TR(BR) 139

# FLOW TOWARDS A PARTIALLY PENETRATING LARGE-DIAMETER WELL


NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE - 247 667 (U.P.)
INDIA
1995-96

## Preface

Nearly 65 percent of the country's land area is occupied by hard rocks which include entire central and south India. The exploitation of groundwater in these areas is mainly through large diameter wells (popularly known as dug wells). The weathered and fractured zones of hard rock has highly heterogeneous nature with low transmissivity varying from 1 $m^2/d$ to 300 $m^2/d$. Assessment of groundwater resources of these areas is vital and requires evaluation of aquifer parameters. These parameters can be evaluated utilizing the drawdown data obtained during pump-tests conducted at large diameter wells.

The Evaluation of aquifer parameters makes use of the theory describing the flow towards a large diameter well. Most of the analytical theories developed in the recent past pertain to fully penetrating large diameter wells. A large diameter well may be of partially penetrating nature due to specific site condition and cost constraint. Rapid and reasonable evaluation of aquifer parameters can be achieved through a computationally simple solution. Therefore, simple solution for the flow problem associated with pumping a partially penetrating large-diameter well is needed.

In the present report, a simple methodology has been developed for obtaining transient drawdowns due to pumping a partially penetrating large diameter well. Flow from bottom of the well has also been taken into account. The temporal variation of contributions from well-storage and aquifer storage have also been analyzed. The present study has been carried out by **Mr. S.K. Singh, Scientist 'C'.** The author is thankful to Dr. G.C. Mishra, Scientist 'F' for going through the draft derivations.

**(S.M. Seth)**
**Director**

## Abstract

Large diameter wells are economical and ideal for groundwater extraction in low transmissivity aquifers, such as fractured or fissured rocks. Storage within the well plays an important role when a large diameter well is pumped. A part of the pumped discharge is contributed by the well-storage which is substantial during initial phase of pumping. Well-storage contribution decreases with increase in time and after sufficiently long time, it becomes zero. Several studies pertaining to the analysis of flow towards a fully penetrating large diameter well, have been reported in the literature. A large diameter well may penetrate the aquifer partially because of construction and other constraints.

The present study deals with the analysis of flow to a partially penetrating large diameter well considering the flow through the bottom of the well. A simple methodology has been evolved for obtaining transient drawdown in the well as well as in the aquifer. The methodology enables the determination of aquifer contribution to the pumped discharge through the circumference as well as through the bottom of the well apart from the determination of well-storage contribution to the pumped discharge.

**Table of Contents**

## List of Figures

## 1.0 INTRODUCTION

Large diameter wells have been dug in India for centuries and millions are still found which serve the primary source of water particularly in hard rock regions of southern India. A large diameter well (dug well) utilizes the well-storage during pumping, hence, is ideally suited for the aquifers with low transmissivity. During initial phase of pumping, a substantial portion of well discharge comes from well storage, and this limits the well-loss component of drawdown to almost negligible. Even during later phase of pumping only a part of discharge is taken from the aquifer and due to this, the well loss component is less than that observed in case of a tube well. When the pump is stopped, water continues to flow into the well and well-storage recoups.

The prominent theoretical studies describing the flow regime associated with fully penetrating large diameter wells are by Papadopulos and Cooper(1967), Basak (1982), Patel and Mishra (1984). In practical situation, a large diameter well may partially penetrate the aquifer. In such case, a part of the aquifer-contribution to the pumped discharge comes through the bottom of the well. Though, few numerical studies have been reported (Herbert and Kitching, 1981 and Sridharan et al., 1990) on partially penetrating large diameter wells, the lone analytical study is by Boulton and Streltsova (1976) which involves a large number of parameters and computations of Bessel function of various kinds and orders. Therefore, analytical/semi-analytical solution involving simple computations to the flow-problem associated with a partially penetrating large diameter well, is needed.

In the present study, a computationally simple methodology has been evolved for finding transient drawdown in partially penetrating well, as well as, in the aquifer when the well is pumped at a constant rate. Temporal variations of well-storage contribution, aquifer-contribution through well-bottom, and through the circumference of the well, have also been analyzed. The methodology is applicable for confined aquifers or aquifers behaving like confined aquifers under natural and imposed conditions.

## 2.0 REVIEW

A detailed review of the past studies done on large diameter wells can be had from Singh (1990). However, a brief review pertaining to the present study is given below.

Papadopulos and Cooper (1967) obtained the following equation for drawdown due to pumping a fully penetrating large diameter well in an infinite confined aquifer assuming that the drawdown in the aquifer at the well face is equal to the drawdown in the well.

$$s(r,t) = \frac{Q}{4\pi T} F(u,\alpha,\phi) \qquad ...(2.1)$$

where,

$$u = \frac{r^2 S}{4Tt} ; \qquad ...(2.2)$$

$$\alpha = \frac{r_w^2}{r_c^2} S ; \qquad ...(2.3)$$

$$\phi = \frac{r}{r_w} \qquad ...(2.4)$$

in which,

$Q$ = constant rate of pumped discharge,
$T$ = transmissivity of the aquifer,
$S$ = storage-coefficient of the aquifer,
$r$ = radial distance from the centre of the well,
$r_w$ = radius of well -screen,
$r_c$ = radius of well casing ( unscreened part of the well),
$t$ = time since the commencement of the pumping.

Thus, the drawdown in the well is given by,

$$s_w(t) = \frac{Q}{4\pi T} F(u_w, \alpha, 1) \qquad \ldots(2.5)$$

After the pioneering work of Papadopulos and Cooper (1967), Patel and Mishra(1984) proposed a simple methodology using discrete kernel approach to find the drawdown in a large diameter well and aquifer contribution to the pumped discharge. They also assumed that the drawdown in the well to be equal to the drawdown in the aquifer at the well face. Since then, several investigators used discrete kernel approach in one or other form for solving flow problems associated with large diameter wells, e.g., Rushton and Singh (1987), Mishra and Chachadi(1985), Singh and Gupta (1986), etc. Basak(1992) has presented analytical solution for recovery in large diameter wells and Rajgopalan and Jose (1986) have proposed a numerical model to simulate the flow towards a dug well.

Flow to Partially penetrating large diameter well has been analyzed using numerical approach by Herbert and Kitching(1981), Rushton and Holt(1982), Sridharan et al.(1990), etc. Boulton and Streltsova(1976) have given a analytical model for the transient flow to a partially penetrating large diameter well in an unconfined aquifer taking into account the anisotropy of the aquifer in respect of hydraulic conductivity and compressibility. Their solution involves a large number of parameters and requires the computations of Bessel functions; this makes its application difficult.

From critical review of the available literature, it is observed that the computationally simple solution for drawdown due to pumping a partially penetrating well has not been obtained so far.

## 3.0 STATEMENT OF THE PROBLEM

A large diameter well of radius $r_W$ partially penetrates a homogeneous isotropic and semi-infinite confined aquifer of thickness D. Depth of well penetration is d and bottom of the well is open. The well draws water from full depth of its penetration. A schematic vertical section of the aquifer and the well is shown in fig.3.1. Initially, the well water level and the aquifer water table are assumed at the equilibrium. The well is pumped for certain period. The problem is to find the following considering also the flow from the bottom of the well.

1. Temporal variations of the contributions to the pumped discharge from well-storage, and aquifer-storage (through well-circumference and well-bottom separately) respectively.

2. Drawdown in the well as well as at a certain distance from the well.

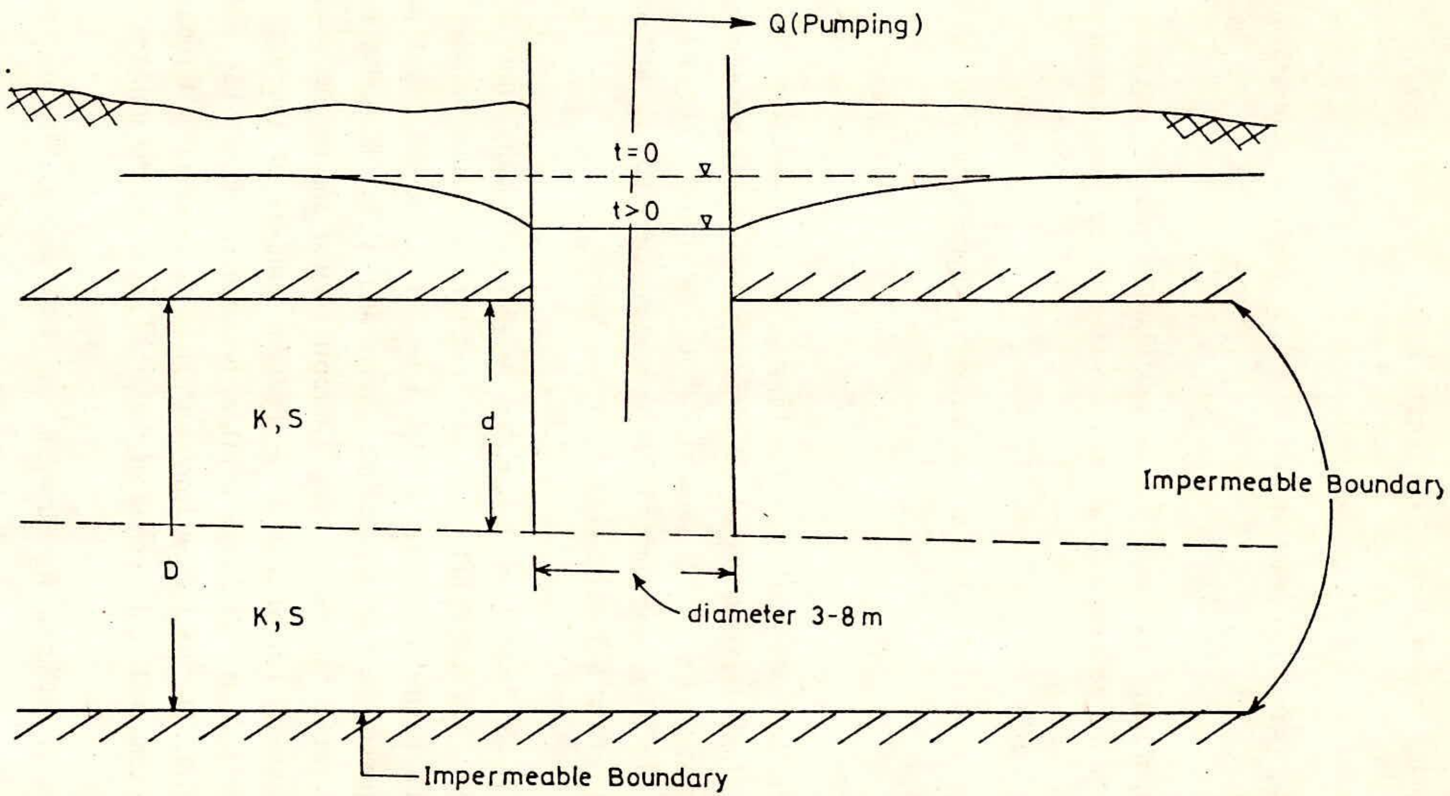


Fig. 3·1—Schematic Vertical Section of the Aquifer and Well

## 4.0 MATHEMATICAL FORMULATION

The following assumptions have been made for the present mathematical formulation.

1. Total pumping period has been discretized into a number of uniform time steps of size $\Delta t$.

2. The abstraction rate, the well storage contribution and the aquifer contribution through the well circumference as well as through the well bottom are constant during each time step.

3. Drawdown in the well is equal to the drawdown in the aquifer at the well face at each time step.

The aquifer has been hydrologically decomposed into two layers (fig.3.1). The thickness of the first layer is equal to the depth of well penetration, i.e., d. Hydraulic conductivity, i.e, K is same for both the layers. $T_1$ and $T_2$ are the transmissivity of the first and second layer respectively and $S_1$ and $S_2$ are the storage coefficients of the top and bottom layer respectively.

Both the layers have been discretized in plan identically into a number of elements(grids) by a set of radial lines and a set of concentric circles with their centres at the well centre as shown in fig. 4.1. Let 'i' be the index denoting the annular space between the two consecutive circles and 'j' be the index denoting the diverging space between two radial lines. Uniform angular spacing between the radial lines has been assumed. Let M and N be the total numbers of diverging spaces and annular spaces respectively. Exchange of flow between the layers has been assumed uniform over a grid. The total flow from one layer to other layer through a grid is assumed to be concentrated at the centre of the grid. Let $\Delta t$ be the uniform time step.

The continuity equation for flow, at the well during $n^{th}$ time step may be written as,

$$Q_a(n) + Q_b(n) + Q_w(n) = Q_p(n) \qquad \ldots(4.1)$$

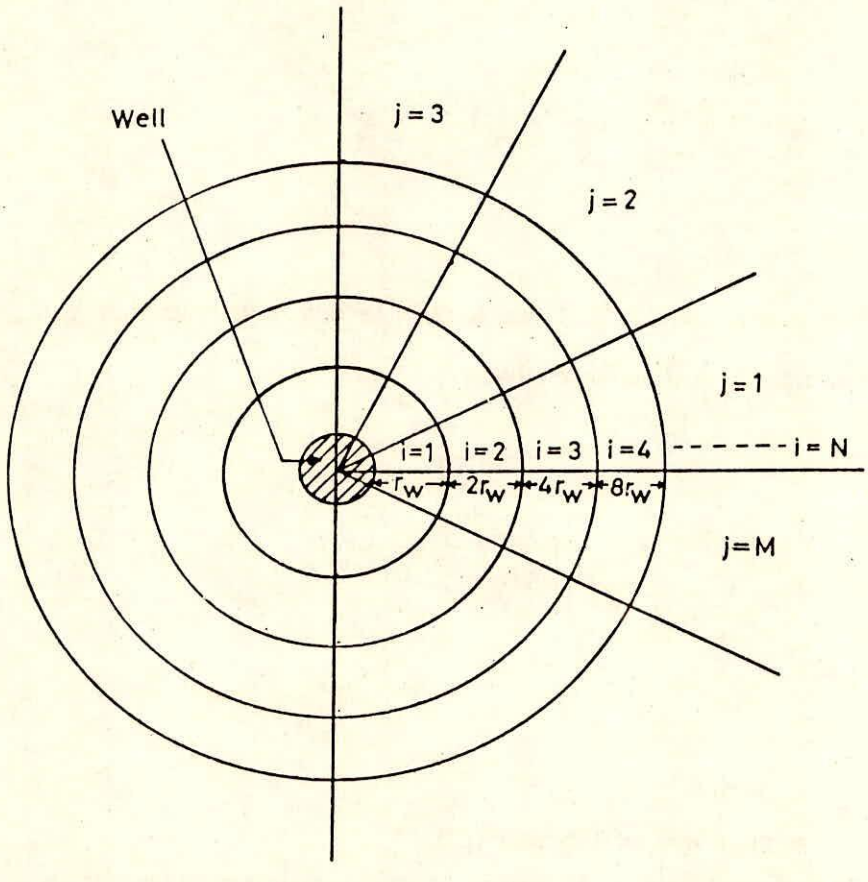


Fig. 4·1- Discretization of Aquifer in Plan where,

$Q_a(n)$ = aquifer contribution to pumped discharge through the circumference of the well during $n^{th}$ time step;

$Q_b(n)$ = aquifer contribution to pumped discharge through well-bottom during $n^{th}$ time step;

$Q_w(n)$ = well storage contribution to well discharge during $n^{th}$ time step, and;

$Q_p(n)$ = pumping rate during $n^{th}$ time step.

Drawdown, $s_w(n)$, in the well at the end of $n^{th}$ time step can be expressed as,

$$\bar{s}_w(n) = \frac{\Delta t}{\pi r_w^2} \sum_{\gamma=1}^{n} Q_w(\gamma) \qquad \ldots(4.2)$$

Recharge from the first layer to the second layer through grid, (i,j), during $n^{th}$ time step, i.e., $q_{i,j}(n)$, is given by,

$$q_{i,j}(n) = \left[\frac{KA_{i,j}}{D}\right]\left[s_{i,j,2} - s_{i,j,1}\right] \qquad \ldots(4.3)$$

where,

$A_{i,j}$ = plan area of the grid (i,j),

$s_{i,j,1}$ = drawdowns at the centre of grid (i,j) in first layer,

$s_{i,j,2}$ = drawdowns at the centre of grid (i,j) in second layer.

Aquifer contribution through the well bottom during $n^{th}$ time step is given by the following equation.

$$Q_b(n) = \frac{2K\pi r_w^2}{(D-d)} \left[ s_w(n) - s_{0,0,2}(n) \right] \qquad \ldots(4.4)$$

where,

$s_{0,0,2}(n)$ = drawdown at grid (0,0) in the second layer at the end of $n^{th}$ time step;

$s_w(n)$ = drawdown in the first layer at the well face at the end of $n^{th}$ time step.

Since, within an annular space all the grids are symmetric and have same value of recharge, $s_w(n)$ and $s_{0,0,2}(n)$ can be expressed by the following equations.

$$s_w(n) = \sum_{\gamma=1}^{n} Q_a(\gamma)\delta_1(0,0;0,0;n-\gamma+1) - \sum_{\gamma=1}^{n} Q_b(\gamma)\delta_1(0,0;0,0;n-\gamma+1) +$$

$$M \sum_{\gamma=1}^{n} \sum_{i=1}^{N} q_{i,1}(\gamma)\delta_1(i,1;0,0;n-\gamma+1) \qquad \ldots(4.5)$$

and,

$$s_{0,0,2}(n) = \sum_{\gamma=1}^{n} Q_b(\gamma)\delta_2(0,0;0,0;n-\gamma+1) -$$

$$M \sum_{\gamma=1}^{n} \sum_{i=1}^{N} q_{i,1}(\gamma)\delta_2(i,1;0,0;n-\gamma+1) \qquad \ldots(4.6)$$

Discrete pulse kernel, $\delta_1(i,j;k,l;m)$ is given by,

$$\delta_1(i,j;k,l;m) = \frac{1}{4\pi T_1} \left[ W\{f(m)\} - W\{f(m-1)\} \right] \qquad \ldots(4.7)$$

in which,

$$W(u) = \int_u^{\infty} \frac{\exp(-u)}{u} du \qquad \ldots(4.8)$$

and,

$$f(m) = \frac{r_{ijkl}^2 S_1}{4T_1 m\Delta t} \qquad \ldots(4.9)$$

where,

$r_{ijkl}$ = distance between the centres of grids (i,j) and (l,k) respectively;
m = index denoting the time step.

The expression for $\delta_2(.)$ can be obtained by substituting $T_2$ and $S_2$ in place of $T_1$ and $S_1$, respectively, in the corresponding equations for $\delta_1(.)$. When (i,j) is equal to (l,k), the grid (i,j) is divided into four sub grids as shown in fig.4.2. Recharge in proportion to the area of sub-grids were assumed to occur at the respective centres of the sub-grids; the total recharge through all the sub-grids being equal to the recharge from grid(i,j). Therefore, the discrete pulse kernel, $\delta_1(i,j;i,j;m)$ is given by,

$$\delta_1(i,j;i,j;m) = \frac{1}{2\pi T_1}\left[W\left\{f_1(m)\right\} - W\left\{f_1(m-1)\right\} + W\left\{f_2(m)\right\} - W\left\{f_1(m-1)\right\}\right] \qquad \ldots(4.10)$$

in which,

$$f_1(m) = \frac{r_1^2 S_1}{4T_1 m\Delta t} \qquad \ldots(4.11)$$

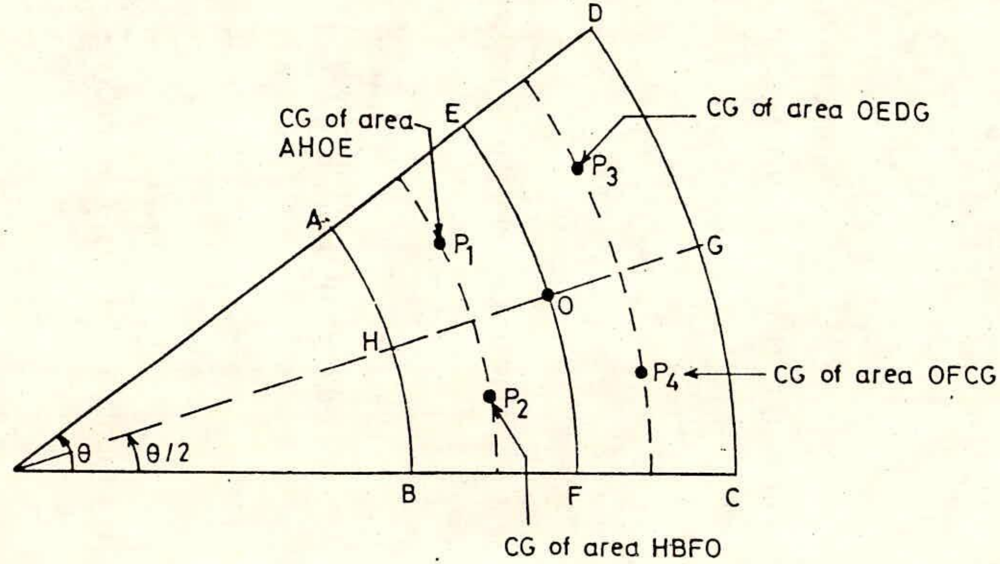


Fig. 4·2 - Sub Grids for a Grid ABCD

and,

$$f_2(m) = \frac{r_2^2 S_1}{4T_1 m\Delta t} \qquad \ldots(4.12)$$

Where, $r_1$ and $r_2$ are the respective distances from the centres of the two unsymmetrical sub-girds to the centre of the grid (i,j). Substituting eqs. (4.5) & (4.6) into eq. (4.4), we get,

$$\frac{D-d}{2\pi K r_w^2} Q_b(n) = \sum_{\gamma=1}^{n} Q_a(\gamma)\delta_1(0,0;0,0;n-\gamma+1) - \sum_{\gamma=1}^{n} Q_b(\gamma)\delta_{12}(0,0;0,0;n-\gamma+1)$$

$$+ M \sum_{\gamma=1}^{n} \sum_{i=1}^{N} q_{i,1}(\gamma)\delta_{12}(i,1;0,0;n-\gamma+1) \qquad \ldots(4.13)$$

$\delta_{12}(.)$ is defined by the following equation.

$$\delta_{12}(.) = \delta_1(.) + \delta_2(.) \qquad \ldots(4.14)$$

Drawdown at the centre of the grid (i,j) in the first layer at the end of $n^{th}$ time step, $s_{i,j,1}(n)$, is given by,

$$s_{i,j,1}(n) = \sum_{\gamma=1}^{n} Q_a(\gamma)\delta_1(0,0;i,j;n-\gamma+1) - \sum_{\gamma=1}^{n} Q_b(\gamma)\delta_1(0,0;i,j;n-\gamma+1)$$

$$+ \sum_{\gamma=1}^{n} \sum_{l=1}^{N} \sum_{k=1}^{M} q_{l,k}(\gamma)\delta_1(l,k;i,j;n-\gamma+1) \qquad \ldots(4.15)$$

Drawdown at the centre of the grid (i,j) in the second layer at the end of $n^{th}$ time step, $s_{i,j,2}(n)$, is given by,

$$s_{i,j,2}(n) = \sum_{\gamma=1}^{n} Q_b(\gamma)\delta_2(0,0;i,j;n-\gamma+1) -$$

$$\sum_{\gamma=1}^{n} \sum_{l=1}^{N} \sum_{k=1}^{M} q_{l,k}(\gamma)\delta_2(l,k;i,j;n-\gamma+1) \qquad \ldots(4.16)$$

From eqs. (4.3), (4.15), & (4.16), we obtain,

$$\frac{D}{2KA_{i,j}} q_{i,j}(n) = - \sum_{\gamma=1}^{n} Q_a(\gamma)\delta_1(0,0;i,j;1) + \sum_{\gamma=1}^{n} Q_b(\gamma)\delta_{12}(0,0;i,n-\gamma+1)$$

$$-M \sum_{\gamma=1}^{n} \sum_{i=1}^{N} \sum_{k=1}^{M} q_{l,k} (\gamma)\delta_{12}(l,k;i,j;n-\gamma+1) \qquad \ldots(4.17)$$

Since, the drawdown in the well is equal to the drawdown in the aquifer at the well face, hence, equating these drawdowns from eqn. (4.2) and (4.5), we get,

$$\frac{\Delta t}{\pi r_w^2} \sum_{\gamma=1}^{n} Q_w(\gamma) = \sum_{\gamma=1}^{n} Q_a(\gamma)\delta_1(0,0;0,0;n-\gamma+1) -$$

$$\sum_{\gamma=1}^{n} Q_b(\gamma)\delta_1(0,0;0,0;n-\gamma+1)$$

$$+ M \sum_{\gamma=1}^{n} \sum_{i=1}^{n} q_{i,1}(\gamma)\delta_1(i,1;0,0;n-\gamma+1) \qquad \ldots(4.18)$$

Re-arranging eqs. (4.13) & (4.18), we get,

$$Q_a(n)\delta_1(0,0;0,0;1) + Q_b\left(\frac{D-d}{2K\pi r_w^2} + \delta_{12}(0,0;0,0;1)\right) -$$

$$M \sum_{i=1}^{N} q_{i.1}(\gamma)\delta_{12}(i,1;0,0;1) = \sum_{\gamma=1}^{n-1} Q_a(\gamma)\delta_1(0,0;0,0;n-\gamma+1)$$

$$- \sum_{\gamma=1}^{n} Q_b(\gamma)\delta_{12}(0,0;0,0;n-\gamma+1) + M \sum_{i=1}^{N} \sum_{\gamma=1}^{n-1} q_{i.1}(\gamma)\delta_{12}(i,1;0,0;n-\gamma+1)$$

$$\ldots(4.19)$$

and,

$$- Q_a(n)\delta_1(0,0;0,0;1) + Q_b(n)\delta_1(0,0;0,0;1) - M \sum_{i=1}^{N} q_{i.1}(\gamma)\delta_1(i,1;0,1) +$$

$$\frac{\Delta t}{\pi r_w^2} Q_w(n) = \sum_{\gamma=1}^{n-1} Q_a(n)\delta_1(0,0;0,0;n-\gamma+1) - \sum_{\gamma=1}^{n} Q_b(\gamma)\delta_1(0,0;0,0;n-\gamma+1)$$

$$+ M \sum_{i=1}^{N} \sum_{\gamma=1}^{n-1} q_{i,1}(\gamma)\delta_1(i,1;0,0;n-\gamma+1) - \frac{\Delta t}{\pi r_w^2} \sum_{\gamma=1}^{n-1} Q_w(\gamma) \qquad \ldots(4.20)$$

Similarly, re-arranging eq. (4.17), we get,

$$Q_a(n)\delta_1(0,0;i,j;1) - Q_b(n)\delta_{12}(0,0;i,j;1) + \frac{D}{2KA_{i,j}} q_{i,j}(n) +$$

$$M \sum_{l=1}^{N} \sum_{k=1}^{M} q_{l,k}(\gamma)\delta_{12}(l,k;i,j;1) = - \sum_{\gamma=1}^{n-1} Q_a(\gamma)\delta_1(0,0;i,j;n-\gamma+1) +$$

$$\sum_{\gamma=1} Q_b(\gamma)\delta_{12}(0,0;i,j;n-\gamma+1) - M \sum_{\gamma=1}^{n-1} \sum_{i=1}^{N} \sum_{k=1}^{M} q_{l,k}(\gamma)\delta_{12}(l,k;i,j;n-\gamma+1)$$

$$\ldots(4.21)$$

Eqs. (4.1), (4.20) & (4.21) can be expressed in matrix form as given below.

$$[A][X] = [B] \qquad \ldots(4.22)$$

where, $[B]$ is a vector, whose elements are,

$b_1 = Q_p(n)$

$b_2$ = R.H.S. of eq. (4.19)

$b_3$ = R.H.S. of eq. (4.20)

$b_{(i+3)}$ = R.H.S. of eq. (4.21) ; i=1,N ; and,

$$[X] = \begin{bmatrix} Q_a(n) \\ Q_b(n) \\ Q_w(n) \\ q_{1,1}(n) \\ q_{2,1}(n) \\ q_{3,1}(n) \\ .. \\ .. \\ .. \\ q_{N,1}(n) \end{bmatrix}$$

Therefore, starting from first time step, $[X]$ can be obtained solving eq. (4.22) for each time step in succession. Knowing $q_{1,1}(n)$, $q_{2,1}(n)$, $q_{3,1}(n)$, ....$q_{N,1}(n)$; drawdowns in the well can be obtained using either eq. (4.2) or (4.5). Drawdowns in the first and second layer can be computed using eqs. (4.15) & (4.16) respectively.

## 5.0 RESULTS

A computer code in Fortran was developed which uses the methodology presented in chapter 4 to compute the transient drawdown in the well as well as in the aquifer along with the well-contribution and aquifer contribution, when a partially penetrating large diameter well is pumped at a constant rate. The results presented herein are for the following range of variables.

| | |
|---|---|
| Diameter of well | = 2.0 m and 4.0 m |
| Hydraulic conductivity of the aquifer | = 5.0 m/d |
| Storage coefficient of the aquifer | = $1.0\text{x}10^{-5}$ |
| Partial penetration | = 0.25, 0.5, and 1.0 |
| Total thickness of the aquifer | = 20.0 m |
| Pumped discharge | = 120.0 $m^3$/d |

Variations of $s_w(t)$ with time is shown in fig. 5.1 for different penetrations for $r_w$=1.0 m. The figure shows that at a particular time drawdown in the well decreases as the well-penetration increases. Fig. 5.2 shows the temporal variations of drawdown for different penetration for $r_w$=2.0 m. It can be concluded from fig 5.1 & 5.2 that the drawdown decreases with increase in depth of penetration. Fig. 5.3 & 5.4 show that the temporal variations of $Q_a$ for $r_w$=1.0m and 2.0m respectively. These figures show that $Q_a$ increases with time for fixed value of $r_w$ ; and decreases with increase in $r_w$ at all time. Variation of $Q_b$ with time for different penetrations and different $r_w$ is shown in figs. 5.5 & 5.6.

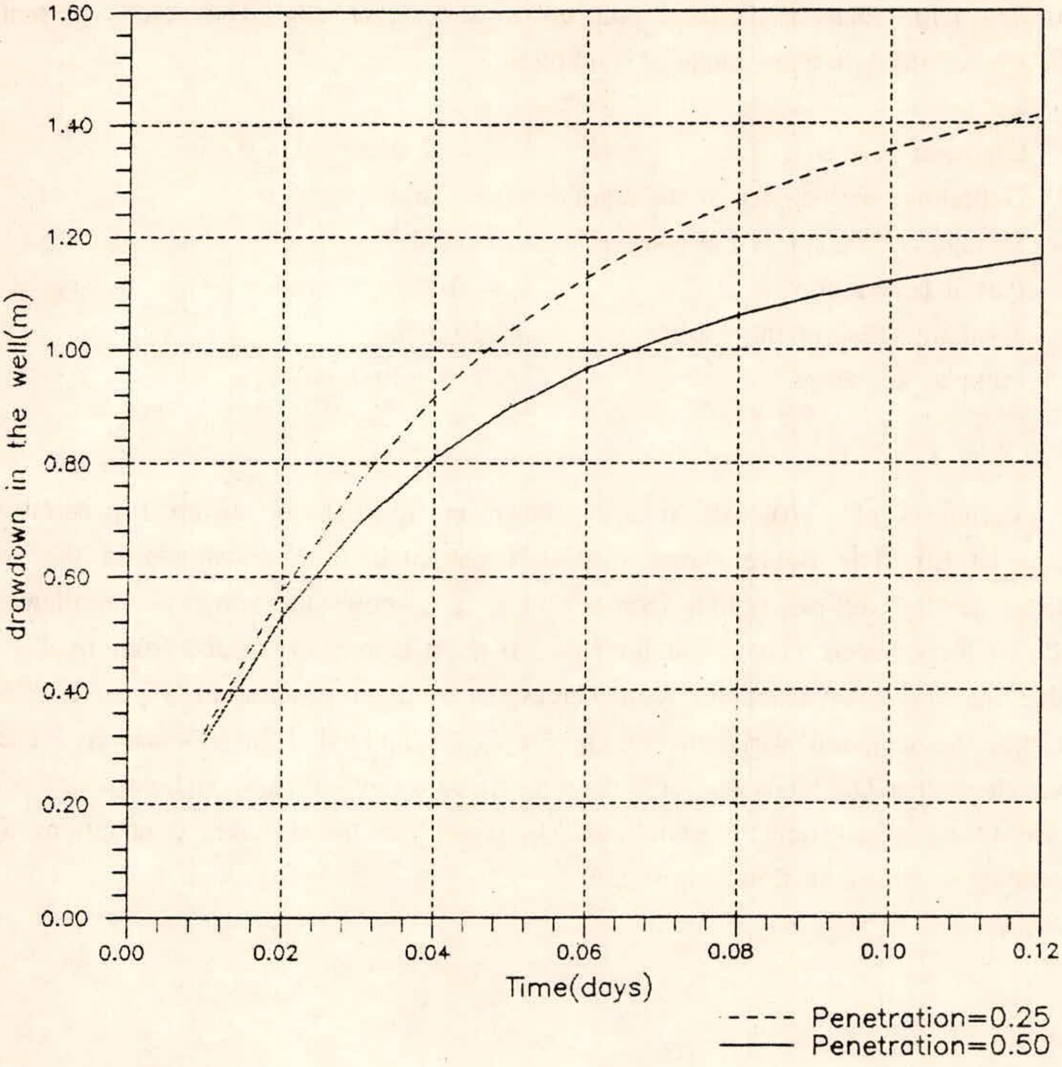


FIG.5.1 Variation of Well–Drawdown with Time ($r_w$=1.0m)

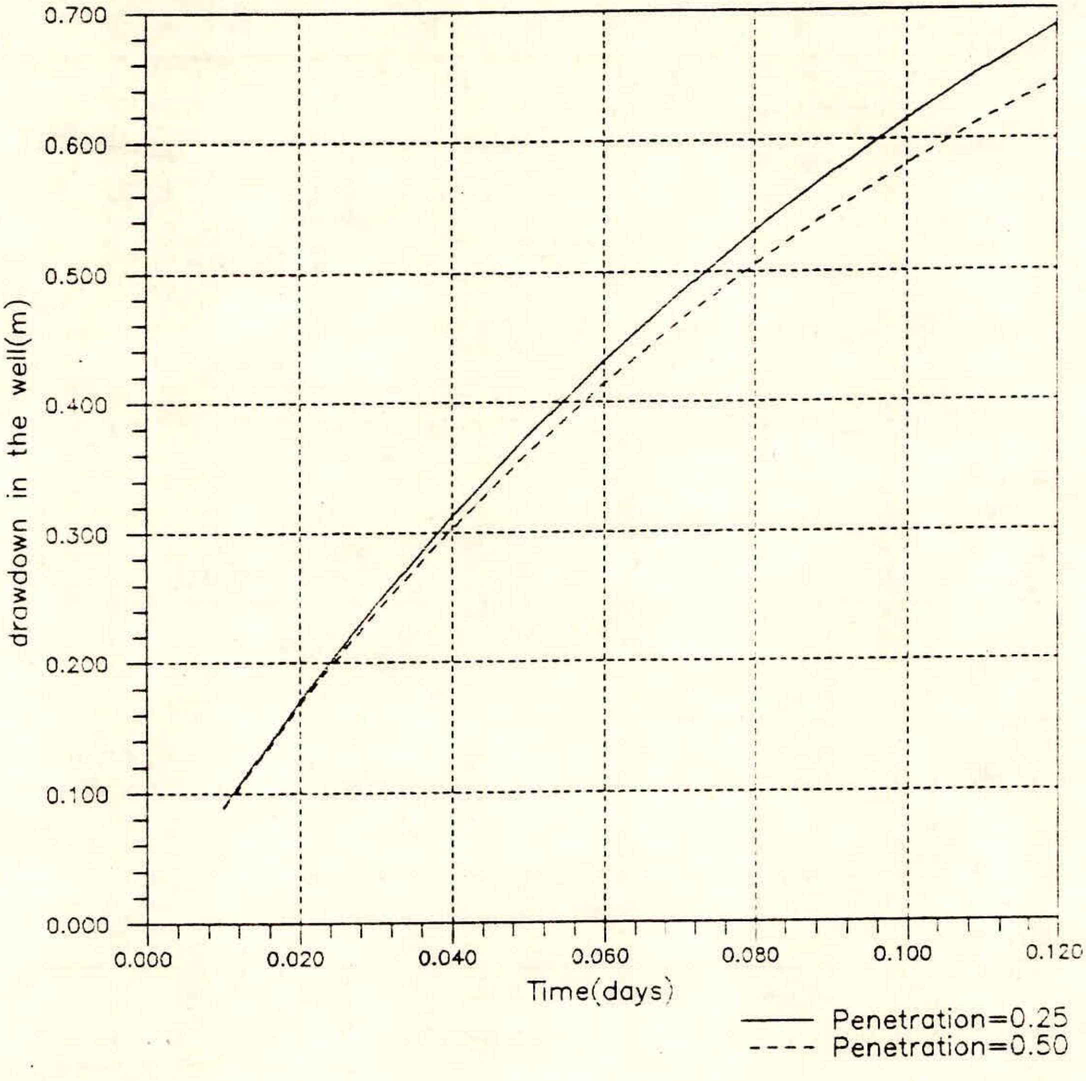


FIG.5.2 Variation of Well–Drawdown with Time ($r_w$=2.0m)

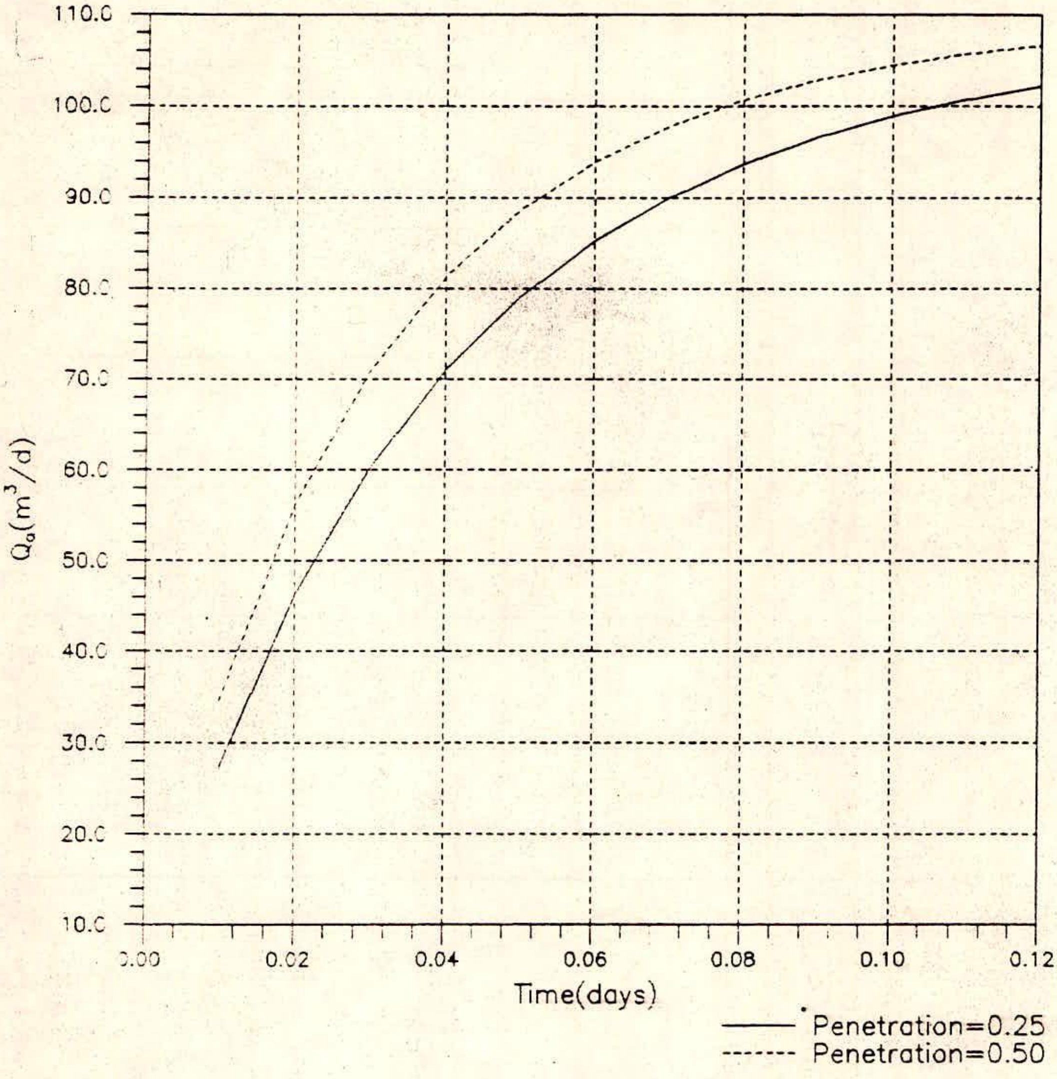


FIG.5.3 Variation of $Q_a$ with Time ($r_w$=1.0m)

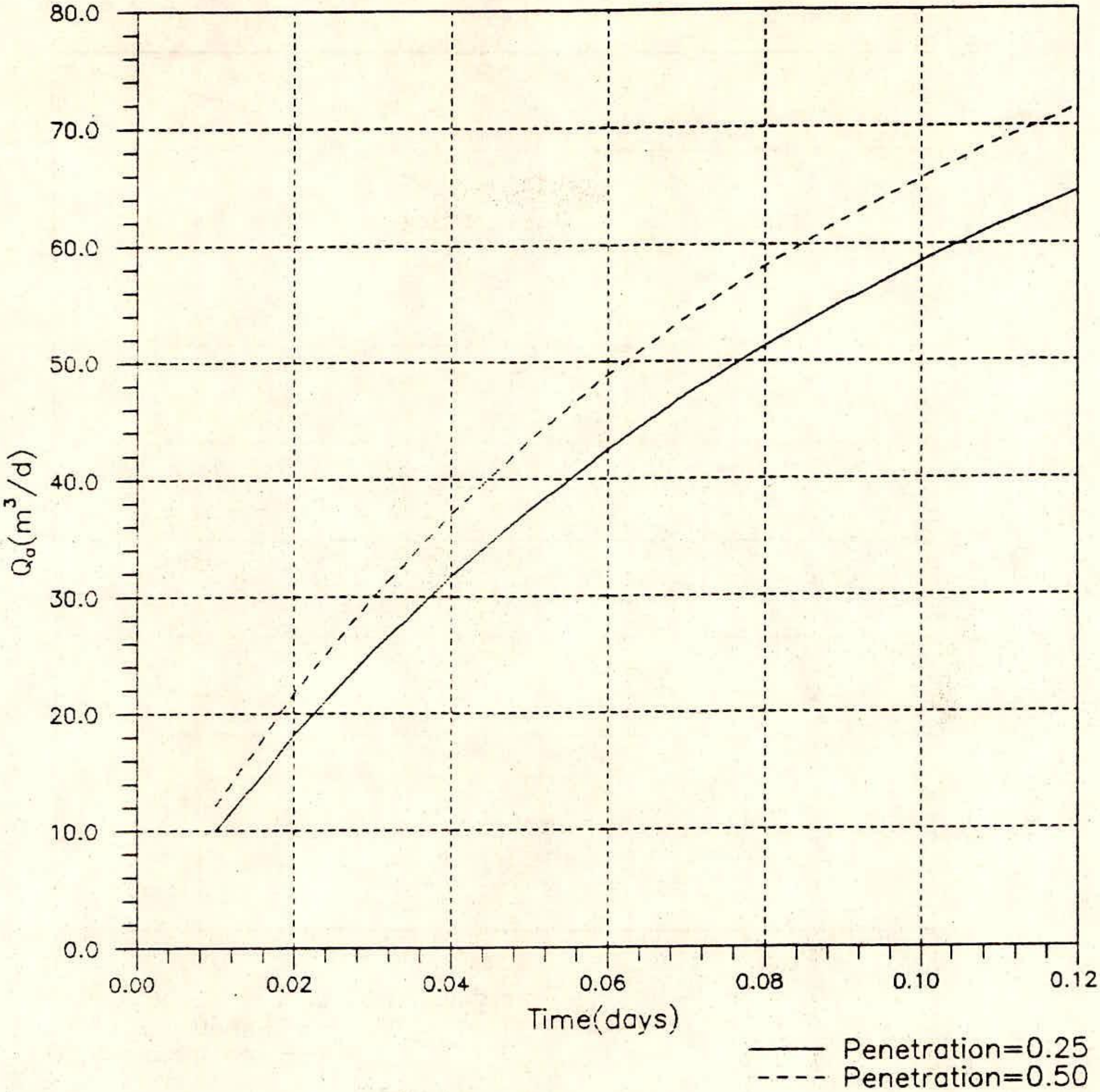


FIG.5.4 Variation of $Q_a$ with Time ($r_w$=2.0m)

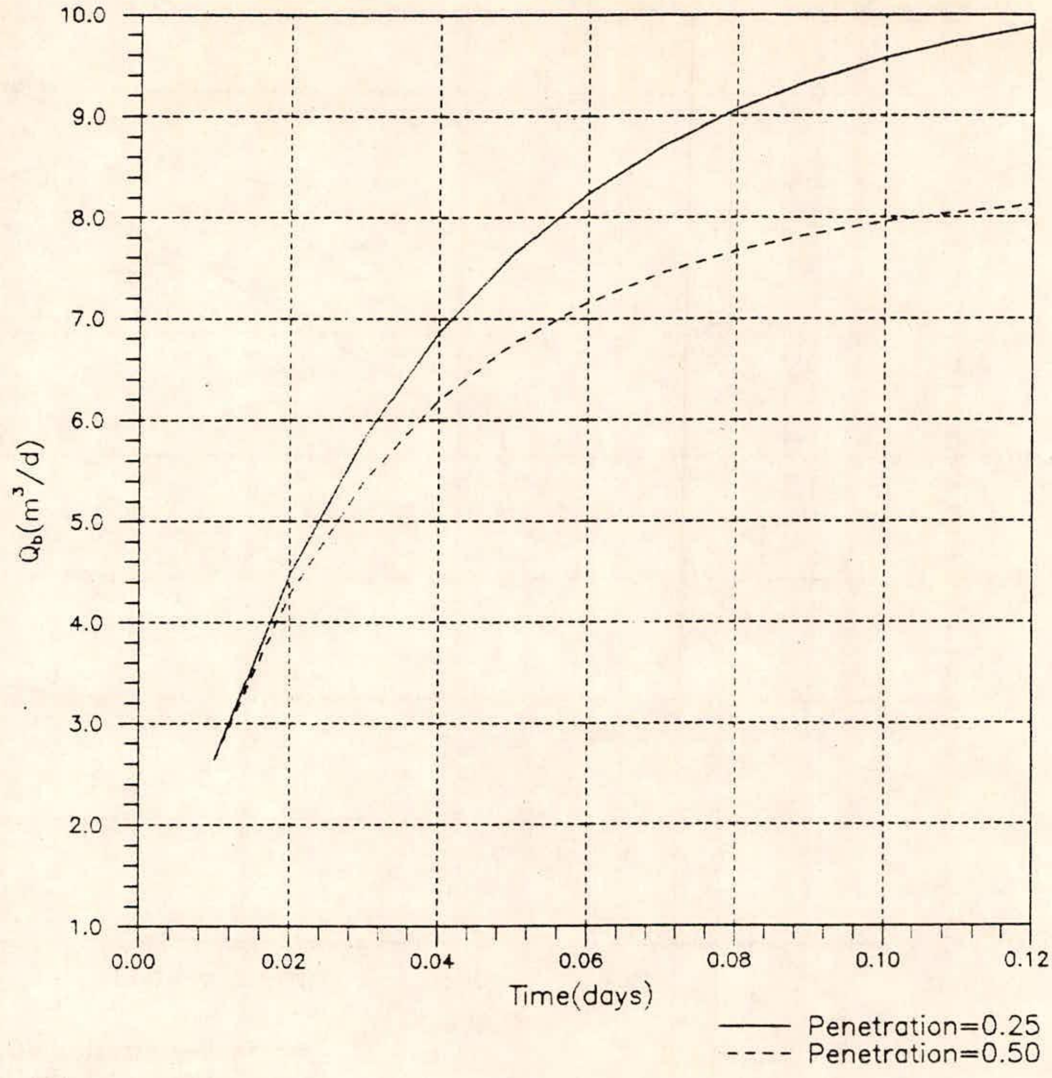


FIG.5.5 Variation of $Q_b$ with Time ($r_w$=1.0m)

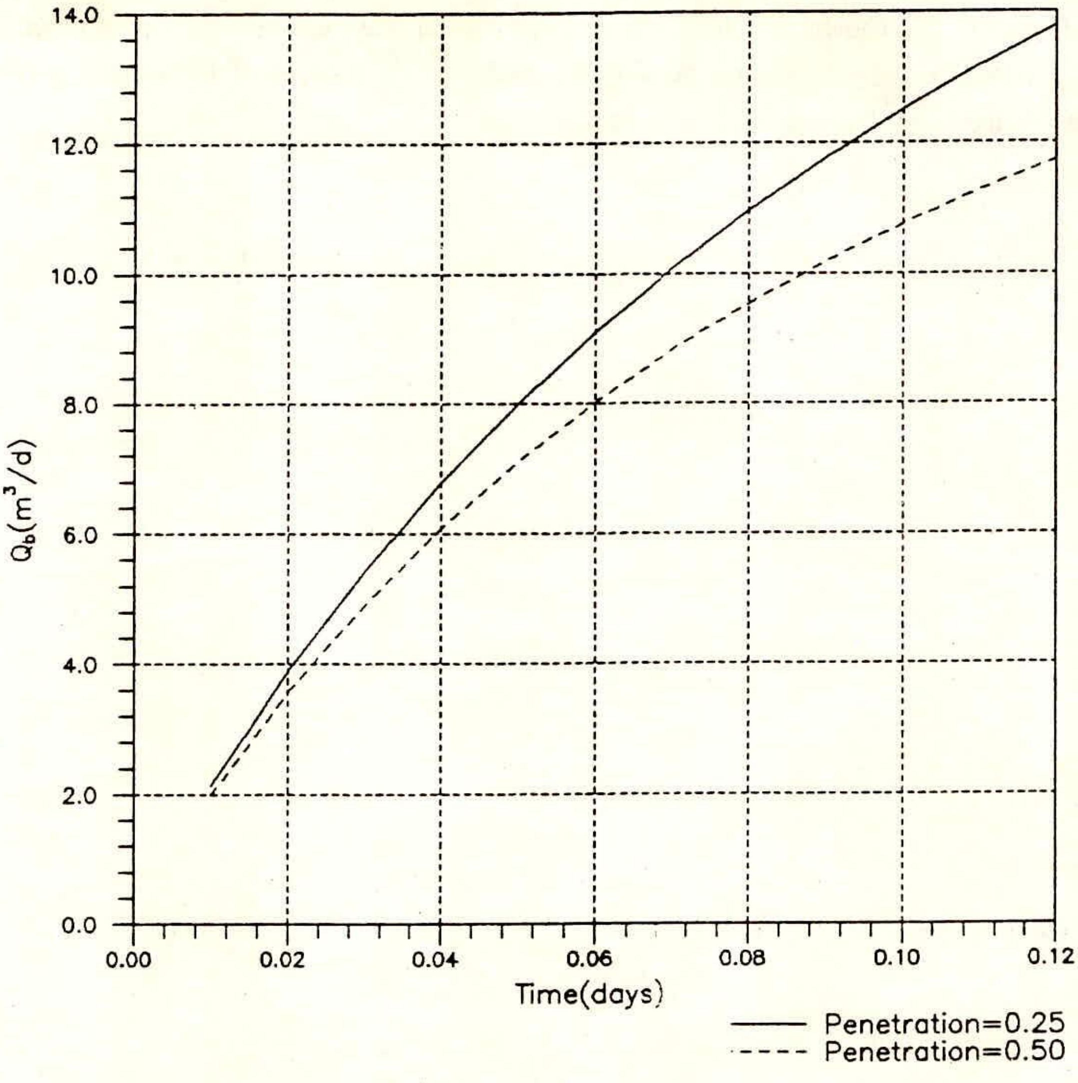


FIG.5.6 Variation of $Q_b$ with Time ($r_w$=2.0m)

## 6.0 CONCLUSION

A simple methodology has been developed using Duhamel's principle for modelling the transient flow towards partially penetrating large diameter well (when the well is pumped at a constant rate) accounting for the flow through the bottom of the well.

A computer code in Fortran has been developed for the same which can be used to find the i) drawdown in the well as well as in the aquifer ii) well-storage and aquifer-storage contribution to the pumped discharge on account of pumping a partially penetrating large diameter well at a constant rate.

## REFERENCES


1. Basak, P.(1982). Recovery in large diameter wells. Jour. of Hyd. Div., ASCE, 108, 1194-1207.

2. 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. Jour. Hydrol., 30, 29-46.

3. Herbert, R. and R. Kitching (1981). Determination of aquifer Parameters from large diameter dug well pumping tests. Ground Water, 19, 593-599.

4. Mishra, G.C. and A.G. Chachadi(1984). Analysis of flow to a large during recovery.

5. Papadopulos, I.S. and H.H. Cooper(1967). Drawdown in a well of large diameter. Water Resour. Res. 3(1), 241-244.

6. Patel, S.C. and G.C. Mishra(1983). Analysis of flow to a large diameter well by a discrete kernel approach. Ground Water, 27(5), 573-576.

7. Rajgopalan, S.P.(1983). Analysis of dug well test data. Jour. Hydrol., 64, 175-188.

8. Rushton, K.R. and S.M. Holt(1981). Estimating aquifer parameters for large diameter well, Ground Water, 19(5),505-509.

9. Rushton. K.R. and V.S. Singh(1987). Drawdown in a large diameter well due to decreasing abstraction rates. Ground Water. 21, 670-679.

10. Singh, S.K.(1990). Analysis of flow to a dug well in an unconfined aquifer by cell theory. Technical Report, TR-87, National Institute of Hydrology, Roorkee.

11. Singh, V.S. and C.P. Gupta(1986). Hydrological parameter estimation from pump test data on a large diameter well. Jour. Hydrol., 87, 223-232.

12. Sridharan, K., D. Satyanarayana, and A. Shiv Reddy(1990). Analysis of flow near a dug well in an unconfined aquifer. J. Hydrology, 119, 89-103.

DIRECTOR : S. M. SETH
DIVISIONAL HEAD : P.V. SEETHAPATHI

STUDY GROUP : S.K. SINGH