not practicable (Herbert and Kitching, 1981).

Remarks: i) Short duration pumping test data cannot be used to estimate reliable values of storage coefficient.

ii) The method can be used to anlyze pumping test data from large-diameter wells tapping unconfined aquifer provided a) the effect of the seepage face can be kept at minimum by using low rate of pumping b) the correction of drawdown is made with the help of Jacob's equation and c) the maximum drawdown in the well is negligible compared to the total thickness of the aquifer.

2.1.2 Constant inflow method

Raju and Rao (1967) have discussed many of the problems encountered in aquifer tests conducted in large-diameter wells. They have presented a method of analysis of pump test data from large-diameter which is described below:

Using a plot of time versus cumulative inflow to the well, it may be possible to find a part of the graph in which the data points fall nearly on a straight line. During this period of time, inflow to the well must have been essentially constant, thus conforming to one of the criteria for the Theis theory. Drawdown measurement in observation wells versus log t are then plotted using only those measurements that fall within the time period for which inflow to the well was nearly contant. T and S are determined by the standard Cooper-Jacob (1946) straight line method.

Although the method has been criticised on theoretical grounds that inflow always varies with changes in head, in practice it may often be possible to detect periods of relatively constant inflow during the later stages of a test when the rate of drawdown in the well has decreased appreciably.

Under certain conditions the method suggested by Raju and Rao may be used to determine the aquifer constants (Sammel, 1974). One condition is that pump test data can be treated as that of a step drawdown test. An weighted-average inflow can be assumed for the early period of pumping and a relatively constant inflow can be assumed during the later part. The drawdown curve for the first period may be extrapolated through the second period. Similarly the discharge used in the calculation for T and S must be the difference between the weighted average for the first step and the constant inflow during the second step. A second condition is that the spatial distribution of hydraulic head in the aquifer be quickly adjustable to the rate of inflow to the well, so that the time period during which discharge is constant corresponds closely to the period during which valid measurements may be obtained in the observation wells.

As pointed out by Sammel a problem arises in determining available weighted-average discharge for the initial period of inflow. Inflow to the well varies from zero at the start of pumping to a maximum at the end of pumping, and in some cases is not even measurable until drawdowns in the well have attained considerable magnitudes, many minutes after the start of pumping. Finally, there is a theoretical difficulty that if hydraulic heads in the aquifer are responsive to changes in water levels in the pumped well, they are responding to a nearly linear time rate of change. Thus, although the Theis equation predicts that drawdowns in the large-diameter well should change as a logarthmic function of time, actual drawdowns in a large-diameter well may change nearly linearly with time for long periods because of the large storage volume in the well. As a consequence, the rate of change of drawdowns in observation wells also will differ from those specified by the Theis analysis. For these reasons, therefore, determination of the aquifer constants by this method may not produce reliable results (Sammel, 1974).

Remark : To arrive at a constant-inflow rates the test has to be carried out for a long durations till the withdrawal from well storage is negligible. This is rather impractical in hard rock areas having low transmissivity.

2.1.3 Zdankus's method

Zdankus (1974) has reported a method of pump test data analysis applicable for dug wells in hard rock areas in which hydraulic conductivity varies linearly, having a maximum at the static water level and zero at the bottom of the aquifer. A drawdown function U has been worked out for the estimation of average hydraulic conductivity (K) and a conditional radius of influence (R).

The set of approximate equations that have been developed to determine hydraulic conductivity are:

(i) $$H_a = H - \frac{s'}{2} \qquad \ldots(1)$$

where H_a is the average thickness of the aquifer, H is the initial saturated thickness of the aquifer and s' is the drawdown in the aquifer adjacent to the well face:

(ii) $$R = 1.5\sqrt{\beta(t+t_i)} \qquad \ldots(2)$$

where R is the conditional radius of influence of the well at instant t since the start of pumping, β is the ratio of the transmissivity T to the specific yield of the aquifer S_y , and t_i is a time correction introduced because of the finite radius of the well r_w and is given by

$$t_i = \frac{r_w^2}{2.25\beta} \;;$$

$$\text{(iii)} \quad \frac{K}{\ln(R/r_w)} = \frac{Q_i}{2\pi U} \qquad \ldots(3)$$

where Q_i is the inflow discharge from the aquifer and U is the drawdown function and is given by

$$U = s' \{ H - (s'/2)\}.$$

During the abstraction phase Q_i is computed as

$Q_i = Q - \pi r_w^2 \left(\frac{\Delta s}{\Delta t}\right)$, and during recovery phase Q_i

is computed as

$$Q_i = \pi r_w^2 \left(\frac{\Delta s}{\Delta t} \right).$$

In the above two expressions, Δs is the incremental change in water level within the well diameter during an incremental time interval Δt between two time instants. Q_i is treated to be the inflow discharge from the aquifer at a time which is at the middle of the two time instants. The values of the permeability of the aquifer K and the conditional radius of influence R for each discrete interval of time period during the abstraction as well as recovery phase are to be obtained using the above equations by a trial and error method. While using equation (2) an assumption has to be made on the specific yield value of the aquifer depending on the rock type at well site.

As concluded by Zdankus himself, this method of analysis is based on approximate equations and the accuracy of the estimates of the aquifer parameters may not be high. However, the method can be useful for preliminary investigations and designing of wells in hard rock areas.

Remark: Drawdown measurements adjacent to well face is difficult.

The equations are useful to analyze flow during recovery phase because during recovery the drawdown in the well is approximately equal to the drawdown in the aquifer at the well face especially towards the later part of the recovery phase.

2.1.4 Method of Fenske

Fenske (1977) derived a set of equations based on Theis solution taking into account the storage in observation as well as production well. To account for the effect of storage in the observation well, the assumption that has been made is that the water stored in the observation well would recharge the aquifer instantaneously with the drop in head in the adjacent aquifer. The effect of observation well storage on drawdown has been analysed. From the results it is found that the effect of observation well storage increases with increasing observation well diameter and number of observation wells. The effect of well storage becomes more significant as the distance between abstraction well and observation well decreases and for aquifer with less storage coefficient.

In the method suggested by Fenske a large number of type curves would be required to analyze the pump test. The type curve as concluded by Fenske is least sensitive to changes in the value of the storage coefficient. Order-of magnitude changes in the storage coefficient caused by moving the data plot from one curve to another is accompanied by a relatively small change in the computed transmissivity. A set of complete type curves would, therefore, probably consist of a separate set of curves for each desired storage coefficient. Each set of curves would consist of a dimensionless plot of drawdown versus time for the discharging well and one observation well located at various distances from the discharging well. At each radial distance several type curves could be therefore required to represent various observation well storages. Therefore the method would be of cumbersome and time consuming. Also, since the rate of recharge from the observation well storage depends upon the aquifer parameters and the head differential between the aquifer and the well, significant error may exist in the early time portion of the drawdown phase by assuming the head in the observation well is equal to the head in the aquifer.

Remarks: The method requires large number of type curves. Therefore it becomes more cumbersome and time consuming to get a unique match for the data plot. The estimation of storage coefficient is not reliable as the case in Papadopulos and Cooper method (1967).

2.1.5 Method of Rushton and Holt

Rushton and Holt (1981) have presented an elegent digital simulation approach for the analysis of abstraction and recovery phase data in large diameter wells tapping confined as well as unconfined aquifers. The existence of the seepage face in the abstraction well, variable abstraction rate and well losses have been included in the digital model. Very high transmissivity and a storage coefficient value of unity are assigned in the free water region inside the large-diameter well to simulate the well storage. A region of low permeability is assigned for the aquifer just adjacent to the discharging well to simulate the effect of seepage face. The drawdown in the well is computed for different combinations of permeability, storage coefficient and other variables and then compared with the field drawdowns. The computation is terminated as and when a better match between the observed and computed drawdowns is obtained.

Since the drawdown under consideration should be relatively insensitive to variations in the specific yield and specific storage values of the aquifer, it is evident that matching of field and computed drawdown data can be obtained for a fairly wide range of these two parameters. Moreover, it is also likely that the exercise of matching field and computed results of drawdown would depend not only on the permeability values used in the programme but also on the extent to which the permeability close to the well is artificially reduced as required in the simulation programme. In other words for different combinations of aquifer permeability and the extent to which the permeability is artificially reduced in the region close to the well, one may possibly obtain near identical drawdowns in the well. Therefore to get a unique values of aquifer parameters the field and computed resultes of drawdown at additional observation wells in the aquifer would also need to be matched.

Remark : Although the digital model simulates the water levels in a confined aquifer quite accurately, the results for unconfined aquifer are not very satisfactory.

2.1.6 Method of Patel and Mishra

Patel and Mishra (1983) have analyzed unsteady flow to a large-diameter well using discrete kernel approach, taking well storage into consideration. The important assumptions made during the analysis are:

i) At any time the drawdown in the aquifer at the well face is equal to that in the well.

ii) The time parameter is discrete. Within each time step, the abstraction rate of water derived from well storage and that from aquifer storage are separate constants.

The variation of drawdown with time has been obtained at the well face and at a point in the aquifer. The validity of the method has been varified by comparing the drawdown at the well with the drawdown given by Papadopulos and Cooper (1967). The method proposed by Patel and Mishra is simple and involves only a 2 x 2 matrix inversion. On the other hand the evaluation of the aquifer response by Papadopulos and Cooper's method requires numerical integration of an improper integral involving Bessel's function. The numerical integration therefore involves large computations.

Remarks : The main objective of the paper is to obtain a simple and rapid solution. The type curves presented by Patel and Mishra are similar to the Papadopulos and Cooper's type curves and hence the shortcomings of Papadopulos and Cooper's method are also inherent in Patel and Mishra's type curves.

2.1.7 Method of Rushton and Singh

Rushton and Singh (1983) have developed type curves quite similar to those of Papadopulos and Cooper using numerical approach. These type curves are given both for constant as well as variable abstraction rates from a large-diameter well. They have suggested plotting of time-drawdown curves with time on log scale and ratio of drawdown at time t divided by drawdown at time 0.4t on arithmatic scale. This field plot is matched with type curves (drawn $s_t/s_{0.4t}$ versus $4Tt/r_w^2$, $s_t/s_{0.4t}$ ranging from 1 to 2.5). By suitable matching of the field curve with the type curve the value of $4Tt/r_w^2$ at any time t is obtained and the transmissivity (T) is estimated from $T = r_w^2 /4t$.

Remarks : Using these type curves it would be possible only to obtain reasonable estimates of transmissivity. The estimation of storage coefficient by this method is questionable. The assumed linear variation of well discharge with drawdown may introduce error in the analysis because in field the variations of well discharge with drawdown are not strictly linear.

2.2 Techniques Related to Unconfined Aquifers

The pumping in unconfined aquifer particularly in hard rock areas result in significant lowering of water level in the well than in aquifer. This difference is attributed to seepage face which considerably effects the aquifer transmissivity due to reduction in saturated thickness of aquifer. These variations result in distortions and errors in curve matching techniques and lead to determination of unrealistic aquifer parameters.

Some of the techniques which take into account these parameters are described below:

2.2.1 Method of Adyalkar and Mani

Adyalkar and Mani (1974) made an attempt to derive an expression for estimation of transmissivity of a trappean aquifer using specific capacity data. The method of Adyalkar and Mani involves the calculation of an empirical factor which is expressed as ratio of transmissivity and specific capacity. This empirical factor has been calculated for few chosen wells in trappean aquifer by using estimated transmissivity from Theis (1963) recovery method and specific capacity from Slichter's (1906) formula. According to these authors, the empirical factor thus obtained can be used for the area in the vicinity so long as the field characteristics of the aquifer do not vary. The value of T can then be estimated using the empirical factor and the specific capacity values.

T = specific capacity x K

where K is the empirical factor and is constant for wells of similar diameter tapping the same aquifer. The authors emphasize that the modified Thiem formula for estimating transmissivity has to be applied with caution in the trappean aquifers because : i) it involves calculation of specific capacity values by using the recovery formula of Slichter, which has its own limitations, and ii) an assumption has to be made regarding the value of outer radius of the depression cone. However, the specific capacity values of large-diameter wells tapping the water-table aquifers in the trappean tract can be utilized to provide approximate values of aquifer transmissivity.

Remarks: The method is too empirical and is not supported by adequate theoretical background. In addition the usual anisotropy of the aquifer and well storage are not taken into consideration.

2.2.2 Method of Boulton and Streltsova

Boulton and Streltsova (1976) have presented an analytical solution for flow to a partially penetrating large-diameter well in an unconfined aquifer. The anisotropy of the aquifer in terms of hydraulic conductivity has been taken into account in the solution. The method relies on curve-matching of early time-drawdown data. Since this method takes into account the compressibility of the aquifer, anisotropy of the aquifer and partial penetration, it offers a more realistic model pertaining to the hard rock field conditions.

Owing to the large number of parameters involved in the solution, it is generally not possible to construct the whole set of type curves and as such there is no complete set of type curves available for use. The very complexity of the solution allows too many options to be selected for the curve-matching process. Therefore, it has been found that the procedure is very intricate and time consuming. It is also clear that the well function involves too many parameters and becomes unwieldy for field use. Rao (1983) has critically analysed the well function proposed by Boulton and Streltsova (1976) and proposed a modified model incorporating relevant field conditions. According to Rao the modified model allows a faster computation of the well function for specified values of parameters. Using this model aquifer parameters for a given test data can be computed more efficiently than with Boulton and Streltsova model (Rao, 1983).

Remarks : The curve matching technique adopted by Boulton and Streltsova fails to provide an unique value of storage coefficient (S) since the well function is non-linear in S. Also it is generally not possible to record all the parameters required in Boulton and Streltsova from the field. Hence, assumptions have to be made for those parameters which are not available, which in turn may lead to erroneous parameter estimation.

2.3 Techniques Related to Semi-Confined Aquifers

2.3.1 Method of Lai and Su

Lai and Su (1974) have given a theoretical solution for non-steady flow in and around a large-diameter well penetrating leaky artesian aquifer induced by an arbitrary time-dependent-pumping rate, using Laplace transform technique. The effect of well storage on the drawdown is found to be significant when the time of pumping is not large or the ratio of transmissivity of the aquifer to its storage coefficient is small. Though the analysis of Lai et al, does allow for the effect of linear abstraction rate, it is often not possible to represent satisfactorily the variation of abstraction rate that actually occurs in practice. Evaluation of drawdown in their method requires numerical integration of improper integral involving Bessel's functions. The numerical integration therefore involves large computations.

Remark : Boulton and Streltsova (1976) have strongly criticised the solution of Lai and Su on the basis that the error exists in the solution given by Lai and Su as the singularity has been neglected.

2.4 Techniques Related to Bounded Aquifers

Most of the pumping test are based on the assumption that the tested aquifer is of infinite areal extent. Although such aquifers do not exist, many aquifers are of such wide extent that for all practical purposes they can be considered infinite. Others however are of limited extent because of the presence of an impervious barrier or a recharge boundary. A recharge boundary exists when an aquifer is having hydraulic connection with a perennial river, a canal, or a lake. If an aquifer is being tested near a recharge or an impervious boundary, this fact must be considered in the analysis of the pumping test data.

Zekai Sen (1981) using the concept of depression cone volume and image well theory, derived type curves for large-diameter wells in aquifers of finite extent limited by an impervious barrier boundary. The solution of Zekai Sen is based on the joint exploitation of the ground water movement equation (Darcy's law) and the continuity equation for large-diameter wells. Type curves can be generated for different positions of the hydrologic boundary. The aquifer parameters are calculated using the same principle as that of Papadopulos and Cooper.

Mishra and Chachadi (1984) and Chachadi and Mishra (1985) have analysed the unsteady flow to a large-diameter well located near a river and a no-flow boundary using discrete kernel approach. Optimization technique has been used to estimate aquifer parameters from inadequate pump test data of a large-diameter well near a river. Transmissivity value has been obtained through curve matching. The storage coefficient is then determined by minimising the error function. The error function is the sum of the square of the difference between observed and predicted drawdown for a chosen value of storage coefficient. Type curves incorporating both the pumping as well as recovery response of the aquifer are presented for a selected locations of the hydrologic boundary. However, type curves can be generated for any combination of the hydrologic boundaries and their locations using the solution presented therein.

Remarks : The discrete kernel approach is simple and rapid as compared to the other techniques. For example, the evaluation of aquifer response by Papadopulos and Cooper's method requires numerical integration of an improper integral involving Bessel's function. The numerical integration therefore involves large computations. On the other hand the discrete kernel approach involves a single inversion of a 2 x 2 matrix. Once the discrete kernel coefficients are generated with the help of known parameters they can be stored and used for drawdown calculation.

2.5 Techniques Related Recovery Tests

A recovery test is considered to be the best and involves minimum errors in the estimated parameters for the following reasons:

During the later stages of the recovery phase, drawdowns and rates of flow into the well are small. Because of this the extra head losses due to turbulent flow in the aquifer as well as in the well will be minimized, well losses will be negligible, and the time-drawdown relationship will be almost the same for both confined and unconfined aquifers.

Thus, the major factors which normally cloud the interpretation of pumping test data are minimized. Also, during the recovery phase, all water that flows into the well must be derived from the aquifer. Thus, unlike the early part of the drawdown phase, aquifer properties must play a significant part in the recovery process and therefore it should be possible to determine aquifer parameters more accurately using recovery data.

2.5.1 Slitcher's method

Slitcher (1906) gave an expression for determination of specific capacity of large-diameter wells with the help of recovery data. The formula as given by Slitcher is,

$$C = 17.25 \; \frac{A}{t'} \; \log_{10} \frac{s_1}{s_2}$$

where C is specific capacity in gpm per foot of drawdown, 'A' is cross-sectional area of the well in square feet, t' is time in minutes measured after pumping stops, s_1 is drawdown in feet at stoppage of pumping, and s_2 is residual drawdown in feet at time t'. Changing to consistent units and substituting $\log_{10} s_1/s_2$ by $2.303 \log s_1/s_2$ the above expression becomes,

$$C' = \frac{A'}{t'} \log_e \frac{s_1}{s_2}$$

where A' is the volume of the well per unit depth (say m^3/m). As pointed out by Sammel (1974) the formula is thus merely an expression, derived by means of the calculus for the change in the volume of water as the water surface , s is integrated from s_1 to s_2. The formula, has no theoretical validity in terms of flow to the well or the configuration of the potentiometric surface in the aquifer. Contrary to the Theis formula, for example Slitcher's formula is expressed as a linear function of time and a logarthmic function of drawdown. Thus, it cannot be used as the specific capacity from which one calculates T, as in the methods of Theis (1963) or Hurr (1966). Furthermore, Slitcher himself pointed out that the recovery in a given well will have different rates depending on whether the well was pumped for a long time at a low rate or a short time at a higher rate, even though maximum drawdown may be the same in both cases.

Nevertheless, Slitcher's formula may provide a useful basis for comparison of the yield of the wells of similar types in similar geologic environments. If one adds the requirement that;

$$\frac{Q_1}{A_1} t_1 = \frac{Q_2}{A_2} t_2 ,$$

where Q_1 and Q_2 are the pumping rates in two wells, t_1 and t_2 are the respective durations of pumping time, and A_1 and A_2 are the cross-sectional areas, there may be a better basis for comparison of the aquifer characteristics.

A useful parameter in the case of large-diameter wells is the time gap that is required between two successive pumpings. This time gap depends upon the time which is required for the well to recoup fully. As per the formula of Slitcher this time period will be infinity. However, it may be assumed that the well is fully recovered if the residual drawdown is 0.01 of the initial saturated thickness D (99%

recovery). By substituting 0.01 D for s_2 in Slitcher's expression the recovery time t'_{rec} can be written as

$$t'_{rec} = 17.25 \frac{A}{C} \log_{10} \left(\frac{100\, s_1}{D}\right)$$

The value of t'_{rec} would however depend on well discharge during abstraction phase because the value of specific capacity is dependent on it.

Remarks : Slitcher's formula may be useful in a qualitative comparison of the productivity of wells at different sites provided, the wells have identical area of cross-section and same rate of discharges during abstraction phase. Some times it is the ratio of C to A' (unit area specific capacity) is compared, in such cases well discharge alone need to be identical.

2.5.2 Method of Muskat

Muskat (1937) gave a formula which, as quoted by Wenzel (1942), involves the cross-sectional area of the well and allows the calculation of transmissivity from recovery measurements. The expression for T is written as

$$T = \frac{CA}{2\pi t'} \log_e \frac{s_1}{s_2} ,$$

where $C = \log_e(r_o/r_w)$, A is the cross-sectional area of the well, r_o is the distance at which drawdown is negligible at the end of the pumping period, r_w is the radius of the well s_1 is drawdown at time when pumping stops, and s_2 is residual drawdown at time t' measured ater stoppage of pumping.

Remarks : As quoted by Sammel (1974) this expression of Muskat extends Slitcher's formula by the addition of the Thiem solution for steady-state flow. Because of the necessity to estimate the distance to a point of zero drawdown, it is not expected to provide a relaiable means of estimating the transmissivity.

2.5.3 Theis method

Theis (1963) suggested a method of estimating transmissivity of water table aquifer from specific capacity values of the well by deriving a general equation, assuming $T = 10.42\ m^2/day$, $S = 0.2$ and $t = 1$ day. The formula for water-table aquifer corrected for variations of that aquifer from average can be written as

$$T' = \frac{Q}{s} (K - 264 \log_{10}(5 S) + 264 \log_{10} t)$$

where,

$$K = - 66 - 264 \log_{10}(3.74\ r^2 x 10^{-6})$$

The values of K for selected values of r are given by Theis (1963). For calculating transmissivity T using T' and specific capacity Q/s Theis gave a chart representing T' vs Q/s for various T values.

According to Theis, within the limits of the idealized assumptions, the transmissivity of a water-table aquifer apparently can be computed without great error from a single measurement of drawdown in a observation well that is at a short distance from a pumped well, even if the storage coefficient is not known. Theis suggested the following equation for wells that have a diameter of about 1 foot and that tap water-table aquifers consisting of unconsolidated sediments:

$$T' = C\ (1 \pm 0.3)\ (\ 1300 - 264 \log_{10}(5\ S) + 264 \log_{10} t)$$

where C is the specific capacity of the well. The factor (1 ± 0.3) should be adjusted upward for small diameter wells which are poorly developed and having poorly perforated casing, and downward for large-diameter wells which are well developed.

Remark : The Theis formula should be used with caution because it involves calculation of specific capacity values either by Slitcher's formula or by any other methods which have their own limitations. The formula can't be used for confined aquifer conditions because the storage coefficient term requires large corrections as it is very small for confined aquifers (Theis, 1963).

2.5.4 Modified Semilog method

Dass (1972) gave an analysis by combining the Theis (1935) formulae for drawdown and recovery and arrived at a formula which permits the use of straight line graphic solution.

Dass in his analysis notes that the plots of drawdown versus t/t' (the ratio of time since pumping started to time since pumping stopped) do not fall on straight line for large-diameter wells. He attributes the discrepancies to: i) partial penetration, (ii) variable pumping rates, and iii) coefficient of storage which are assumed to be constant for both drawdown and recovery phases. As reviewed by Sammel (1974) there is no mention of the problem of storage in the large-diameter well. Dass's derivation contains an algebraic error which invalidates his final expression (Sammel, 1974), but the basic problem is that when transmissivities and storage coefficients are small, neither drawdown nor recovery in a large-diameter well conform to the Theis model. No amount of manipulation of the Theis equation will produce valid results unless the storage in the well can be accounted for.

2.5.5 Method of Kumaraswamy

Kumaraswamy (1973) has reported solutions for the recovery phase of large-diameter wells in hard rock aquifers. An equation for inflow is given as

$$q = W\,(D^2 - y^2) \qquad \ldots(4)$$

where q is the inflow discharge from the aquifer when the depth of water column in the well is y, W is a parameter defined as hard rock well permeability, and D is the depth of water column in the well prior to pumping. After the stoppage of pumping the inflow into the well obtained using equation (4) is equated to the rate of change in well storage and by integrating over a finite time period as is done in Slitcher's method, a recuperation equation is obtained as,

$$t' = \frac{2.303A}{2WD} \log \left\{\frac{(D+y)\ (D-y_o)}{(D-y)\ (D+y_o)}\right\} \qquad \ldots(5)$$

Equation (5) can be rewritten as,

$$W = \frac{2.303A}{2D(t_2'-t_1')} \log \left\{\frac{(D+y_2)\ (D-y_1)}{(D-y_2)\ (D+y_1)}\right\} \qquad \ldots(6)$$

in which A is the cross-sectional area of the well.

Any two time instances t'_2 and t'_1 and the corresponding water column depths y_2 and y_1 are taken from the recovery data and substituted in equation (6) to obtain an estimate for W. In case the well is pumped completely ($y_0 = 0$) and is allowed to recoup then the time required for 99 percent recovery t'_{rec} (Max) can be obtained from equation (5) as,

$$t'_{rec}\ (\text{max}) = \frac{2.303A}{2WD} \log (19). \qquad \ldots(7)$$

It is suggested in the paper that an average of the W value obtained from different parts (t'_2, y_2 and t'_1, y_1 ... etc) of recovery data can be used in equation (7).

However, the following drawbacks in Kumaraswamy's method have been pointed out:

(i) The variation of the abstraction rates during pumping phase are not taken into account and these variations will give rise to different values of W for the same well.

(ii) It is said in the paper that the W values may be different at different depths in the well and that an average of the W values obtained from analysing different pair of recovery data can be used. However, this contradicts the fact that the recuperation equation itself has been derived by integrating an expression in which W is treated as a constant. Hence the correct approach is to plot the recovery data with (D+y)/ (D-y) in the logarithmic scale and t' in ordinary scale, and fit a straight line through the plotted data (in case a straight line can't be fitted then equation (5) will not be valid). Any two convenient pairs of data (t_2', y_2 and t_1' , y_1) from the straight line should be selected and substituted in equation (**6**) to obtain an estimate for W.

(iii) The method of Kumaraswamy is based on the assumption that the fracture porosity can be represented as radial conduits in the rock spaced at an average interval around the well. By assuming that the loss of hydraulic head is represented by frictional loss in conduits, an expression is derived for discharge in terms of a friction factor, drawdown, radius of influence, average number of conduits and depth and radius of the well. As pointed out by Sammel (1974), such a modelling of field rock fracture system based on numerous arbitrary assumptions wherein the parameters are unmeasurable are not likely to be realistic and useful. As suggested by Sammel, it is probably best to regard hard rock aquifers as porous media at a macroscopic scale.

Remarks : Inspite of the limitations mentioned above, the method is useful in obtaining qualitative comparison of productivity of different wells.

2.5.6 Method of Herbert and Kitching

Herbert and Kitching (1981) have proposed approximate expressions for finding out the transmissivity of an unconfined aquifer. Two expressions were derived : one using 50 percent recovery data and other using 90 percent recovery data of a large-diameter partially penetrating well. Singh (1982) has used the expressions derived by

Herbert and Kitching for estimating aquifer parameters from pump test data of large-diameter well. Singh has found that the expressions of Herbert and Kitching give inaccurate estimates of the parameters of an aquifer. Consequence to the criticism by Singh the authors of the paper also agree to the fact that the method is inaccurate and the estimates of transmissivity from their expressions might be in error by a factor of 2 multiplied or divided.

Remarks : As the expressions derived by Herbert and Kitching involves definite flaws and inaccuracies the method should not be used. Field measurement of many variables are required, to use the formula which is generally not feasible. Instead a numerical technique of Rushton and Redshaw (1979) should be used, as this technique involves efficient method of solving the Boussinisq's equation by the finite difference approach.

2.5.7 Method of Basak

Recently Basak (1982) has reported an approximate analytical solution for unsteady flow to a large-diameter well during recovery phase in a finite aquifer. A very elegant method of solving a particular class of partial differential equations describing transient ground water flow has been used to arrive at the approximate solutions. For the particular case when the drawdown in the well is very small it has been shown that Kumaraswamy's(1974) solution reduces to the Basak's solution. However, the method developed by Basak has the following limitations:

The assumption of restricting the aquifer to a finite extent in the radial directions has been probably made under a notion that the cone of depression stops expanding as soon as pumping is discontinued. This is true when the inflow discharge into the well during recovery is negligible. However, in case of large-diameter dug wells the inflow discharge is significant during the recovery phase (Zdankus, 1974). The analysis of Basak only leads to the determination of a lumped parameter. The recovery phase has been considered in isolation from the abstraction phase.

2.5.8 Method of Rajagopalan

Rajagopalan (1983) presented a mathematical model. Approximate equations for recovery phase are obtained on the assumption that the partial derivative of hydraulic head with respect to radius along the well face is linearly related to the drawdown in the large-diameter well. The use of these equations leads to the determination of a parameter of the form $P_r B$, (where P_r is the lateral permeability of the aquifer and B is a constant) and of the time required for the large-diameter well to recoup fully. A simple field test procedure is adopted to obtain conditions of different discharges from the well and an empirical relationship between the parameter $P_r B$ and the well discharge is established for the test well site. The approximate equations that are developed also find use in correcting some of the common anomalies in the abstraction phase data.

The expression for the parameter $P_r B$ is written as

$$P_rB = 2.303A / 2\pi r_w D \, \Delta t' \qquad \ldots(8)$$

where

A is the cross-sectional area of the dug-well

r_w is the radius of the dug well,

D is the depth of water column in the well prior to puming, and

$\Delta t'$ is the time difference for one log cycle of the residual drawdown in a semilog plot of s versus t', where s is the residual drawdown at time t' after the stoppage of pumping.

The time taken for complete recuperation of the large-diameter well is expressed as

$$t'_{rec} = \frac{2.303A}{2\pi r_w D P_r B} \log \left(\frac{100 \, s_o}{D}\right) \qquad \ldots(9)$$

where s_o is the maximum drawdown attained when pumping is stopped.

The maximum drawdown in a well can be obtained by variety of ways thereby giving rise to different rates of recovery in the same well and consequently different P_rB values. Therefore the extent of aquifer contribution to flow is a function of the discharge from the well and this in turn reflects in the different recovery rates. This fact is taken care of by different initial conditions that would prevail in the aquifer at the end of different discharges during the abstraction phase. An experiment in the dug well can be so designed as to obtain recovery data for different discharges from the well. An empirical relationship between P_rB and Q (where Q is the rate of discharge) can be derived from the analysis of such experimental data.

Expressions were also given for different types of hydraulic head distribution at the well face ($r = r_w$). Another important contribution by Rajagopalan is presented in the form of correcting the anomalies in the drawdown during abstraction phase using his approximate equations.

Remarks : The expressions derived by Rajagopalan are approximate but they are supported by sound mathematical validity. Unlike Slitcher's formula these expressions take care of the effect of variable discharges on the rate of recovery and hence should provide useful means of parameter estimation from large-diameter wells. Zdankus (1974) method in conjunction with the method of Rajagopalan should be the best combination to estimate the reliable aquifer parameters from recovery data of large-diameter wells.

2.6 Miscellaneous Techniques

Under this heading some of the general but useful topics related to performance of large-diameter well have been discussed.

Cooper (1967) presented a solution for the change in water level in a well of finite diameter after a known volume of water is suddenly injected or withdrawn. A set of type curves computed from this solution permits determination of the transmissivity of the aquifer just around the well. As concluded by the author the duration of a slug is very short hence the estimated transmissivity determined from the test will be representative only of the aquifer close to the well. Serious errors will be introduced unless the well is fully developed and it completely penetrates the aquifer. The judgement of an experienced hydrologist is needed to decide the significance, if any, of a determination of transmissivity by this method.

Thomas (1982) has reported the significance of bottom entry to the open wells and has discussed about the relations between depth of penetration and radius of the well with production of the open wells. Besides, Thomas has discussed about cost comparison for different type of well design.

If the saturated thickness is more than five times the well radius, the bottom entry well can increase production by 70 percent by doubling its diameter. This is a major point of difference between bottom entry well and small diameter screened wells. As concluded by Thomas the most efficient bottom-entry well would penetrate to about 75 percent of the saturated thickness of the aquifer . Dudgeon and Cox (1977 and 1978) have studied the steady-state flow to bottom entry well. They concluded that the most efficient open-bottom well should penetrate to about 70 to 80 percent of the saturated gravel thickness.

Athavale and Singh (1983) have developed a device for controlling a constant rate of discharge during pumping test in a large-diameter wells. As the water declines the rate of discharge also decreases with time. The device developed by the authors is simple and inexpensive and it can be used to maintain a constant rate of discharge. The device is also useful for pumping the well for a long duration.

Barker (1984) has derived an expression for a drawdown in a large-diameter observation well near a pumping well of negligible diameter. The analysis provides an estimate of the delay in response of an observation well with finite storage capacity. The solution is derived using the Laplace transform technique. It is shown in the analysis that the drawdown in a large-diameter observation well response to pumping of a production well of negligible diameter, is identical to the drawdown that would be observed if the roles of the wells were reversed.

Limitation : The solution does not provide an expression for the drawdown in the aquifer other than at the surface of the single observation well. So it is not possible to use the results to determine the extent of the effect of the observation-well storage on the response of theaquifer.

Holt and Rusthon (1984) have analysed numerically the effect of cyclic pumping on drawdown in a large-diameter well. The main objective of the paper is to find maximum withdrawal of water from the aquifer without creating excessive drawdown. When a single pumping phase is used to withdraw a certain volume of water, a major proportion of the water withdrawn comes from well storage. By increasing the number of pumping phases, drawdown in the well is decreased and more water is drawn from the aquifer while pumping is taking place. As reported by Holt and Rushton, in the long term, the pumping regime has a marked influence on the length of the time the well can be used during crop growing season. As the quantity of water taken out each day is increased, the advantage of using more than one pumping phase becomes greater. As suggested by the authors more than one pumping phase per day should be used to withdraw maximum water from a large-diameter well without inducing excessive drawdown.

Karanjac (1975) has presented a semi-empirical formula to estimate the optimum yield of a large-diameter well using recovery data.

The expression for the optimum yield of the well is written as

$$Q_R = Q_P \frac{t_P}{t_P + t_R} \qquad \ldots(10)$$

where,

Q_R = optimum yield equivalent to the average inflow-rate from the aquifer,

t_P = total time of pumping,

t_R = time of recovery , and

Q_P = steady rate of discharge during pumping.

In an area where numerous dug wells of large-diameter exist, a comparative study of the 'optimum yields' of the wells may help in identifying localities where favourable hydrogeological conditions exists for development of shallow ground water.

Mishra and Chachadi (1985) have derived expressions for the drawdown in a large-diameter well for variable abstraction rates. A single linear relationship between pumping rate and drawdown has been assumed to be valid for the entire range of drawdown phase. The results of aquifer and well storage contributuon and drawdown under time variant pumping rate have been presented for a particular case. The comparative study of the drawdown under average constant and variable pumping rates show considerable difference and hence it is suggested that the average situation can't substitute the variable abstraction case. It is also suggested that the piece-wise linear approximation can be made to represent the relationship between discharge and drawdown to obtain more accurate results.

3.0 CONCLUSIONS AND RECOMMENDATIONS

A review of current methods of analysis of aquifer tests in large-diameter wells indicate that most of the methods have theoretical and practical deficiencies. However, the method of Papadopulos and Cooper (1967) and Rushton and Holt (1981) are the best available approaches for confined aquifer provided accurate long duration test data are available. Although the models assume a confined aquifer, they may be applied to unconfined aquifers if drawdowns are small relative to aquifer thickness. The more complexity of the model by Boultan and Streltsova (1976) for unconfined aquifer discourages its practical utility. The discrete kernel approach by Mishra and Chachadi (1984) and Chachadi and Mishra (1985) should provide a simple model for bounded aquifers. The models of Zdankus (1974) and Rajagopalan(1983) should be the best to adopt for the analysis of the recovery data.

The models dealing with the analysis of the recovery test are thought to be the best to use because of the fact that during the later part of the recovery the well losses and the turbulant flow are negligibly small. Secondly during recovery the water that flows into the well is derived from the aquifer. Thus, unlike the early part of the drawdown phase, aquifer properties must play a significant role in the recovery process and therefore it should be possible to determine the aquifer parameter more accurately from the study of the recovery data.

The following recommendations are made for further research in this line:

(i) The hard rocks generally possess some primary and more secondary porosity and therefore, instead of treating them as homogeneous media the concept of "double porosity" should be emphasized.

(ii) The simpler and reliable models are yet to be evolved for partially penetrating wells in unconfined aquifer. This fact should be given importance as most of the wells are partially penetrating.

(iii) A detailed study regarding the optimum yield, diameter, depth and spacing of large-diameter wells in different rock formations is warranted.

(iv) It is always necessary and important to record the recovery data more accurately as this provides important informations about the actual aquifer properties.

(v) In some situations the water bearing fractures are encountered at different levels which are separated by unfractured formations. Therefore, it is recommended to develop a multilayer model to test the distribution of aquifer parameters in different layers.

(vi) Integrated surveys employing geological, remote sensing, geophysical and drilling techniques to evaluate hydrogeological conditions for cost effective and proper utilization of ground water resources should be promoted.

(vii) To acquire more knowledge about the wells and their performances in hard rocks, data banks should be created and such data should be supplied to the research organisations and institutions as and when required by them.

REFERENCES

1. Adyalkar, P.G. and V.V.S.Mani (1974), 'Application of groundwater hydraulics to a basaltic water table aquifer'.Journal of Hydrology.V.21, pp. 211-218.

2. Athavale, R. N, V S Singh and K Subrahmanyam (1983), 'A constant discharge device for aquifer tests on large-diameter wells'. Ground Water. V.21, pp.752-756.

3. Athavale, R.N., V.S.Singh and K. Subrahmanyam (1983), 'Use of a new device for low and constant discharge in pumping tests on dug wells'. Paper presented in symp. on Methods and Instrumentation for Investigation of Ground Water System, The Netherlands. May, 1983. pp.479-488.

4. Boulton, N.S. and T.D. Streltsova (1976), 'The drawdown near an abstraction well of large-diameter under non-steady conditions in an unconfined aquifer'. Journal of Hydrology. V.30, pp.29-46.

5. Boulton, N.S. and T.D. Streltsova, (1978),'Unsteady flow to a pumped well in an unconfined fissured aquifer'. Journal of Hydrology. V.37, pp.349.

6. Bourdet, D. and A.C. Gringarten, (1980), 'Determination of fissure volume and block size in fractured reservoirs by type curve analysis', presented at SPE-AIME, 55th annual tech. conference, Dallas, Soc. of Petroleum Engrs., SPE-9293.

7. Basak, P.(1982), 'Recovery in large diameter wells', Journal of ASCE hydraulics division. V.108, pp.1194-1207.

8. Barker, John A.(1984), 'Pumping tests using large-diameter observation wells'. Journal of Hydrology. V. 67, pp.375-379.

9. Cooper, H.H., Jr. and C.E. Jacob, (1946), 'A generalized graphical method for evaluating formation constants and summarizing well-field history', Am.Geophys. Union Trans. V.27, no.4, pp.526-534.

10. Cooper, H.H., Jr., John D. Bredehoeft, and I.S. Papadopulos, (1967), 'Response of a finite -diameter well to an instantaneous charge of water'. Journal of water resources research. V.3., no.1, pp.263-269.

11. Chachadi, A.G. and G.C. Mishra, (1985), 'Unsteady flow to a large-diameter well influenced by a river and an impervious boundary'. Proceedings of the CBIP 52nd annual research and development session, Aurangabad Feb.1985.V.4,pp.177-186.

12. Dass, T.(1972), 'Determination of transmissibility and storage coefficient in shallow open wells in hard rock terrain'. Paper presented at the seminar on problems in ground water development, Madras, Oct.1972.

13. Dudgeon, C.R. and R.J. Cox, (1978), 'Flow to a large diameter bottom wells'. Australian Institute of Engrs, Symposium of Hydrology, Perth.

14. Dudgeon, C.R. and R.J.Cox, (1977), 'Hydraulic design data for water wells in uncosolidated sediments'. Australian Water Resources Council Technical Paper, No.22, Canberra.

15. Fenske, Paul R.(1977), 'Radial flow with discharging-well and observation-well storage'. Journal of Hydrology. V.32, pp.87-96.

16. Gringarten, A.D.(1982), 'Flow-test evaluation of fractured reservoirs in Narasimhan, T.N., Recent Trends in Hydrogeology', Geol. Soc. Am.Special paper 189, pp. 237-263.

17. Hurr, T.R., (1966), 'A new approach for estimating transmissivity from specific capacity'. Water Resources Research. V.2, pp.657-664.

18. Herbert, R. and R. Kitching, (1981), 'Determination of aquifer parameters from large-diameter dug well pumping tests'. Ground water .V.19, pp.593-599.

19. Holt, S.M. and K.R.Rushton, (1984), 'An investigation into the effect of different pumping regimes on drawdown in large-diameter wells'. Journal of Hydrological Sciences . V.29.pp.271-278.

20. Kumaraswamy, P.(1973), 'Laminar inflow theory for hard rock open wells'. Indian Geohydrology. V.9, no.2, pp.53-65.

21. Karanjac, J., (1975), 'Brief note on testing the possibility of defining optimum yield of dug wells of large-diameter'. Ground Water. V.13, no.4,pp.366-367.

22. Kitching, R. and A.R.Lawrence, (1980), 'Analysis of dug well pumping tests at chakpatni and Khejra'. Institute of Geological Sciences, London. Indo-British Betwa Report No.1.

23. Lai, R.Y.S. and Cheh-Wu Su, (1974), 'Non-steady flow to a large well in a leaky aquifers'. Journal of Hydrology. V.22, pp.333-345.

24. Muskat, M., (1937), 'Use of data on the build up of bottom hole pressure. Am.Inst.Min. Met. Eng.Trans. V.123, pp.44-48.

25. Mishra, G.C. and A.G. Chachadi, (1984), 'Analysis of flow to a large-diameter well near a river and estimation of storage coefficient'. Hydrology, Journal of the Indian Association of Hydrologists. V.VII, no.1, pp.18-24.

26. Mishra, G.C. and A.G. Chachadi, (1985), 'Analysis of unsteady flow to a large-diameter well'. Proceedings of the International Workshop on rural hydrogeology and hydraulics in fissured basement zones. March 1985. Department of Earth Sciences, University of Roorkee, India.

27 Narasimhan, T.N. (1968), 'Pumping tests on open wells in palar alluvium near Madras city, India, An application of the Papadopulos-Cooper method'. Bull. International Assoc.Sci.Hydrology.V.XIII, no.4, pp.91-105.

28. Narasimhan, T.N., (1965), 'On testing open wells' Indian Geohydrology. V.I.

29. Narahari Rao, K.L. (1983), 'Characteristics of precambrian aquifers in the Malaprabha basin', Karnatka Ph.D. Thesis, Dept of Civil Engg. IIT Kanpur.

30. Papadopulos, I.S. (1967), 'Drawdown distribution around a large-diameter well', Proc. Symp. on Groundwater Hydrology. San Francisco. Nov. 1967. Am.Water Resources Assoc. Proc. no.4, pp.157-168.

31. Papadopulos, I.S. and H.H. Cooper Jr., (1967), 'Drawdown in a well of large-diameter', Water Resources Res.V.3, no.1, pp.241-244.

32. Patel, S.C. and G.C. Mishra, (1983), 'Analysis of flow to a large-diameter well by a discrete kernel approach'. Ground Water. V.27, no.5, pp.573-576.

33. Raju, T.S. and K.V.Raghava Rao, (1967), 'New a-proach for the analysis of pump test data of an open well', Paper presented at the symposium on ground and lake water resources in India. Hyderabad, Dec.1967.

34. Rushton, K.R. and S.C. Redshaw, (1979), 'Seepage and Ground Water flow', Wiley, Chichester, 332,pp.

35. Rushton, K.R. and S.M.Holt, (1981), 'Estimating aquifer parameter for large-diameter well', Ground Water, V.19, pp.505-516.

36. Rushton, K.R. and V.S. Singh (1983), 'Drawdown in large-diameter wells due to decreasing abstraction rates', Ground Water, V.21, pp.670-679.

37. Rajagopalan, S.P., (1983),'Analysis of dug-well test data', Journal of Hydrology, V.64, pp.175-188.

38. Slitcher, C.S.(1906), 'The underflow in Arkansas Valley in Western Kansas', U.S. Geol, Survey Water-Supply paper, no.153, p.61.

39. Sammel, E.A.(1974), 'Aquifer tests in large-diameter wells in India', Ground Water,V.12, pp.265-272.

40. Singh, V.S.(1982), A discussion on 'determination of aquifer parameters from large-diameter dug well pumping tests', Ground Water. V.20, pp.616-617.

41. Theis, C.V.(1935), 'The relation between the lowering of piezometric surface and the data and duration of discharge of a well using ground water storage', Trans. Am.Geophy. Union. 16th Annual Meet., part-2 pp.519-524.

42. Theis, C.V. (1963),'Estimating the transmissivity of aquifers from the specific capacity of wells', In Bentall Ray compiler. Methods of determining permeability, transmissibility and drawdown, U.S.Geol. Survey water supply paper 1536-I, pp.332-336.

43. Thomas, Robert G(1982),'Bottom-entry large-diameter wells', Ground Water, V.20, no.1, pp.96-98.

44. Zdankus, N.T.(1974),'Analysis of shallow hard rock wells pumping and recovery test data' Ground Water V.12, no.5, pp.310-317.

45. Zekai, Sen,(1981), 'Type curves for large-diameter wells near barriers', Ground Water, V.20, no.3,pp. 274-277.