TN-30

DESIGN AND PERFORMANCE OF LARGE-DIAMETER WELLS IN HARD ROCK AREAS

SATISH CHANDRA
DIRECTOR

STUDY GROUP

A G CHACHADI

G C MISHRA

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAVAN
ROORKEE-247667 (UP) INDIA

1985-86

CONTENTS

LIST OF SYMBOLS

a	a constant
b	a constant
c	a constant
C_E	cost of excavation
C_o	cost of excavation per unit volume of soil at ground surface
CROP	Production per unit area of a particular crop
C	a constant
D	total depth of excavation of large-diameter well
E(.)	an exponential integral
m	integer
m'	cost parameter
n'	cost parameter
n	integer
N	integer
PRICE	market value of the crop per unit quantity
Q	rate of discharge
Q_I	initial rate of pumping
$Q_P(n)$	discharge rate at time step n
$Q_A(n)$	rate of withdrawal from aquifer storage at time n
$Q_W(n)$	rate of withdrawal from well storage at time n
r_c	radius of the well casing
r_w	radius of the well screen
RATE	interest rate
S_o	depth of water level below ground surface

$s_r(n)$ drawdown in the aquifer at distance r at time step n

s_F drawdown corresponding to zero pumping rate

$s_A(n)$ drawdown at the well point at time step n due to abstraction from well storage

t_p total time of pumping

T transmissivity

ϕ storage coefficient

$\delta_{rw}(N)$ discrete kernel coefficeint for drawdown at well point

$\delta_r(N)$ discrete kernel coefficient for drawdown at distance r from the well

LIST OF FIGURES

ABSTRACT

Unsteady flow to a large-diamter well in a confined aquifer has been analysed by discrete kernel approach for the case where the pumping rate is a quadratic function of drawdown. The equation assumed to hold good between pumping rate and drawdown is of the form

$$Q_p(n) = \left[1 - (1 - C) \frac{S_W(n)}{S_F} - C \frac{S_Q^2(n)}{S_F^2} \right] Q_I,$$

in which S_F and C are the pump characteristaics, Q_I is the initial pumping rate and $S_W(n)$ is the drawdown at the large-diameter well at time n. Results have been presented for variation of $Q_p(n)$, $S_W(n)$, and recovery of well storage with time. Variation of specific capacity of large-diameter well with time for different well storage has been studied. The relationships between transmissivity and specific capacity at various time after the onset of continuous pumping have been presented for different values of well storage and specific yield which can be used for estimating transmissivity.

Analysis of the design criteria for a large-diameter well has been carried out. The procedure for finding the optimum depth and diameter of the large-diamter well for which the cost of excavation is minimum has been presented. It has been found that the large-diameter wells are useful in the aquifers of low transmissivity.

1.0 INTRODUCTION

1.1 Performance of Large-Diameter Well for Non-Linear Abstraction

Large-diameter wells are extensively used in many parts of the world. The cheapness and simplicity of construction and operation of dug wells are often the main reasons for their use (Jain, 1977). Another important advantage of these wells is that they are suitable for shallow aquifers with low transmissivity. In India and other South Asian countries, people have been using large-diameter shallow dug wells tapping mostly the phreatic and in some cases the semi-confined aquifers near to the surface. Dug wells continue to be the primary source of ground water in rural India. According to Baweja (1979), of the total 9.5 million wells in India, 79 percent were dug wells with large-diameter, 18 percent were shallow tubewells in hard and soft rocks, and the remaining 3 percent were deep tubewells in alluvial basins. Lahiri (1975) had estimated that about 71 percent of the ground water abstracted in the year 1971 was from large-diameter wells. The farming community in hard rock areas is mostly dependent on large-diameter dug wells as a supplemental source for irrigation and domestic water. Aquifer tests are generally conducted on the existing large-diameter wells for evaluating the aquifer paramters. A better understanding of the performance of large-diameter well is therefore, necessary for an optimal development of ground water resources.

1.2 Design of Large-Diameter Well

There are no defined guidelines for the design of the large-diameter wells. It is generally not known in advance as to how much should be the depth and diameter of the large-diameter well to be constructed under a given set of hydrogeological conditions. Therefore, a comprehensive analysis of the optimum depth, diameter and cost of excavation should be made for better utilization of resources.

2.0 REVIEW

2.1 Performance of Large-Diameter Well

Analytical solutions of unsteady flow to a well considering well storage have been developed by several research workers (Papadopulos and Cooper, 1967, Lai et al, 1973, Lai and Wusu, 1974, Boulton and Streltsova, 1975, Fenske, 1977, Rushton and Holt, 1981 and Herbert and Kitching, 1981). The solution given by Papadopulos and Cooper for flow to a large-diameter well in a confined aquifer is based on the solution given by Carslaw and Jaeger (1959) for an analogous problem in heat flow. 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.

Rushton and Holt (1981) have presented an elegant numerical solution for analysis of flow to a large-diameter well both during abstraction as well as recovery phases. The existence of the seepage face in the abstraction well, variable abstraction rate and well losses can be included in their numerical model. The model simulates the water levels in a confined aquifer quite accurately, however, the results for unconfined aquifer are not quite satisfactory. Rushton and Singh (1983) have analysed flow to a large-diameter well wherein the abstraction rate is a linear function of drawdown.

In the last decade, many complex ground water flow problems have been analysed by the discrete kernel approach (Morel-Seytoux and Daly, 1975, and Morel-Seytoux,1975). Patel and Mishra (1983) have analysed flow to a large-diameter well during pumping using discrete kernel approach. The same approach has been extended for analysis of recovery phase by Mishra and Chachadi (1985). Using discrete kernel approach the unsteady flow to a large-diameter well induced by time variant pumping has been analysed by Mishra and Chachadi (1985) for the case when the pumping rate is a linear function of drawdown. In the present report analysis of unsteady flow to a large-diamter well has been carried out for the case when the pumping rate is a quadratic function of drawdown.

2.2 Design of Large-Diameter Well

In the existing literature there exists no specific guidelines for deciding the optimum depth and diameter of the large-diameter well under given set of hydrogeological conditions. Therefore, in the present report an attempt has been made to find the optimum depth and diameter of the large-diameter well for which the cost of excavation is minimum.

3.0 PROBLEM DEFINITION AND METHODOLOGY

3.1 Performance of Large-Diameter Well

3.1.1 Statement of the problem

Figure 1 shows a schematic cross section of a large-diameter well in a homogenous, isotropic confined aquifer of infinite areal extent which was initially at rest condition. The radius of the well screen is r_w and that of the unscreened part is r_c. Pumping is carried out up to time t_p and the rate of pumping depends on drawdown. It is required to determine i) the drawdown in piezometric surface at the well face and at any distance r from the centre of the well at time t after the onset of pumping, ii) the pumping rate and contribution of well storage to pumping and iii) the recovery of well storage after stoppage of pumping.

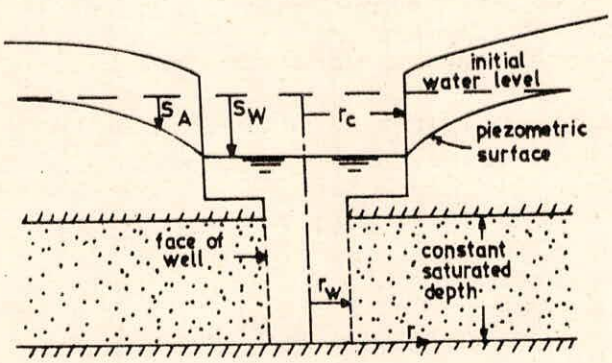

Fig.1- Schematic Cross-Section of a Large-Diameter Well

3.1.2 Methodology

The following assumptions have been made in the analysis:

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.

Let the total time of pumping, t_p, be discretised to m units of equal time steps. The quantity of water pumped during any time step n can be written as

$$Q_A(n) + Q_W(n) = Q_P(n) \qquad \ldots(1)$$

in which

$Q_A(n)$ = water withdrawn from aquifer storage and,

$Q_W(n)$ = water withdrawn from well storage.

For $n > m$, $Q_P(n) = 0$. Otherwise $Q_P(n)$ is equal to rate of pumping per unit time period. When centrifugal pump is used for abstraction the pumping rate decreases with the increase in drawdown. A typical variation of discharge with drawdown at the well face is shown in Fig.2. In such cases the pumping rate can be expressed as:

$$Q_P(n) = \left[1 - (1-C) \frac{S_W(n)}{S_F} - C \frac{S_W^2(n)}{S_F^2} \right] Q_I, \qquad \ldots(2)$$

in which, S_F and C are the pump characteristics, Q_I is the initial pumping rate and $S_W(n)$ is the drawdown at the large-

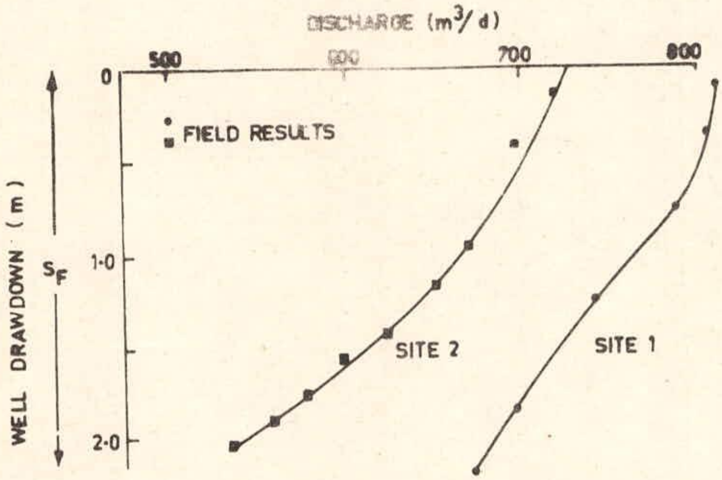

Fig. 2- Typical Variation of Abstraction Rate with Drawdown

diameter well at time n. C = 0 corresponds to the case where the pumping rate is a linear function of drawdown. Drawdown, $S_w(n)$, at the well face at the end of time step n is given by

$$S_w(n) = \frac{1}{\pi r_c^2} \sum_{\gamma=1}^{n} Q_w(\gamma) \qquad \ldots(3)$$

where $Q_w(\gamma)$ represents rate of withdrawal from well storage or replenishment at time step γ. $Q_w(\gamma)$ values are unknown a priori. A negative value of $Q_w(\gamma)$ means there is replenishment of well storage which occurs during recovery period. Making use of equations 1, 2 and 3 the following expression is obtained:

$$Q_A(n)+Q_w(n) = \left[1 - \frac{(1-C)}{S_F \pi r_c^2} \sum_{\gamma=1}^{n} Q_w(\gamma) - \frac{C}{S_F^2 \pi^2 r_c^4}\left(\sum_{\gamma=1}^{n} Q_w(\gamma)\right)^2\right] Q_I \qquad \ldots(4)$$

Rearranging

$$Q_A(n) + Q_w(n)\left[1 + \frac{(1-C)Q_I}{S_F \pi r_c^2} + \frac{2\,C\,Q_I}{S_F^2 \pi^2 r_c^4} \sum_{\gamma=1}^{n-1} Q_w(\gamma)\right]$$

$$+ \frac{C\,Q_I}{S_F^2 \pi^2 r_c^4} Q_w^2(n) - Q_I\left[1 - \frac{1-C}{S_F \pi r_c^2} \sum_{\gamma=1}^{n-1} Q_w(\gamma)\right.$$

$$\left. - \frac{C}{S_F^2 \pi^2 r_c^4}\left(\sum_{\gamma=1}^{n-1} Q_w(\gamma)\right)^2\right] = 0 \qquad \ldots(5)$$

Drawdown at the well face at the end of time step n due to abstraction from aquifer storage is given by (Morel-Seytoux, 1975)

$$S_A(n) = \sum_{\gamma=1}^{n} Q_A(\gamma) \quad \delta_{rw}(n - \gamma + 1) \qquad \ldots (6)$$

where,

$$\delta_{rw}(N) = \frac{1}{4 \pi T} \left[E_1 \left(\frac{\phi r_w^2}{4 T N} \right) - E_1 \left(\frac{\phi r_w^2}{4 T (N-1)} \right) \right]$$

$$\ldots (7)$$

$$E_1(x) = \int_x^\infty \frac{e^{-y}}{y} \, dy$$

where,

T = transmissivity of the aquifer,

ϕ = storage coefficient, and

N = an integer.

$\delta_{rw}(N)$ are known as discrete kernel coefficeint.

Because $S_w(n) = S_A(n)$, therefore,

$$\sum_{\gamma=1}^{n} Q_A(\gamma) \, \delta_{rw}(n-\gamma+1) = \frac{1}{\pi r_c^2} \sum_{\gamma=1}^{n} Q_w(\gamma) \qquad \ldots (8)$$

Rearranging

$$\delta_{rw}(1) \; Q_A(n) - \frac{1}{\pi r_c^2} \; Q_w(n) = \frac{1}{\pi r_c^2} \sum_{\gamma=1}^{n-1} Q_w(\gamma)$$

$$- \sum_{\gamma=1}^{n-1} Q_A(\gamma) \; \delta_{rw} \; (n-\gamma+1) \qquad \ldots (9)$$

From equation (9) $Q_A(n)$ in terms of $Q_w(n)$ is found to be

$$Q_A(n) = \left[\frac{Q_w(n)}{\pi r_c^2 \; \delta_{rw}(1)} + \frac{1}{\pi r_c^2 \; \delta_{rw}(1)} \sum_{\gamma=1}^{n-1} Q_w(\gamma) - \frac{1}{\delta_{rw}(1)} \sum_{\gamma=1}^{n-1} Q_A(\gamma) \; \delta_{rw}(n-\gamma+1) \right] \quad \ldots (10)$$

Substituting for $Q_A(n)$ by equation (10) in equation (5) the following quadratic equation in $Q_w(n)$ is obtained:

$$\left[\frac{C\,Q_I}{S_F^2 \pi^2 r_c^4} \right] Q_w^2(n) + Q_w(n) \left[\frac{1}{\pi r_c^2 \; \delta_{rw}(1)} + 1 + \frac{(1-C)\,Q_I}{S_F \pi r_c^2} + \frac{2CQ_I}{S_F^2 \pi^2 r_c^4} \sum_{\gamma=1}^{n-1} Q_w(\gamma) \right] + \left[\frac{1}{\pi r_c^2 \; \delta_{rw}(1)} \sum_{\gamma=1}^{n-1} Q_w(\gamma) - \frac{1}{\delta_{rw}(1)} \sum_{\gamma=1}^{n-1} Q_A(\gamma) \; \delta_{rw}(n-\gamma+1) - Q_I + \frac{(1-C)\,Q_I}{S_F \pi r_c^2} \sum_{\gamma=1}^{n-1} Q_w(\gamma) + \frac{C\,Q_I}{S_F^2 \pi^2 r_c^4} \left(\sum_{\gamma=1}^{n-1} Q_w(\gamma) \right)^2 \right] = 0 \quad \ldots (11)$$

Equation (11) is an usual quadratic equation. Defining the quantities in 1st, 2nd and 3rd squre brackets of equation (11) as a,b,c respectively, the roots of the equation are

$$Q_w(n) = \frac{-b + \sqrt{(b^2 - 4ac)}}{2a} \quad \ldots (12)$$

At any step n all terms but $Q_w(n)$ are known in equation (11), and $Q_w(n)$ can be solved in succession starting from time step 1. At any time step when $Q_w(n)$ is solved, $Q_A(n)$ can be known from equation (10). Once $Q_A(n)$ values are known, the drawdown, $S_r(n)$, in the aquifer at any distance r from the centre of the well can be found, using the relation:

$$S_r(n) = \sum_{\gamma=1}^{n} Q_A(\gamma)\ \delta_r(n - \gamma + 1) \qquad \ldots (13)$$

where,

$$\delta_r(N) = \frac{1}{4\pi T}\left[(E_1 \left(\frac{\phi r^2}{4\,T\,N}\right) - E_1\left(\frac{\phi r^2}{4T\,(N-1)}\right) \right]$$

In particular, for the first time step i.e. n = 1 the quadratic equation (11) reduces to

$$\frac{CQ_I}{S_F^2\ \pi^2 r_c^4}\, Q_w^2(1) + Q_w\ (1) \left[\frac{1}{\pi r_c^2\ \delta_{rw}(1)} + 1 + \frac{(1-C)\,Q_I}{S_F\ \pi r_c^2}\right] - Q_I = 0$$

$$\ldots (14)$$

3.2 Design of Large-Diameter Well

3.2.1 Statement of the problem

Fig.3 shows a schematic cross-section of large-diameter well to be constructed in a homogeneous isotropic confined aquifer of infinite areal extent. Water level in the area exist at depth S_o below ground. Pumping at a rate of Q per unit time for a duration of t_p, is required to meet the water demand. Let the total depth of excavation be represented by D. The maximum drawdown that can be caused is $D-S_o$. It is necessary to find the radius r_c of the well and depth D which meet the water demand and for which the cost of excavation is minimum. The transmissivity (T),

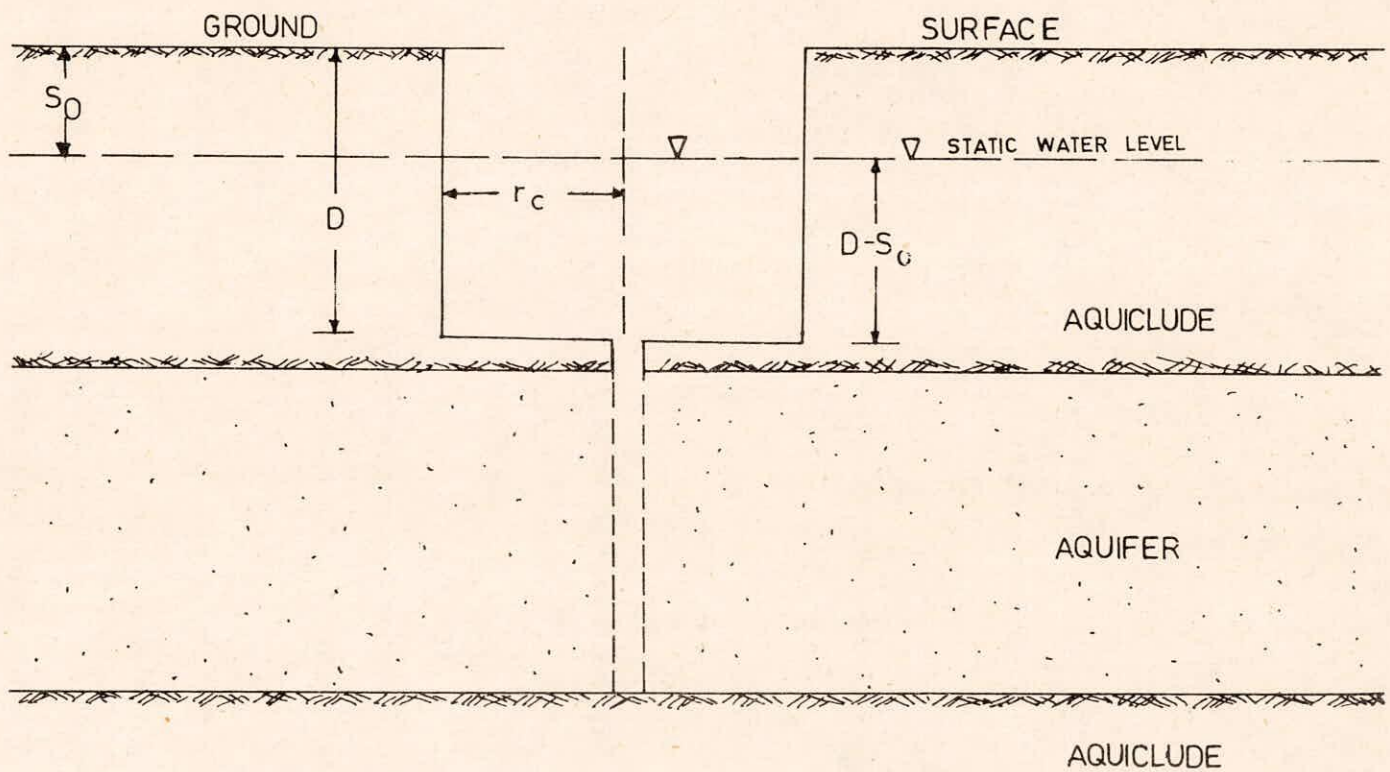

FIG.3 - SCHEMATIC CROSS SECTION OF A LARGE-DIAMETER WELL IN AN AREA WHERE WATER TABLE EXISTS AT A DEPTH S_o BELOW GROUND SURFACE

storativity (ϕ), discharge rate (Q) , and the duration of pumping (t_p) are known a priori.

3.2.2 Methodology

The following procedure has been adopted for finding the optimum depth and diameter of a large diameter well under a given set of hydrogeological conditions:

i) For known values of transmissivity, storage coefficient, discharge rate and duration of pumping the maximum drawdowns at the well point have been calculated for different values of r_c using computer programme presented in Appendix-I .

ii) From these graphs, the various combination of r_c and $D-S_o$ which could meet a required water demand for known values of T, ϕ , Q and t_p can be determined.

iii) Knowing the radius r_c and the corresponding D the cost of excavation (C_E) can be expressed as

$$C_E = C_o \pi r_c^2 D + m' \pi r_c^2 \frac{D^{n'}}{n'+1}$$

$$= \pi r_c^2 D \left(C_0 + m' \frac{D^{n'}}{n'+1} \right) \qquad \ldots(15)$$

The above expression has been derived on the assumption that the cost of excavation per unit quantity of soil at a depth y from ground surface is given by

$$C_E = C_o + m' y^{n'}$$

where,

C_o = the unit cost of excavation (Rs) at ground surface, and

m', n' = cost parameters.

iv) If the well is constructed in a agricultural land the productivity of the land in which the well has been excavated will be lost and this loss has to be incorporated in the total cost of the well. Therefore, equation (15) can be rewritten as

$$C_E = \pi r_c^2 D \left(C_o + m' \frac{D^{n'}}{n'+1}\right) + \pi r_c^2 \times CROP \times PRICE \times \sum_{i=1}^{N} \frac{1}{(1+RATE)^i} \quad \ldots(16)$$

where,

CROP = the production per unit area of a particular crop that can be grown in the well command area,

PRICE= the market value of the crop per unit quantity,

N = the number of years after which the present worth of the loss of the productivity of the land used for digging the well is negligible, and

RATE = the interest rate

v) Using equation (16) the cost of excavation for different depths and radii of the well can be found from which the optimal depth of excavation and the radius r_c can be known. The computer programme for computing cost of excavation for different depths and radii of the well is given in Appendix-II.

4.0 RESULTS AND DISCUSSIONS

4.1 Performance of Large-Diameter Well

The discrete kernel coefficients, $\delta_{rw}(N)$, have been generated using equation (7) for known values of T, ϕ and r_w. After generating the discrete kernels, $Q_w(n)$ values are solved in succession starting from time step n=1 to time step n=m using equation (11) for known values for Q_I, S_F, C, m and r_c. When pumping is stopped i.e. for n>m, $Q_P(n) = 0$. The recovery of well storage starts after stoppage of pumping. The values of $Q_A(n)$ and $Q_w(n)$ during recovery period are solved using equation (1) and (10). The variation of $Q_P(n)$ with $S_w(n)$ during pumping is shown in Fig.4 for different values of C. The values of Q_I and S_F adopted for obtaining numerical results correspond to field values reported by Rushton and Singh (1983). C= 0 corresponds to the case where pumping rate is a linear function of drawdown. For C = 0.1 the values of $Q_P(n)$ at the end of 300 minutes of pumping is found to be 65% of Q_I. When C = 1, the corresponding value is 80% of Q_I. A typical variatiion of $S_w(n)$ with time is shown in Fig.5 for different values of C. The variation of $-\sum_{\gamma=m+1}^{n} Q_w(\gamma)/\sum_{\gamma=1}^{m} Q_w(\gamma)$ with time since pumping stopped is shown in Fig. 6(a) through 6(f) for different values of ϕ, r_w/r_c and t_p and for a set of values of C, S_F and Q_I. $\sum_{\gamma=1}^{m} Q_w(\gamma)$ represents the total quantity of water withdrawn from well storage during pumping, and $-\sum_{\gamma=m+1}^{n} Q_w(\gamma)$ represents the total quantity

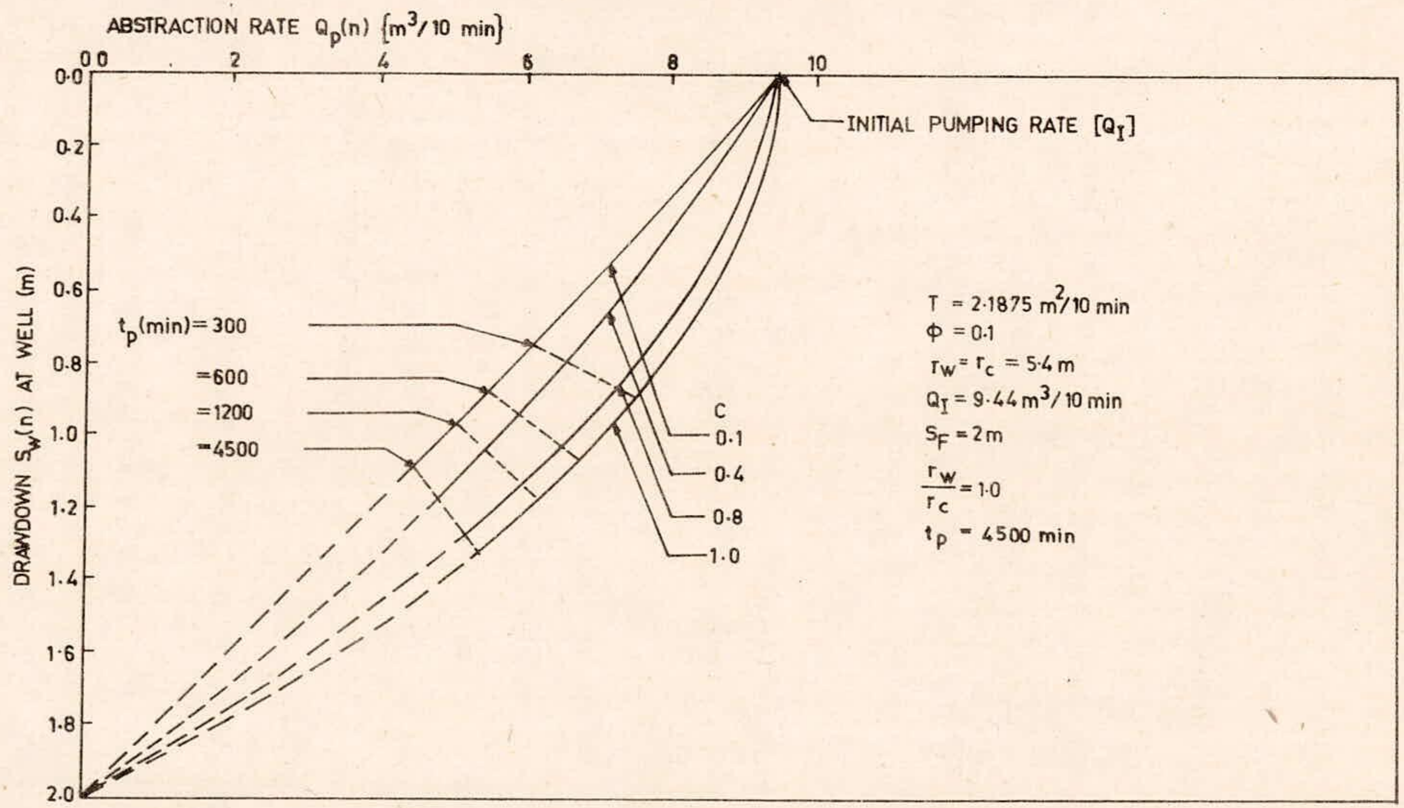

FIG.4 - VARIATION OF $Q_p(n)$ WITH $S_w(n)$

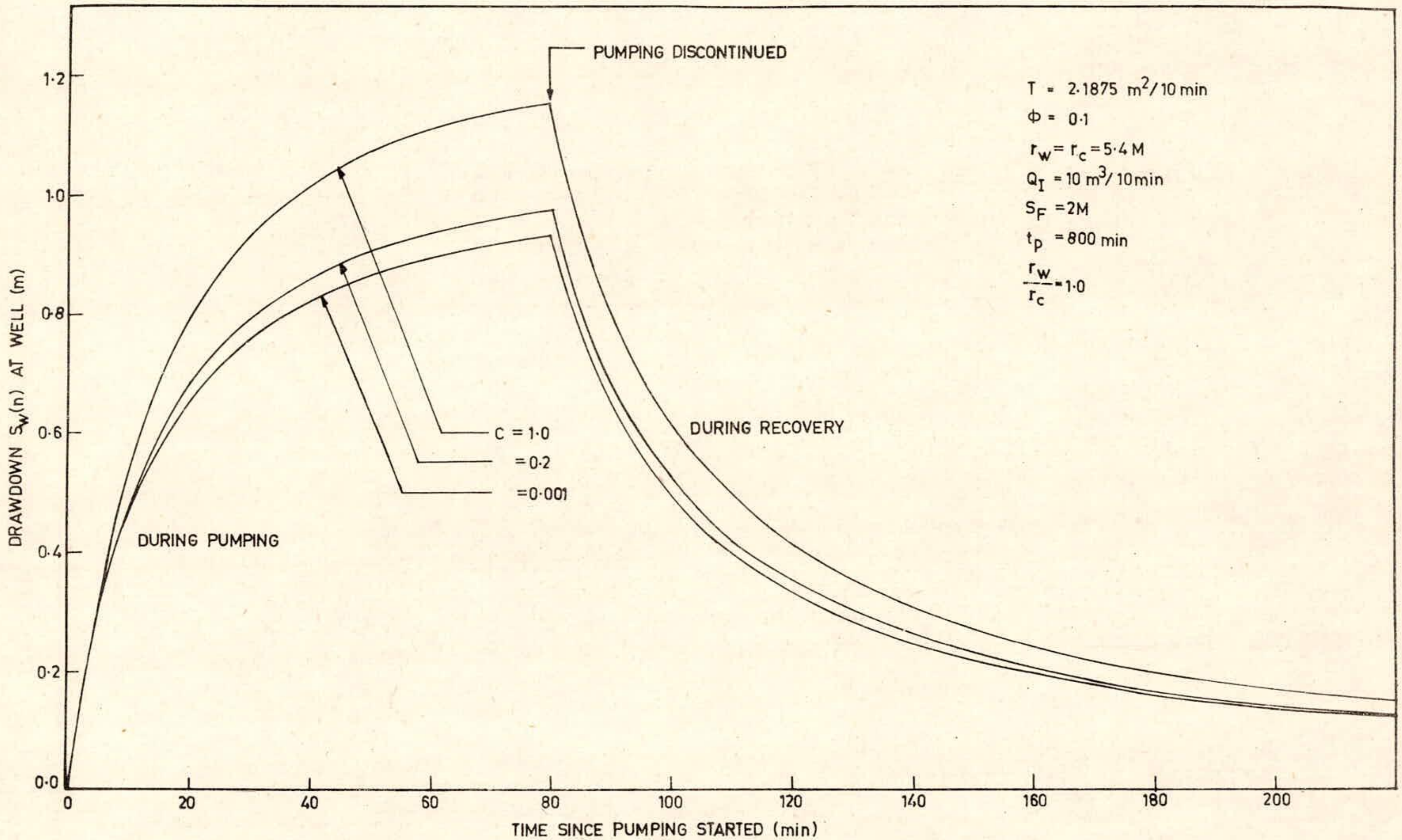

FIG.5 - VARIATION OF DRAWDOWN $S_w(n)$ WITH TIME

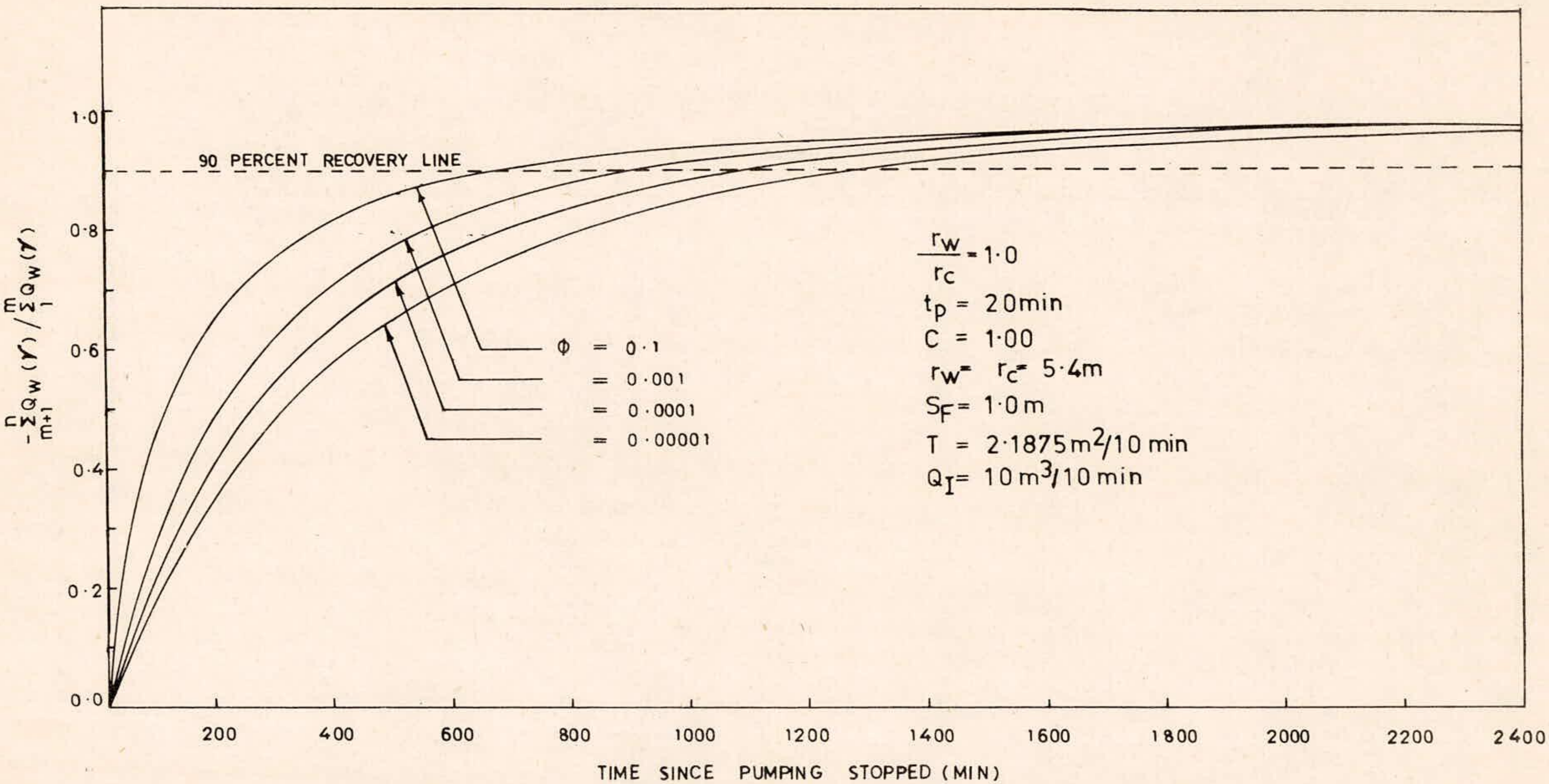

FIG.6(a) - RECOVERY OF WELL STORAGE WITH TIME FOR r_w/r_c = 1.0 AND t_p = 20 MINUTES

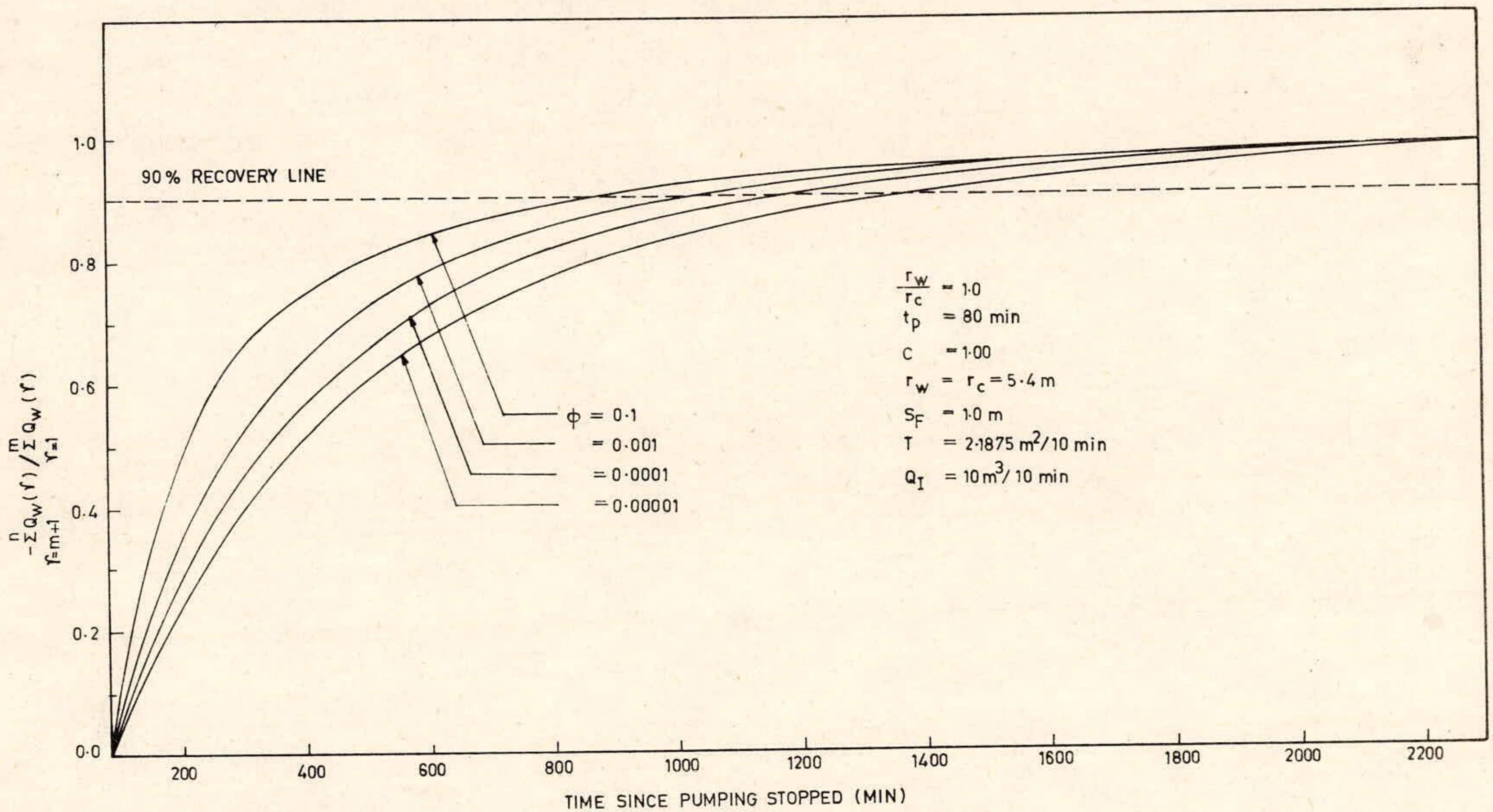

FIG.6(b) - RECOVERY OF WELL STORAGE WITH TIME FOR $r_w/r_c = 1.0$ AND $t_p = 80$ MINUTES

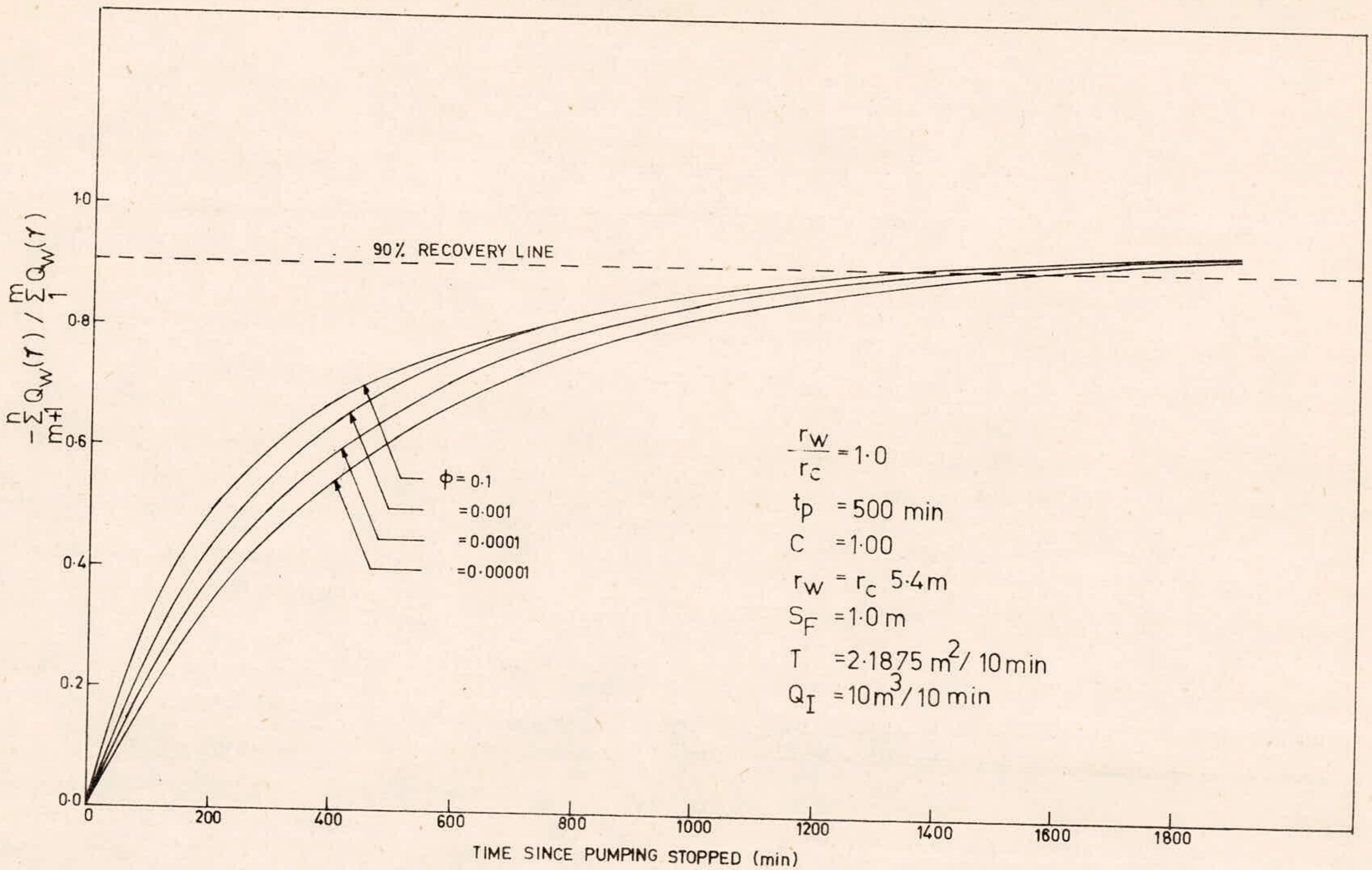

FIG.6(c) - RECOVERY OF WELL STORAGE WITH TIME FOR $r_w/r_c = 1.0$ AND $t_p = 500$ MINUTES

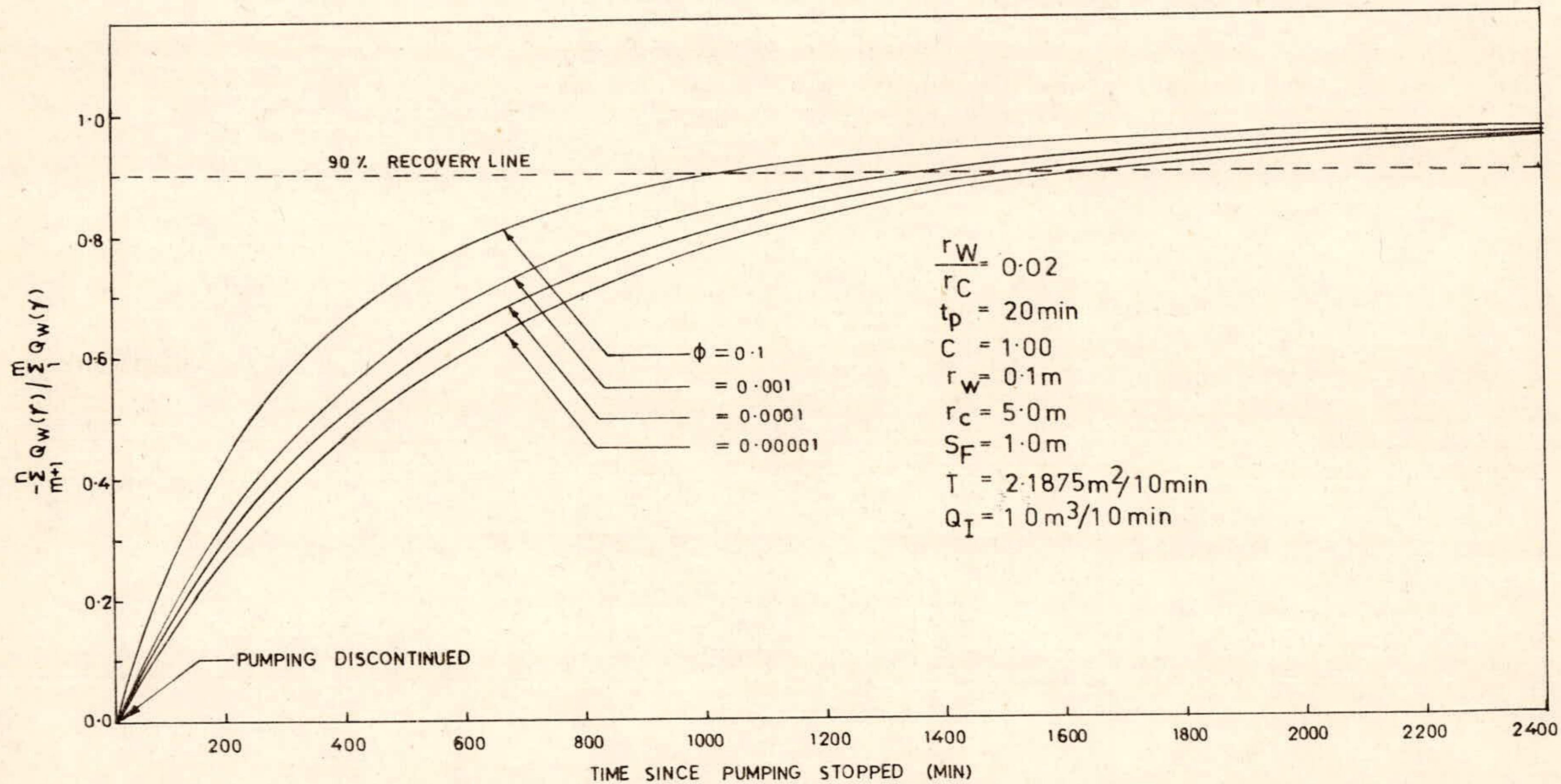

FIG.6(d) - RECOVERY OF WELL STORAGE WITH TIME FOR r_w/r_c = 0.02 AND t_p = 20 MINUTES

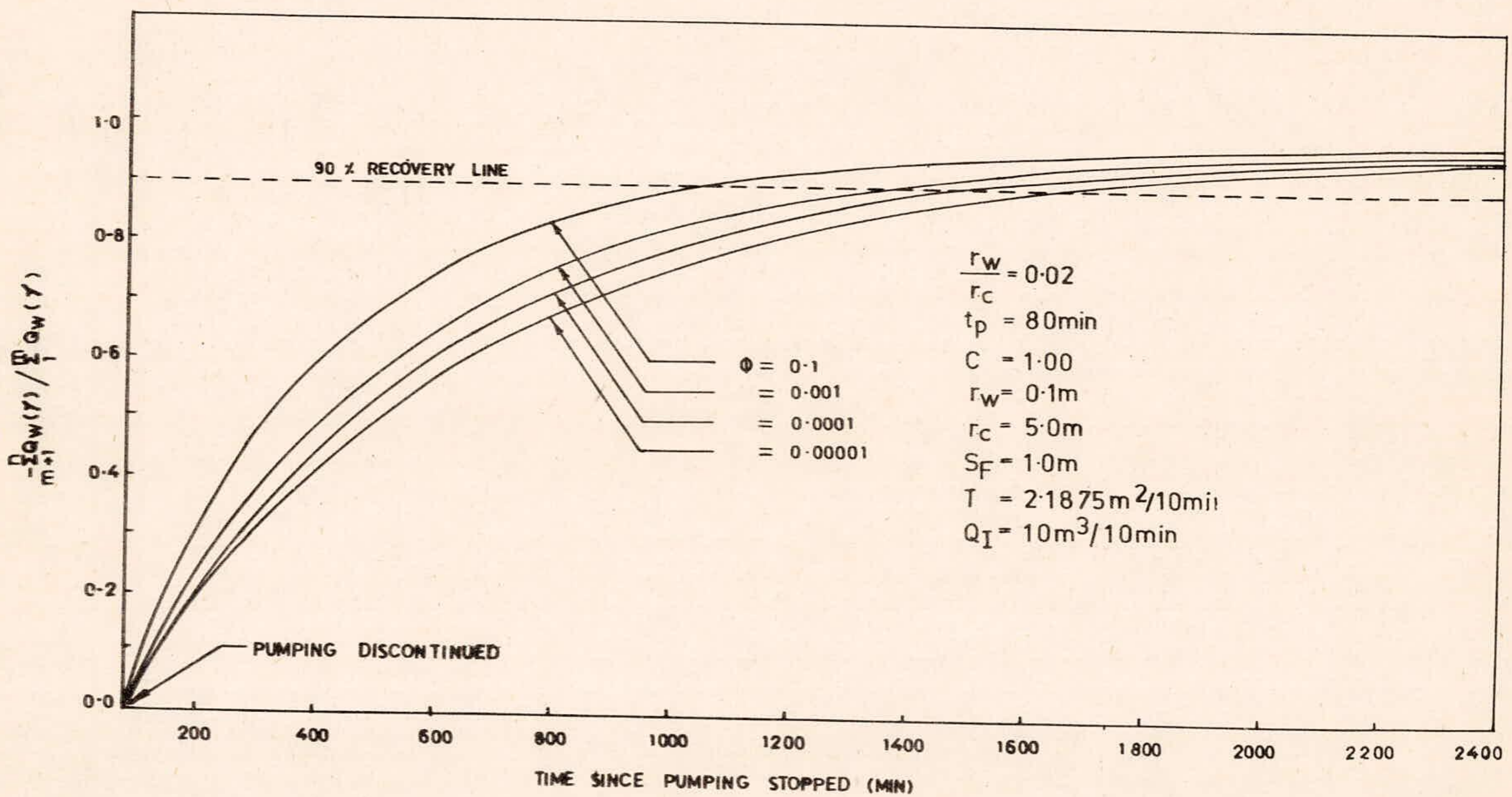

FIG.6(e) - RECOVERY OF WELL STORAGE WITH TIME FOR $r_w/r_c = 0.02$ AND $t_p = 80$ MINUTES

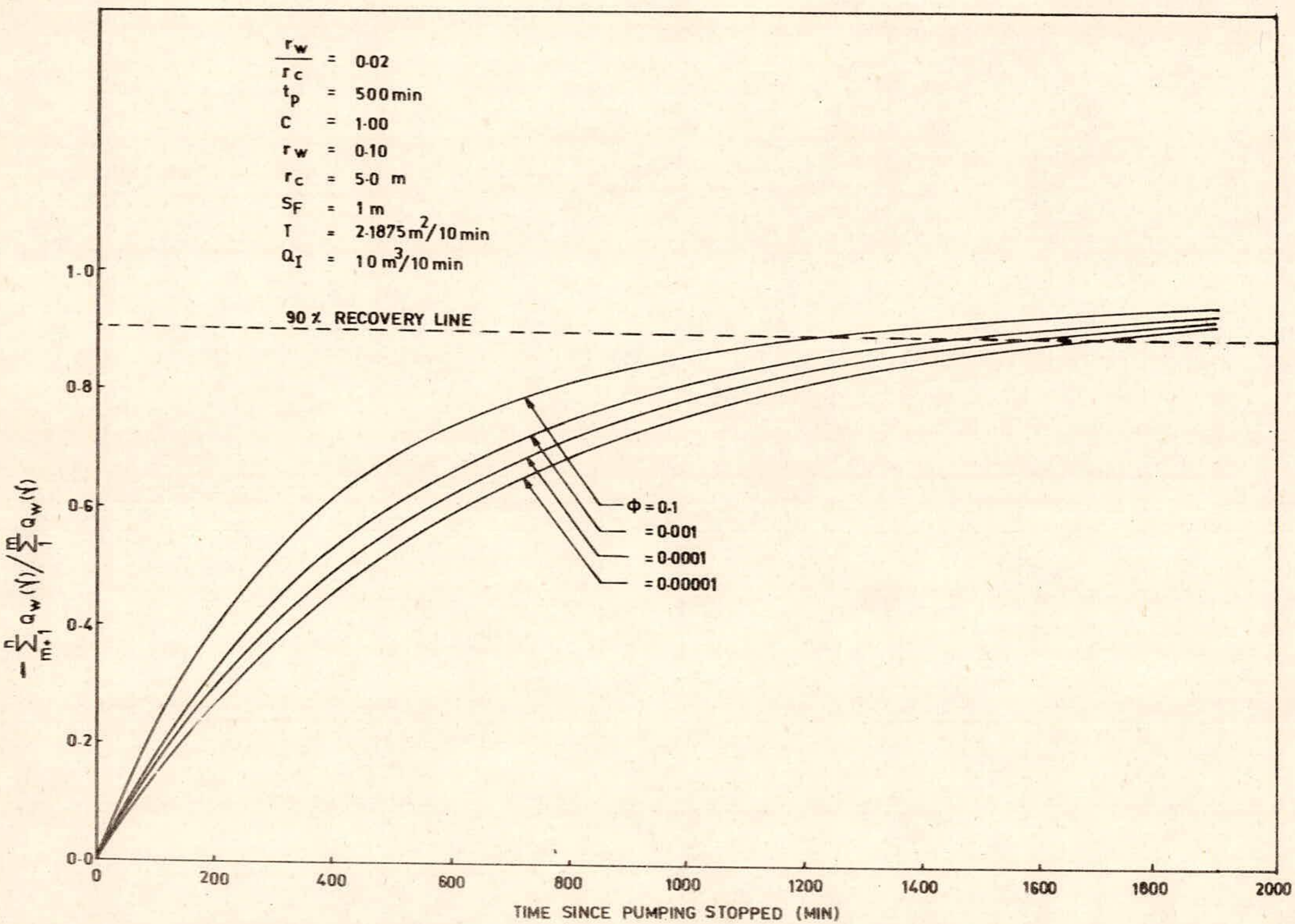

FIG.6(f) - RECOVERY OF WELL STORAGE WITH TIME FOR $r_w/r_c = 0.02$ AND $t_p = 500$ MINUTES recouped up to time step n during recovery. It can be seen from the figures that smaller the value of ϕ longer will be the duration for 90 percent recovery. Recovery rate is rapid for higher values of ϕ . For $\phi = 0.1$, the 90 percent recovery occurs at 850 minutes after the stoppage of pumping. For ϕ = 0.00001 the corresponding time is 1350 minutes (Fig. 6 b). It is also seen from the figures that for higher values of t_p and smaller ratio of r_w/r_c the 90 percent recovery of well storage takes longer time.

The productivity of a well is often expressed in terms of the specific capacity, which is defined as $Q_P(n)/S_w(n)$, where $Q_P(n)$ is the pumping rate and $S_w(n)$ is the drawdown at the end of time step n. In other words specific capacity is the discharge per unit drawdown and it is time variant. The variation of specific capacity with time for the cases where the pumping rates are either a quadratic function or a linear function of drawdown are shwon in Fig.7 for different well storages. It is seen from the figure that the specific capacity decreases with increase in the time. As seen from the figure the specific capacity becomes asymptotic to abscissa indicating that a near stready state condition has been reached. Higher the storage coefficient higher will be the specific capacity.

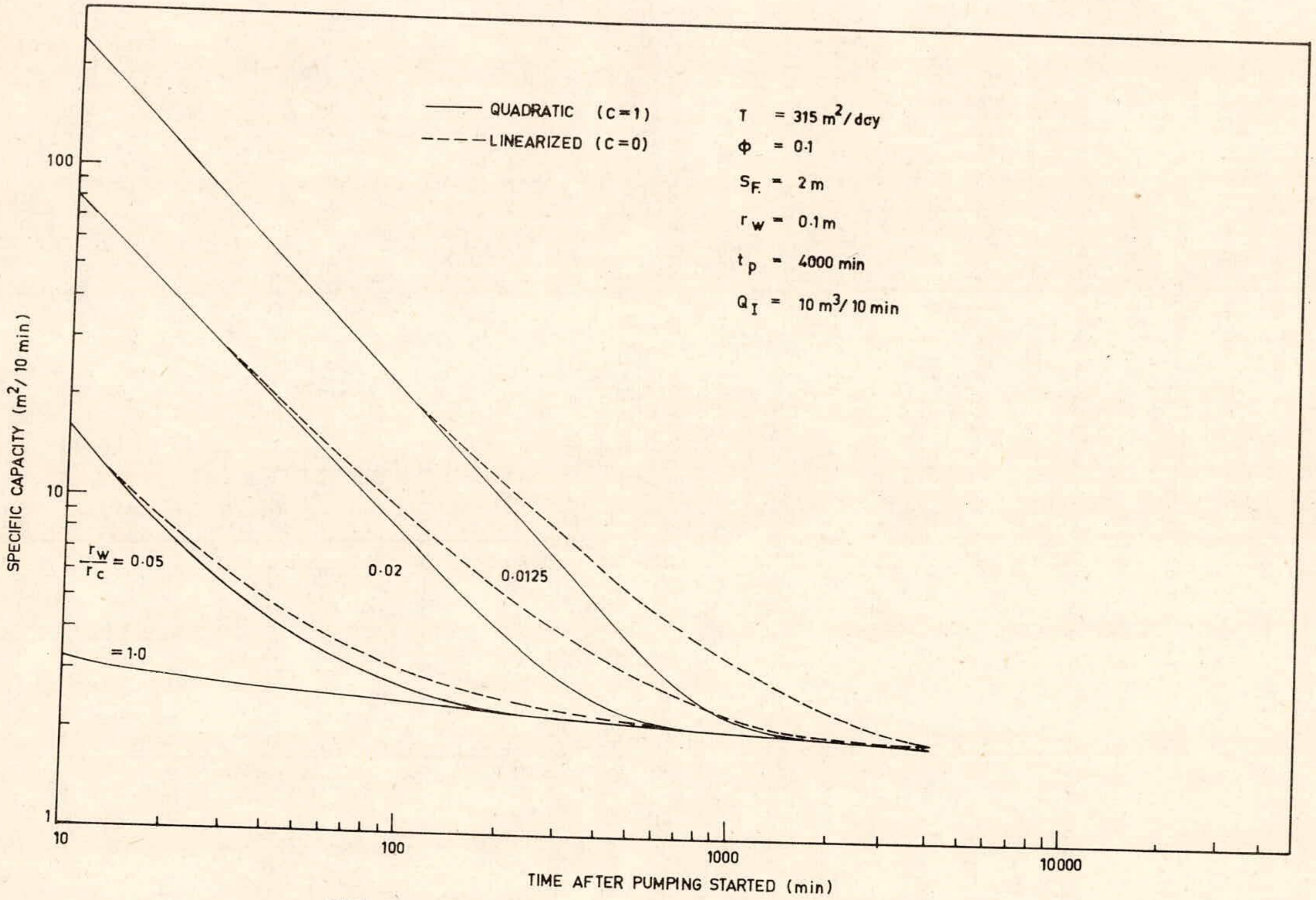

FIG.7 - VARIATION OF SPECIFIC CAPACITY WITH TIME

In many cases, especially, in reconnaissance groundwater investigations, the hydrogeologic parameters of an aquifer are estimated based on well-log, water level, and specific capacity data. High specific capacities usually indicate a high transmissivity. For a quick estimate of transmissivity, an examination of the relation between the transmissivity, and specific capacity is useful. The relationship between the specific capacity and transmissivity for a large-diameter well is shown in Fig.8 (b) through 8(g) for the case where the $Q_P(n)$ is a quadratic function of the drawdown. Pumping periods of 1, 2, 3, 4, 5, 6, and 7 hours, ϕ = 0.2, 0.15, 0.1, 0.05, 0.01, 0.005 and 0.001, S_F = 2 m, and Q_I = 800 m^3/day have been assumed in constructing the graphs. These graphs may be used to obtain rough estimates of the transmissivity from specific capacity data for a large-diameter well. The coefficient of storage could be estimated from well log and water level fluctuation data.

4.2 Design of Large-Diameter Well

The variation of the maximum drawdown ($D-S_O$) with r_c are presented in Figs.9 (a) through 9(h) for values of T ranging from 1 m^2/day to 1000 m^2/day and for ϕ = 0.1, Q=500 m^3/day and t_p= 4,6,8 and 12 hours. It is seen from the figures that for transmissivity values greater than 100 m^2/day the variation in drawdown for different values of t_p and r_c are small

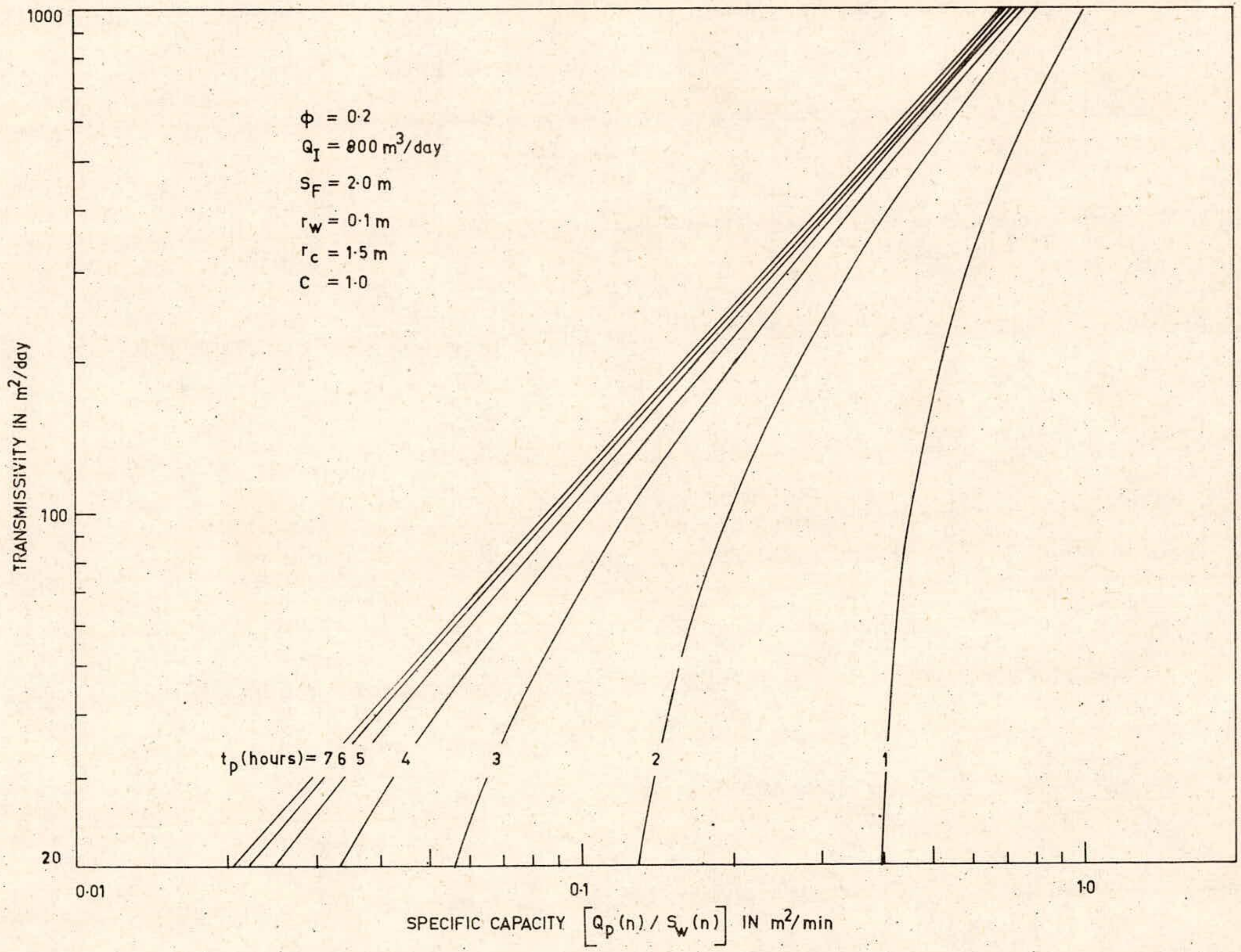

FIG.8(a) - PLOT OF TRANSMISSIVITY VERSUS SPECIFIC CAPACITY WHEN THE ABSTRACTION RATE IS QUADRATIC FUNCTION OF DRAWDOWN FOR ϕ = 0.2

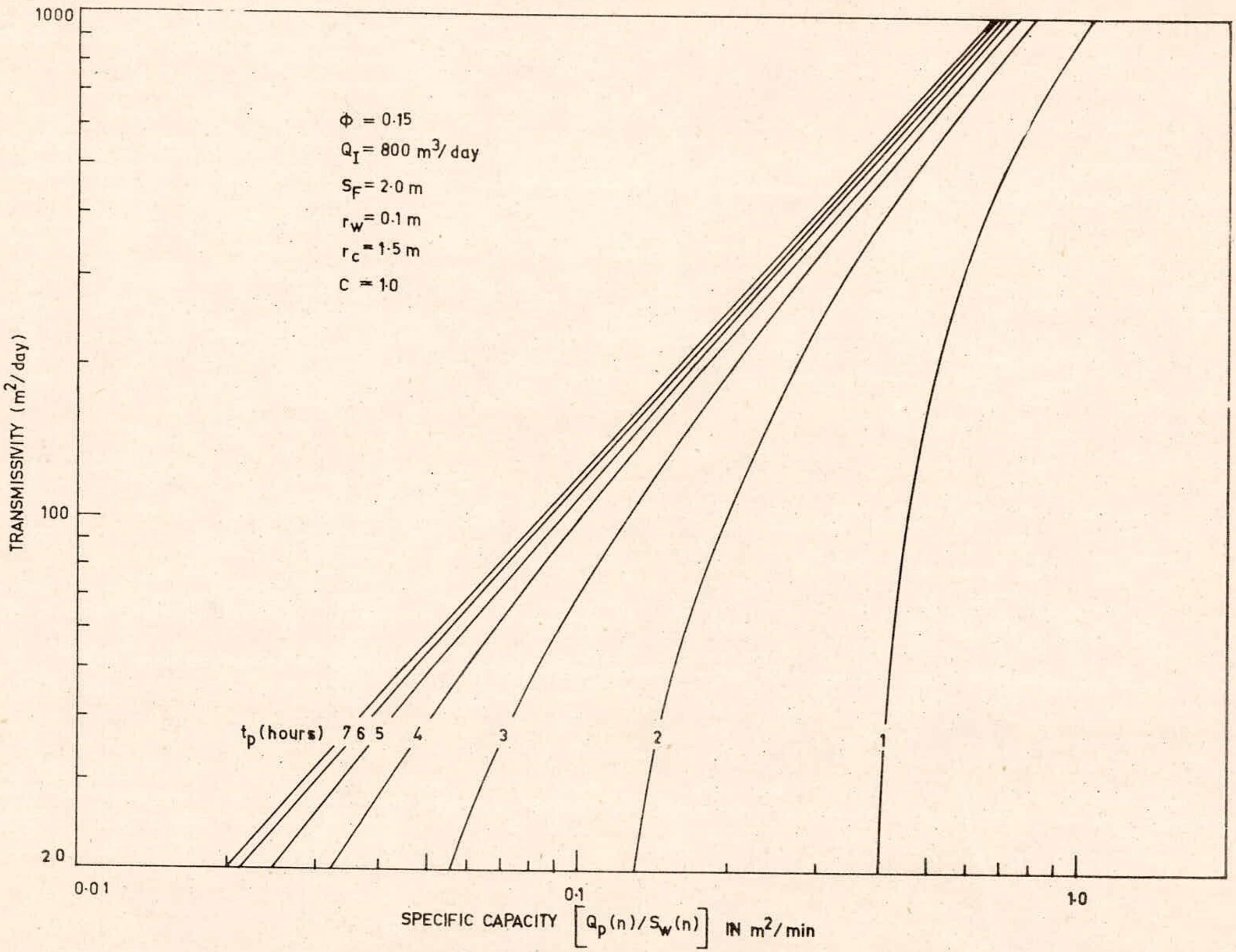

FIG. 8(b) - PLOT OF TRANSMISSIVITY VERSUS SPECIFIC CAPACITY WHEN THE ABSTRACTION RATE IS QUADRATIC FUNCTION OF DRAWDOWN FOR $\phi = 0.15$

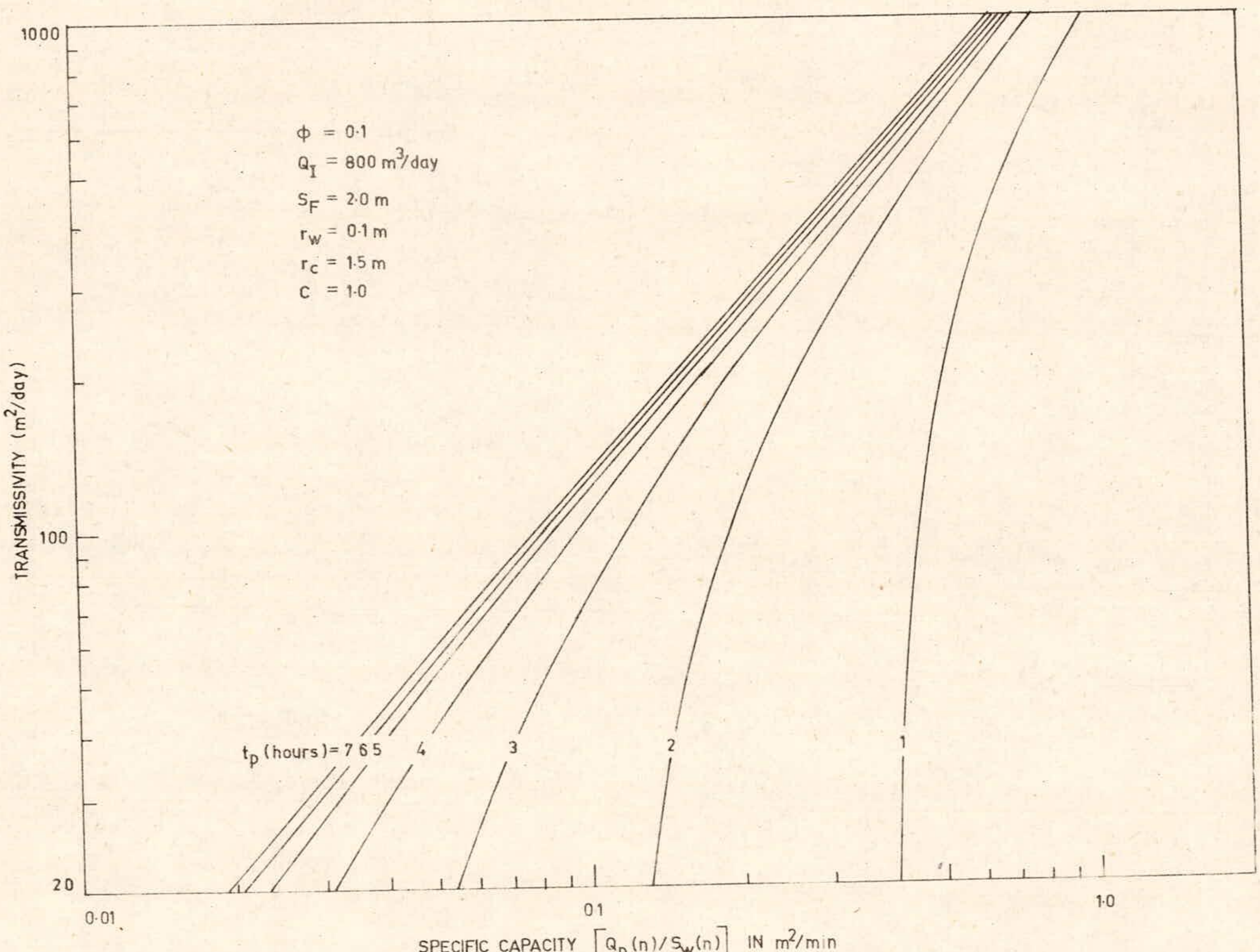

FIG. 8(c) - PLOT OF TRANSMISSIVITY VERSUS SPECIFIC CAPACITY WHEN THE ABSTRACTION RATE IS QUADRATIC FUNCTION OF DRAWDOWN FOR $\phi = 0.1$

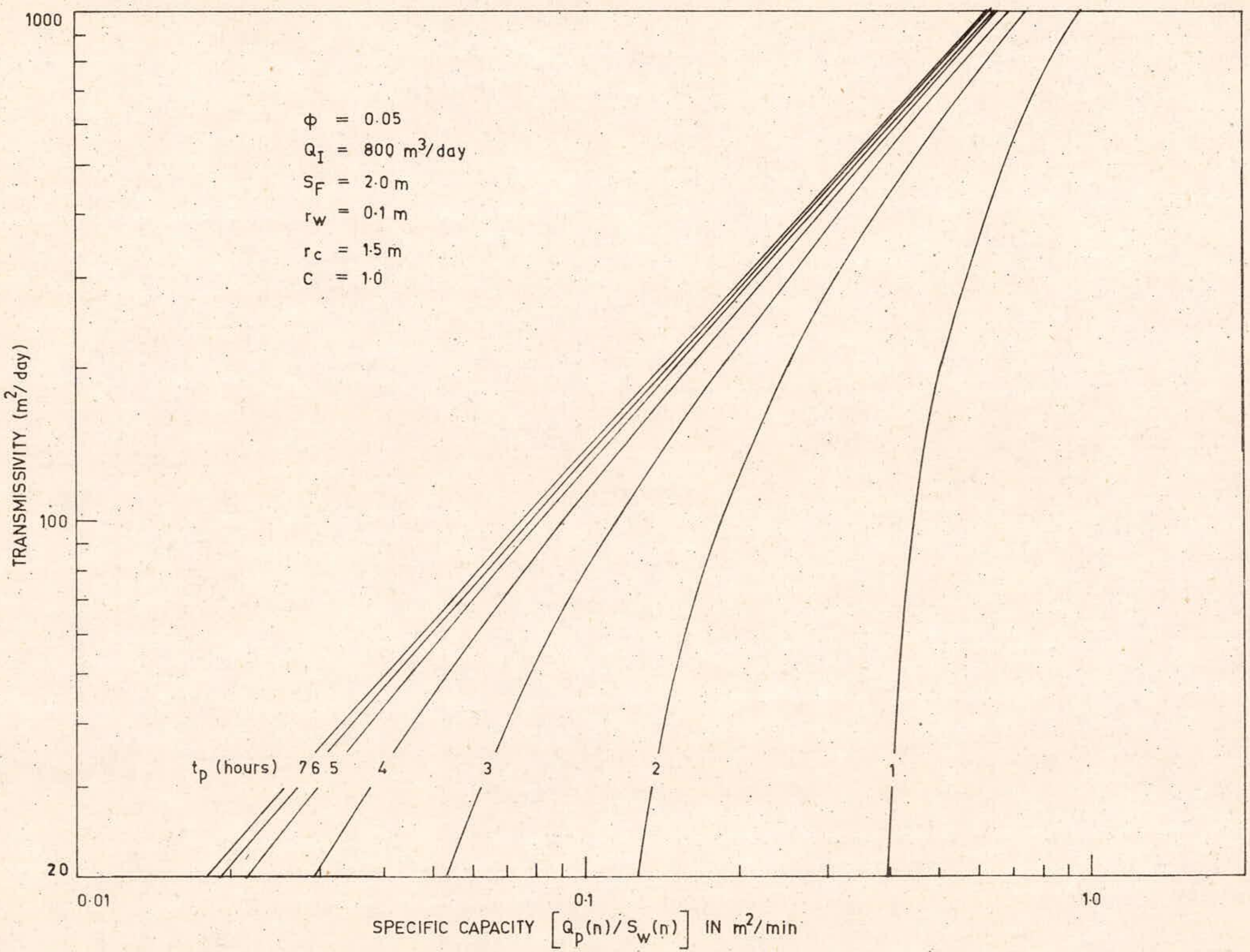

FIG. 8(d) - PLOT OF TRANSMISSIVITY VERSUS SPECIFIC CAPACITY WHEN THE ABSTRACTION RATE IS QUADRATIC FUNCTION OF DRAWDOWN FOR $\phi = 0.05$

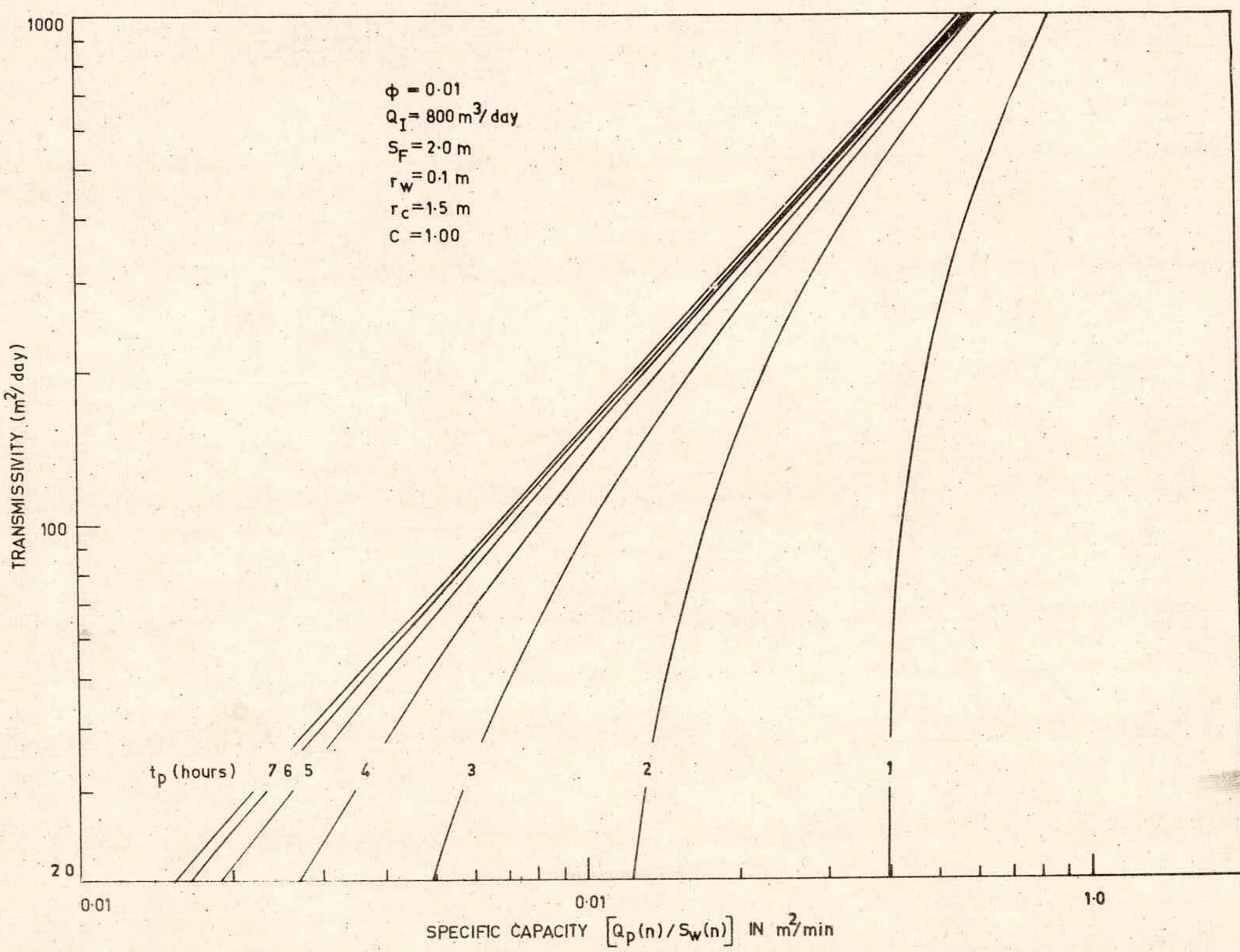

FIG. 8(e) - PLOT OF TRANSMISSIVITY VERSUS SPECIFIC CAPACITY WHEN THE ABSTRACTION RATE IS QUADRATIC FUNCTION OF DRAWDOWN FOR ϕ = 0.01

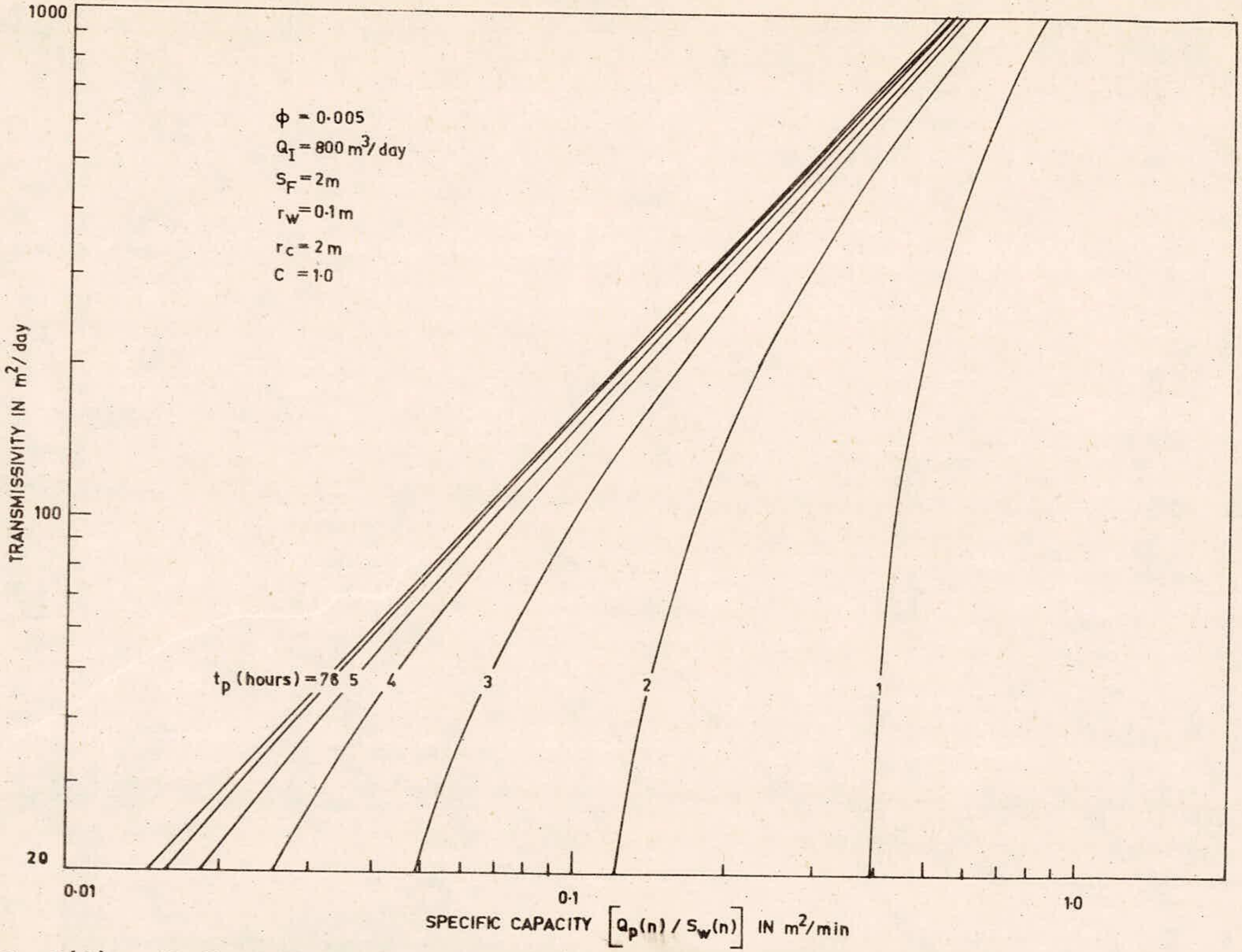

FIG. 8(f) - PLOT OF TRANSMISSIVITY VERSUS SPECIFIC CAPACITY WHEN THE ABSTRACTION RATE IS QUADRATIC FUNCTION OF DRAWDOWN FOR ϕ = 0.005

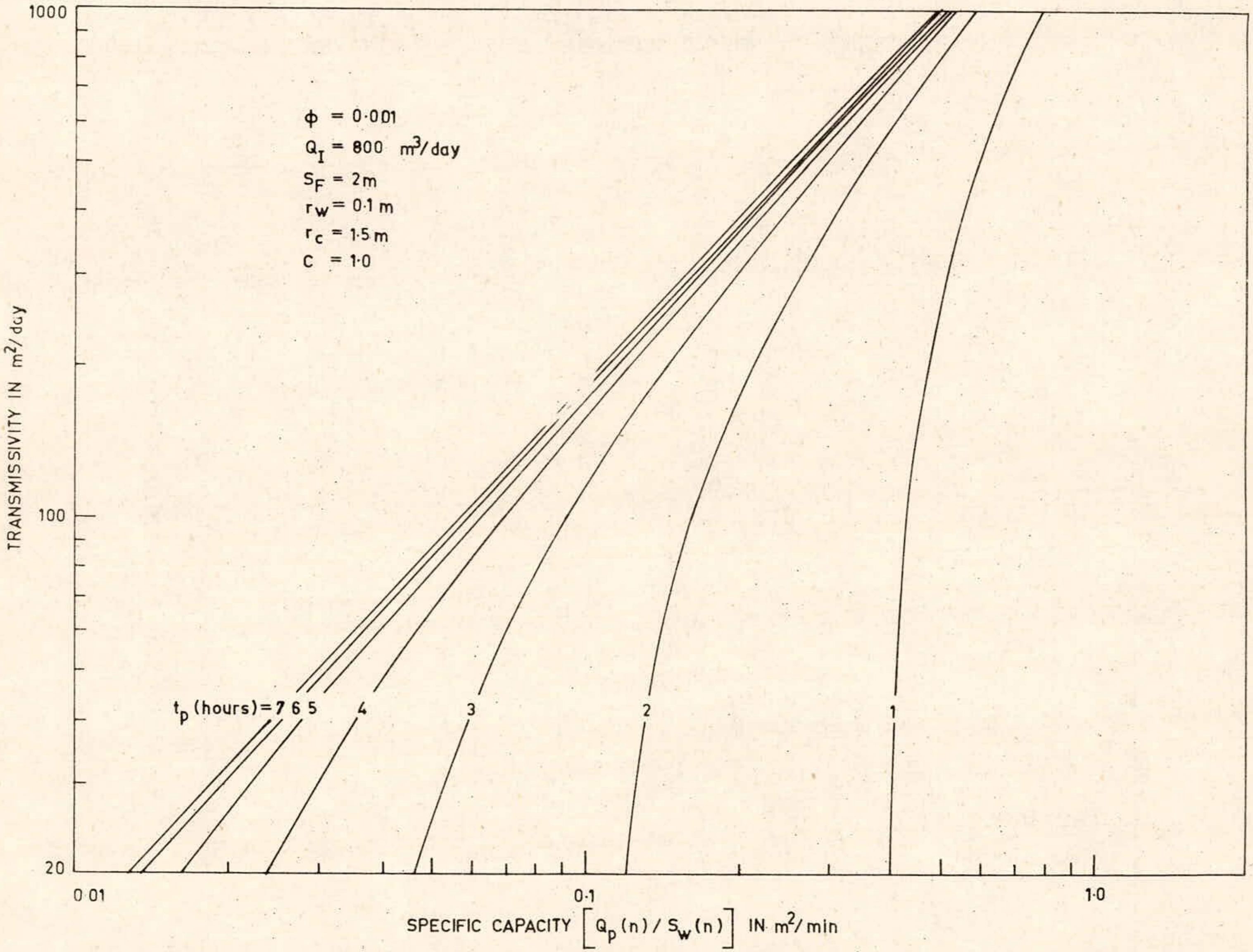

FIG. 8(g) - PLOT OF TRANSMISSIVITY VERSUS SPECIFIC CAPACITY WHEN THE ABSTRACTION RATE IS QUADRATIC FUNCTION OF DRAWDOWN FOR $\phi = 0.001$

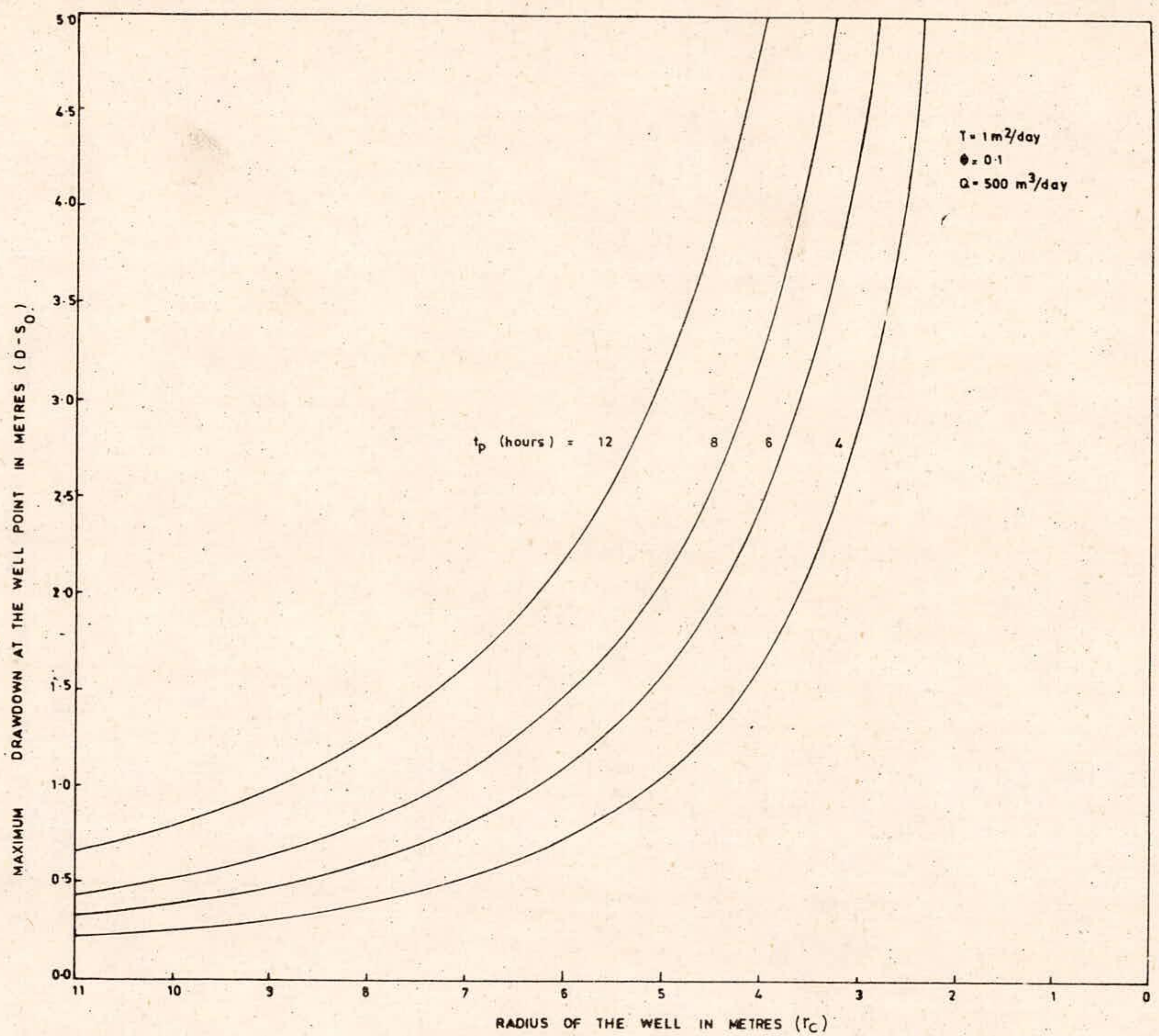

FIG. 9(a) - PLOT OF MAXIMUM DRAWDOWN VERSUS RADIUS OF THE WELL FOR T = 1 m^2/DAY AND VARIOUS DURATION OF PUMPING

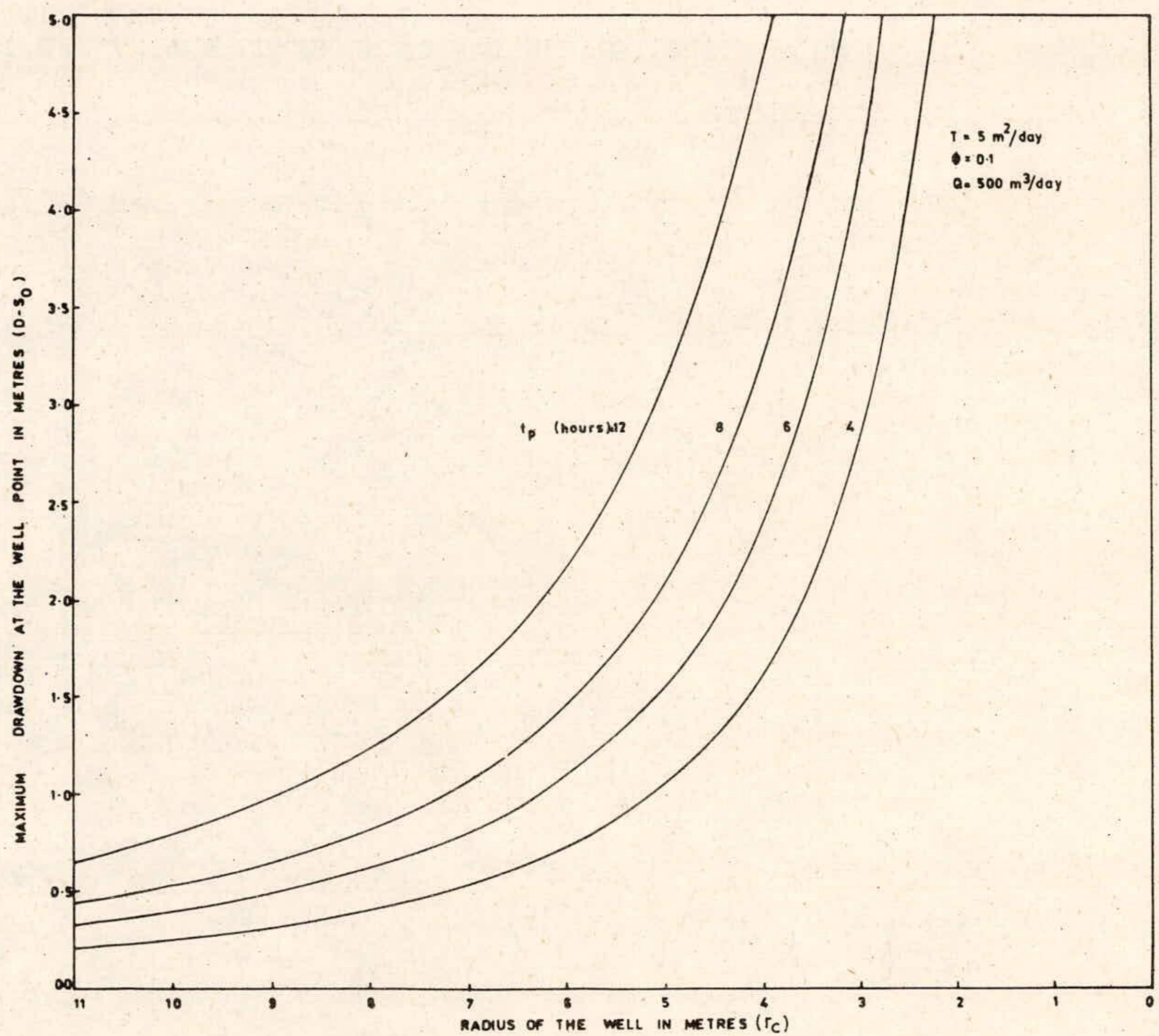

FIG. 9(b) - PLOT OF MAXIMUM DRAWDOWN VERSUS RADIUS OF THE WELL FOR T = 5 m^2/DAY AND VARIOUS DURATION OF PUMPING

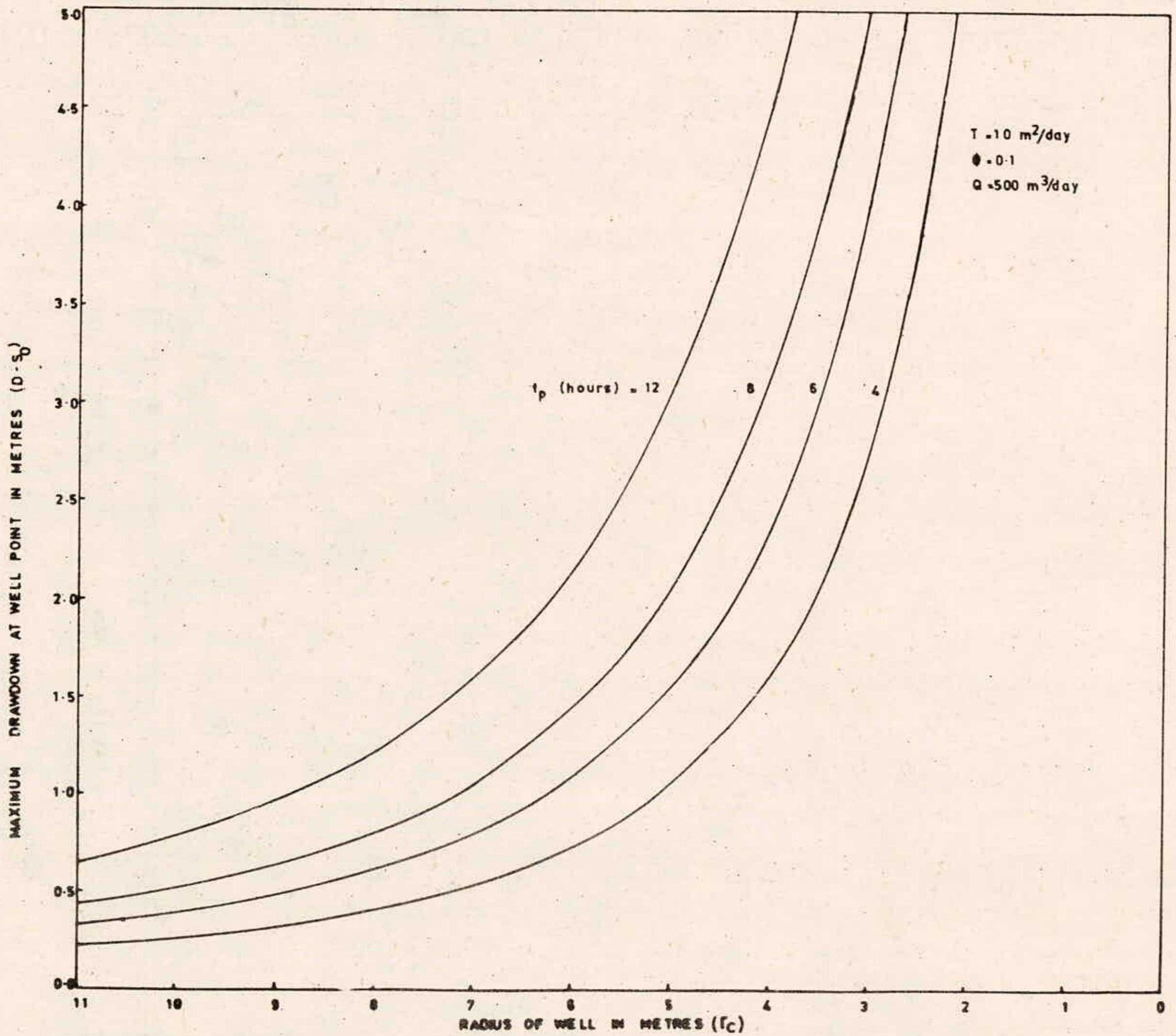

FIG. 9(c) - PLOT OF MAXIMUM DRAWDOWN VERSUS RADIUS OF THE WELL FOR T = 10 m^2/DAY AND VARIOUS DURATION OF PUMPING

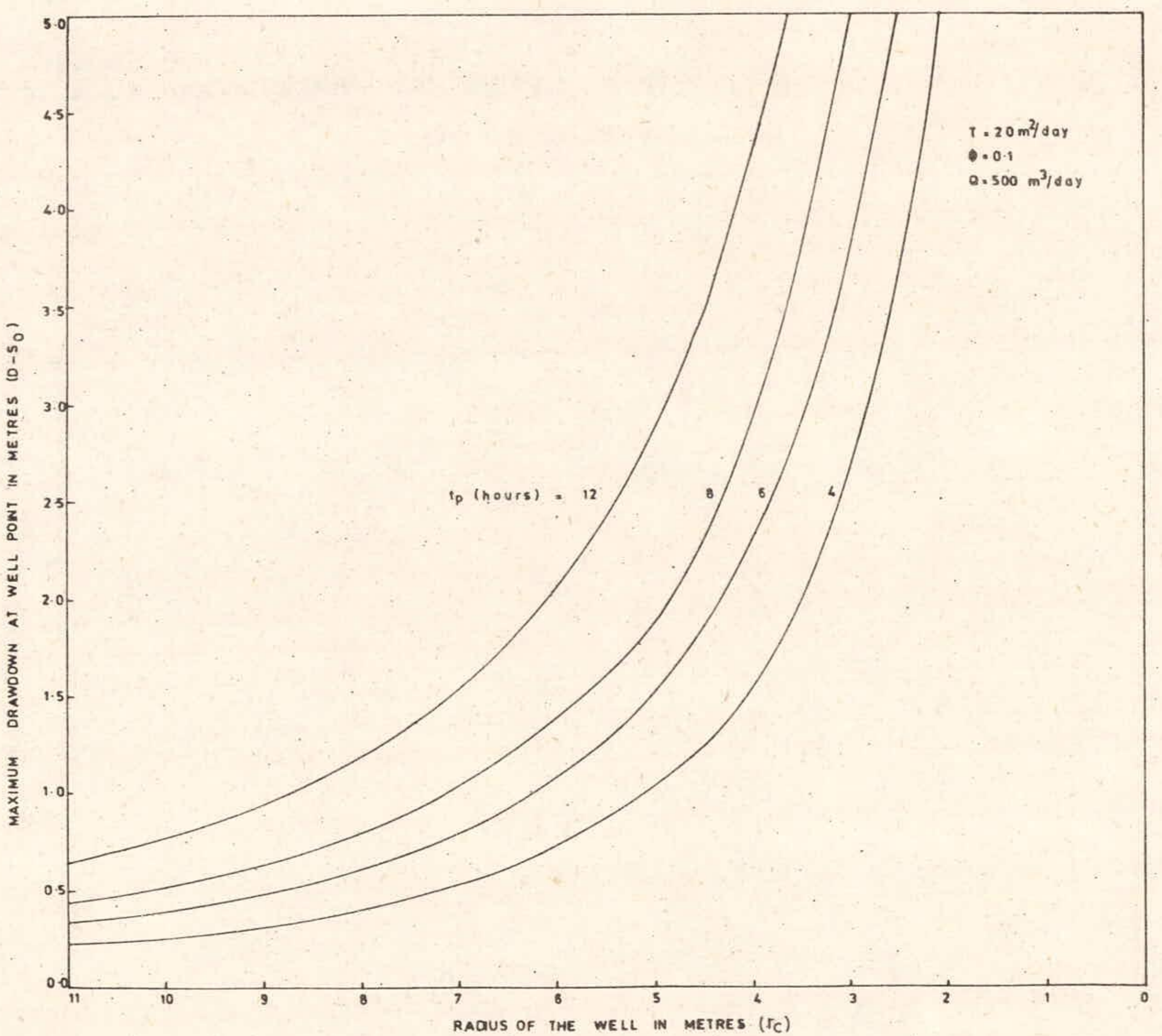

FIG. 9(d) - PLOT OF MAXIMUM DRAWDOWN VERSUS RADIUS OF THE WELL FOR T = 20 m^2/DAY AND VARIOUS DURATION OF PUMPING

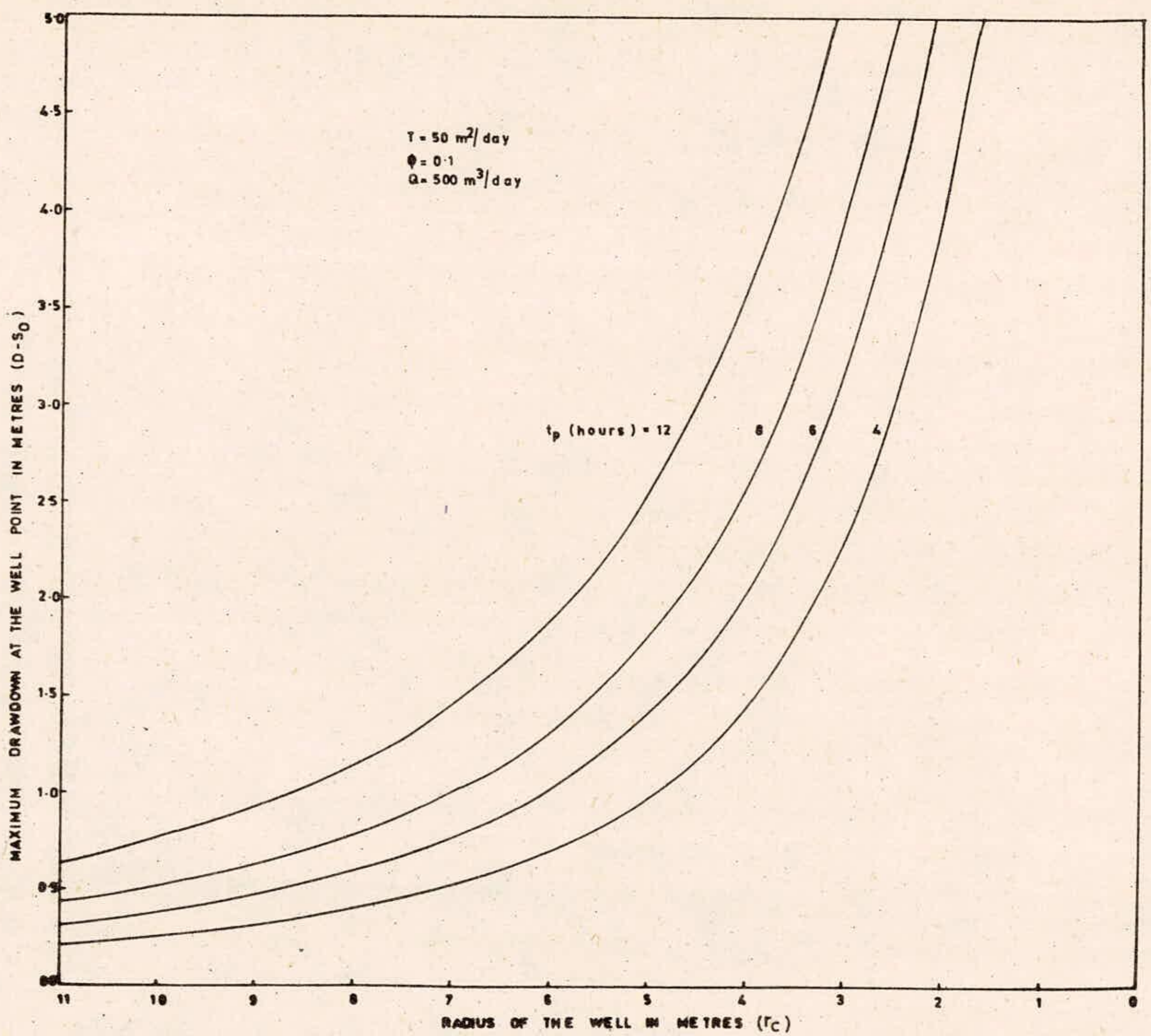

FIG. 9(e) - PLOT OF MAXIMUM DRAWDOWN VERSUS RADIUS OF THE WELL FOR T = 50 m^2/DAY AND VARIOUS DURATION OF PUMPING

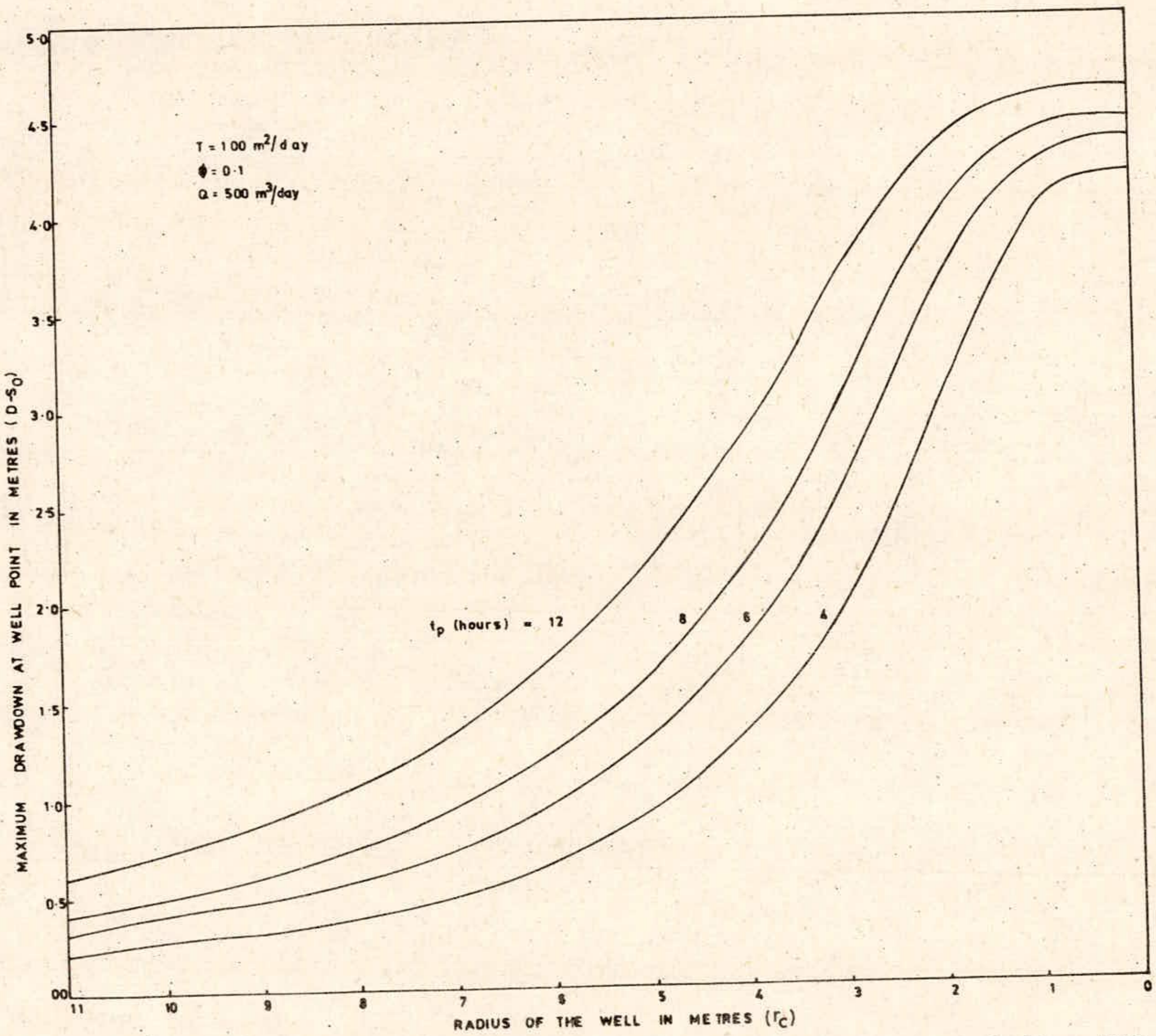

FIG. 9(f) - PLOT OF MAXIMUM DRAWDOWN VERSUS RADIUS OF THE WELL FOR T = 100 m^2/DAY AND VARIOUS DURATION OF PUMPING

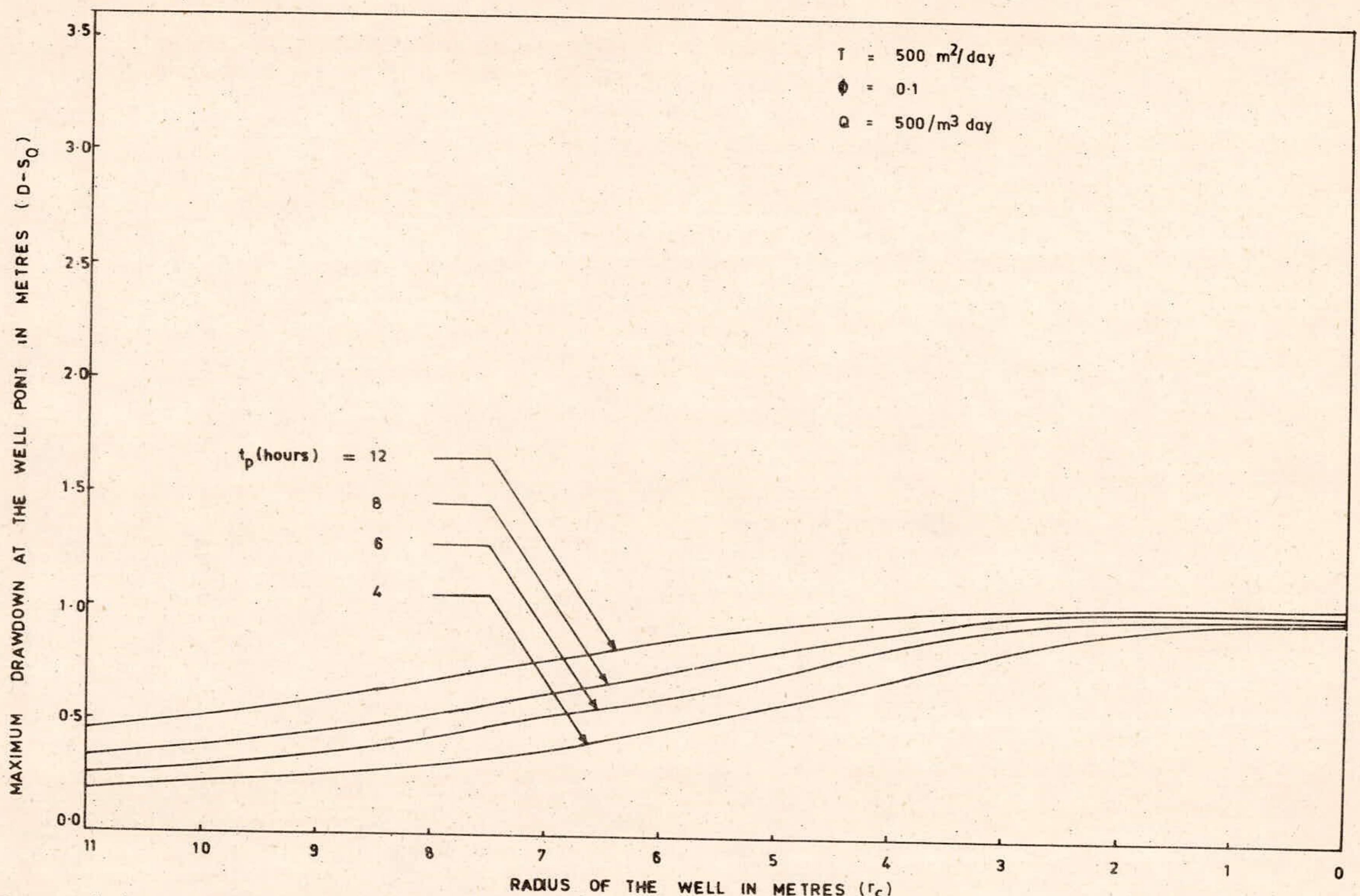

FIG. 9(g) - PLOT OF MAXIMUM DRAWDOWN VERSUS RADIUS OF THE WELL FOR T = 500 m^2/DAY AND VARIOUS DURATION OF PUMPING

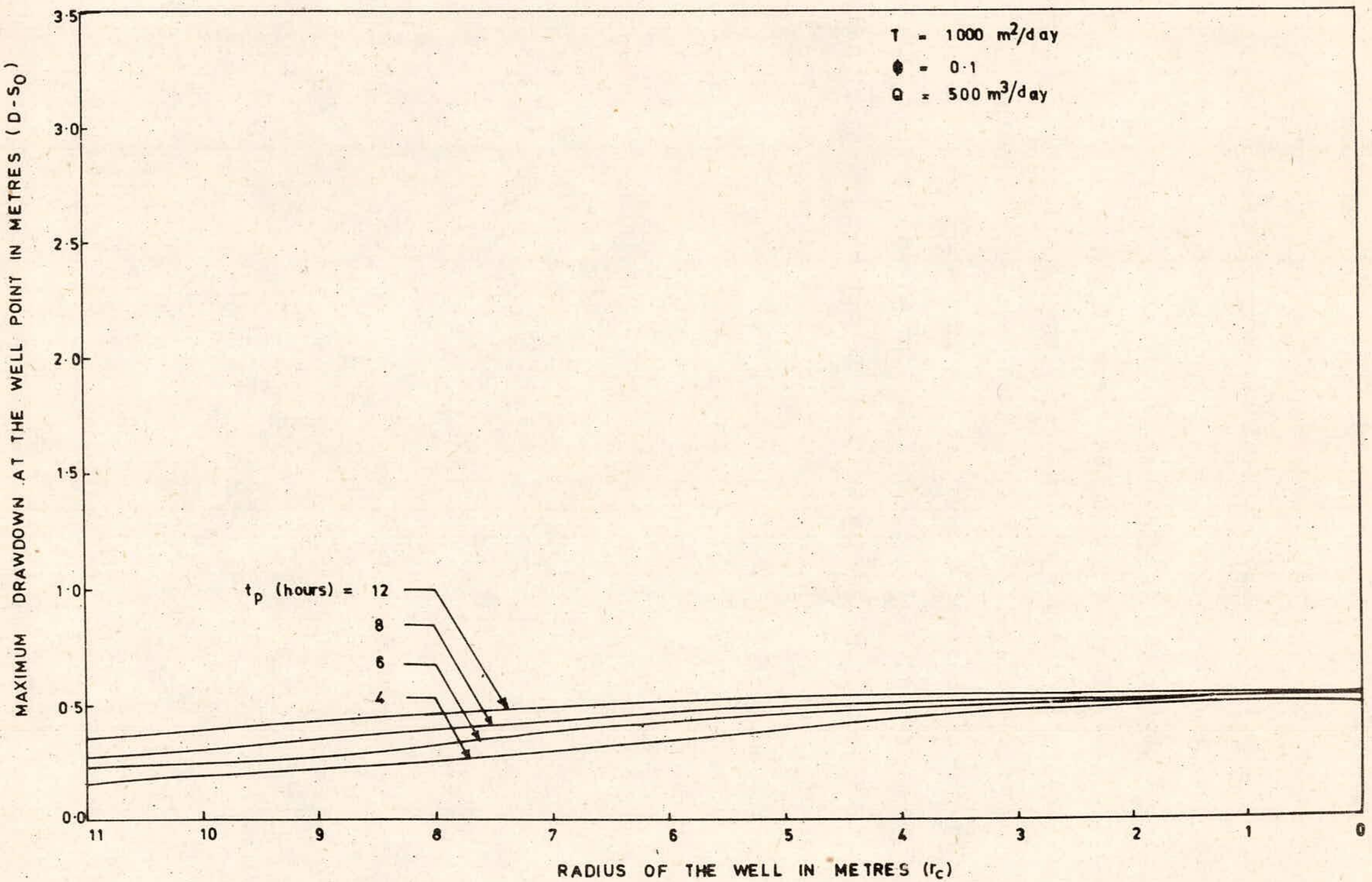

FIG. 9(h) - PLOT OF MAXIMUM DRAWDOWN VERSUS RADIUS OF THE WELL FOR T = 1000 m^2/DAY AND VARIOUS DURATION OF PUMPING

Therefore, large-diameter wells will have no additional benefits if constructed in an area having high values of T. These graphs can be used to find the set of values of r_c and D for the given set of T, ϕ, t_p, Q and S_o. The r_c and D set is one of the inputs for estimating the cost of excavation by equation (16). Table 1 shows the costs of excavation for different sets of depth and radius of the well for m'=2 (Rs/m^5) n' = 2, PRICE-1.7(Rs.)/Kg., CROP=0.08 kg/m^2 and RATE=10%. In Fig. 10 the cost of excavation are indicated for different sets of depth and radius of the well for given T, ϕ, t_p, Q, S_o. It is seen from the figure that the optimum depth (D) and radius (r_c) for which cost of excavation is minimum are 8.5 m and 3.1 m respectively.

TABLE COST OF EXCAVATION FOR DIFFERENT DEPTHS AND RADII OF THE WELL FOR $C_o = 6\,(Rs)/m^3$, $m' = 2\,(Rs/mm^5)$, CROP=0.08 kg-m^2, PRICE = 1.7/kg, $S_o = 5$ m, RATE=10% and $n' = 2$.

Depth from ground (m)	Radius (m)	Cost of excavation (Rs.)
5.25	12.00	58,450
5.50	9.00	36,936
5.75	7.25	26,829
6.00	6.25	22,241
6.25	5.60	19,851
6.50	5.10	18,248
6.75	4.70	17,125
7.00	4.30	15,794
7.25	4.05	15,396
7.50	3.80	14,856
7.75	3.60	14,578
8.00	3.40	14,184
8.25	3.25	14,105
8.50	3.10	13,937
8.75	3.00	14,147
9.00	2.90	14,300
9.25	2.80	14,393
9.50	2.70	14,424
9.75	2.61	14,502
10.00	2.52	14,522

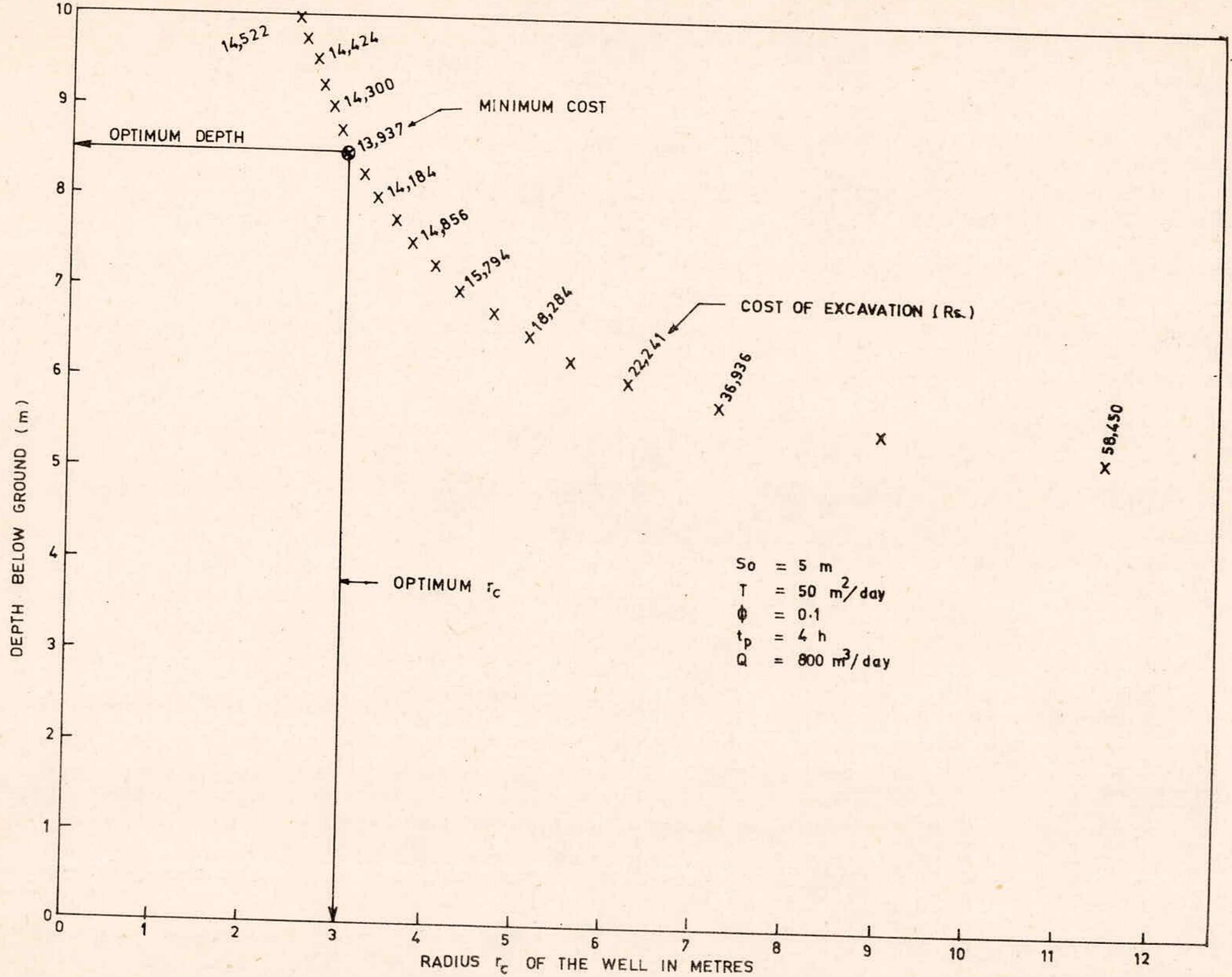

FIG. 10 - COST OF EXCAVATION OF LARGE-DIAMETER WELL AT DIFFERENT DEPTHS AND WELL RADII FOR A SET OF T, Ø, S_o, t_p and Q

5.0 CONCLUSIONS

Unsteady flow to a large-diameter well in a confined aquifer has been analysed by discrete kernel approach for a case where the pumping rate is a quadratic function of drawdown. Tractable analytical expressions have been obtained for determining aquifer contribution, well storage contribution and drawdown at any point in the aquifer. The time for 90 percent recovery of well storage for various values of storage coefficient, t_p and r_w/r_c has been presented. The graphs showing variation of transmissivity with specific capacity at different time after onset of pumping have been presented to facilitate rough estimate of transmissivity.

Analysis for the design of large-diameter well has been done. The optimum depth and radius of the large-diameter well for which the cost of excavation is minimum can be found by adopting the procedure suggested. Construction of large-diameter wells in areas having transmissivity greater than 100 m^2/day will not be beneficial.

REFERENCES

Baweja, B.K.,1979. Hydrogeological set up of India and status of work of the Central Ground Water Board. Lecture delivered at UNESCO regional training course at N.G.R.I., Hyderabad.

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, Vol.30,pp.29-46.

Carslaw,H.S., and J.C. Jaeger, 1959. Conduction of heat in soils, Oxford University Press, N.Y.

Herbert, R., and R. Kitching, 1981. Determination of aquifer parameters from large-diameter dug well pumping tests. Ground Water, Vol.19, pp.593-599.

Ilaco, B.V. (Edited), 1981. Agricultural compendium for Rural Development in the tropics and subtropics. Elsvier Scientific Publishing Company, New York.

Jain, J.K., 1977. Underground water resources. Phil.Trans. R.Soc.,Lon.B.278,pp.507-524.

Lahiri,A., 1975. A long range perspective for India, water resources - 2000 A.D. Publication, operation research group, Baroda, India,p.43.

Lai, R.Y.S., and Cheh-Wu Su,1974. Non-steady flow to a large well in a leaky aquifer. Journal of Hydrology, Vol.22, pp.333-345.

Morel-Seytoux, H.J., 1975. Optimal legal conjunctive operation of surface and ground water. Second World Congress, International Water Resources Association, New Delhi, Vol.IV pp.119-129.

Morel-Seytoux, H.J., and C.J. Daly., 1975. A discrete kernel generator for stream aquifer studies. Water Resources Research, Vol.II, No.2, pp.253-260.

Mishra, G.C. and A.G.Chachadi, 1985. Analysis of unsteady flow to a large-diameter well. International Workshop on 'Rural Hydrogeology and Hydraulics in Fissured Basement Zones', Dept. of Earth Sciences, University of Roorkee, Roorkee, Feb.1985.

Mishra, G.C. and A.G. Chachadi, 1985. Analysis of flow to a large-diameter well during the recovery period. Ground water, Vol.23, No.5, pp.646-651.

Papadopulos, I.S., and H.H.Cooper, 1976. Drawdown in a well of large diameter. Water Resources research, Vol.3, pp. 241-244.

Patel, S.C., and G.C. Mishra, 1983. Analysis of flow to a large-diameter well by a discrete kernel approach. Ground Water, Vol.21, No.5, pp.573-576.

Rushton, K.R., and S.M. Holt, 1981. Estimating aquifer parameters for large-diameter well. Ground Water, Vol.19, pp. 505-516.

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

```
C                                 APPENDIX-I
C------------------------------------------------------------------------------------------
C      THIS PROGRAM CALCULATES THE MAXIMUM DRAWDOWNS AT THE WELL
C      POINT FOR PUMPING TIME EQUAL TO 4,6,8 AND 12 HOURS FOR
C      DIFFERENT WELL RADII RC.
C
C
C        GROUND-------------^----            -------^-----------LEVEL
C                           SD   !             !       :
C        ...................X......................:..........SWL
C                           !    !             :       D
C      MAXIMUM DRAWDOWN =D-SD   !<----2RC--->!       :
C         (DRAMAX)              !    !             !       :
C      .....................X..........  .........X...............
C      IMPERVIOUS----------------------------------------------LAYER
C                                     : :
C                                     : :
C                    CONFINED         : :         AQUIFER
C                                     : :
C                                     : :
C         BED ------------------------------------------------ROCK
C
C
C
      DIMENSION DRW(500),QP(500),A(5,5),B(5),QA(500),QW(500),
     1 SW(500),SA(500),RC(20)
      OPEN(UNIT=5,FILE='WELDESIGN.DAT',STATUS='OLD')
      OPEN(UNIT=6,FILE='WELDESIGN.OUT',STATUS='NEW')
      READ (5,*),T,PHI,RW,QP(1),MPUMPT,SD,D
      READ(5,*) (RC(I),I=1,20)
      DO 76 I=1,20
      WRITE(6,55)
 55   FORMAT(//6X,'PHI',11X,'T',13X,'RW',12X,'RC(I)',9X,'QP(1)'
     1 9X,'SD',12X,'D',13X,'DRAMAX',9X,'MPUMPT')
      WRITE(6,66),PHI,T,RW,RC(I),QP(1),SD,D,DRAMAX,MPUMPT
 66   FORMAT(1X,8E14.5,5X,I5/)
      PAI=3.1415926
      DO 2 N=1, MPUMPT
      AM=N
      CALL DPQ (AM,T,PHI,RW,DM)
 2    DRW(N)=DM
      A(1,1)=DRW(1)
      A(1,2)=-1./(PAI*RC(I)*RC(I))
      A(2,1)=1.
      A(2,2)=1.
      N=2
      CALL MATIN(A,N)
      B(1)=0.
      B(2)=QP(1)
      QA(1)=A(1,1)*B(1)+A(1,2)*QP(1)
```

```
      QW(1)=A(2,1)*B(1)+A(2,2)*QP(1)
      DO 3 N=2,MPUMPT
 3    QP(N)=QP(1)
      DO 5 N=2,MPUMPT
      SUM1=0.
      SUM2=0.
      JJ=N-1
      DO 6 JP=1,JJ
      SUM1=SUM1+QW(JP)/(PAI*RC(I)*RC(I))
 6    SUM2=SUM2+QA(JP)*DRW(N-JP+1)
      B(1)=SUM1-SUM2
      B(2)=QP(N)
      QA(N)=A(1,1)*B(1)+A(1,2)*QP(N)
 5    QW(N)=A(2,1)*B(1)+A(2,2)*QP(N)
      DO 8 J=1,MPUMPT
      SUM=0.
      DO 9 JJ=1,J
 9    SUM=SUM+QW(JJ)/(PAI*RC(I)*RC(I))
 8    SW(J)=SUM
      WRITE (6,206)
 206  FORMAT(51X,'DRAMAX(I)',5X,'TP(HOURS)')
      WRITE(6,201) (SW(4),4,SW(6),6,SW(8),8,SW(12),12)
 201  FORMAT(47X,F10.5,6X,I5)
 76   CONTINUE
      STOP
      END
C
      SUBROUTINE DPQ(AM,T,PHI,RW,DM)
      PAI=3.1415926
      CAPA=T/PHI
      X=RW*RW/(4.0*CAPA*AM)
      CALL EXI(X,EXFN)
      AA=EXFN
      IF(ABS(AM-1.0)-0.001)1,1,2
    2 X=RW*RW/(4.0*CAPA*(AM-1.0))
      CALL EXI(X,EXFN)
      DM=(AA-EXFN)/(4.0*PAI*T)
      GO TO 3
    1 EXFN=0.0
      DM=AA/(4.0*T*PAI)
    3 CONTINUE
      RETURN
      END
      SUBROUTINE EXI(X,EXFN)
      IF(X-1.0)1,1,22
    1 EXFN=-ALOG(X)-0.5772156+0.99999193*X-0.24991055*X**2+0.05519968*
     1X**3-0.00976004*X**4+0.00107857*X**5
      GO TO 3
   22   CONTINUE
        IF(X-81.) 5,4,4
```

```
   5    CONTINUE
    2 EXFN=(((X**4+8.5733287*X**3+18.059017*X**2+8.6347608*X+0.26777373)
     1/(X**4+9.5733223*X**3+25.632956*X**2+21.099653*X+3.9584969))/
     2(X*EXP(X)))
        GO TO 3
   4    EXFN=0.
    3 CONTINUE
      RETURN
      END
C
        SUBROUTINE MATIN(AUX,N)
        DIMENSION AUX(5,5),B(5),C(5)
        NN=N-1
        AUX(1,1)=1./AUX(1,1)
        DO 8 M=1,NN
        K=M+1
        DO 3 I=1,M
        B(I)=0.0
        DO 3 J=1,M
3       B(I)=B(I)+AUX(I,J)*AUX(J,K)
        D=0.0
        DO 4 I=1,M
4       D=D+AUX(K,I)*B(I)
        D=-D+AUX(K,K)
        AUX(K,K)=1./D
        DO 5 I=1,M
5       AUX(I,K)=-B(I)*AUX(K,K)
        DO 6 J=1,M
        C(J)=0.0
        DO 6 I=1,M
6       C(J)=C(J)+AUX(K,I)*AUX(I,J)
        DO 7 J=1,M
7       AUX(K,J)=-C(J)*AUX(K,K)
        DO 8 I=1,M
        DO 8 J=1,M
8       AUX(I,J)=AUX(I,J)-B(I)*AUX(K,J)
        RETURN
        END
C
C*********************************************************************************************
```

```
C                                   APPENDIX-II
C-----------------------------------------------------------------------------------
C        PROGRAM FOR CALCULATING COST OF EXCAVATION OF DUG WELL
         DIMENSION  RC(50),DRAW(50),COST(50),D(20)
         OPEN(UNIT=6,FILE='COSTX.DAT',STATUS='OLD')
         OPEN(UNIT=2,FILE='COSTX.OUT',STATUS='NEW')
         PAI=3.14159265
         READ (6,1) CO,CROP,PRICE,SM,AN,SO,RATE
 1       FORMAT(7F10.5)
C    COST OF EXCAVATION AT DEPTH Y FROM GROUND IS GIVEN BY CO+SM*Y**AN
C        D(I)=DEPTH OF EXCAVATION
C        CROP=PRODUCTION PER UNIT AREA
C        PRICE=PRICE OF CROP PER UNIT QUANTITY
C        SO=DEPTH TO WATER TABLE FROM GROUND SURFACE
C   DRAW(I)=DRAWDOWN THAT WILL BRING WATER TABLE TO BOTTOM OF THE WELL
C        RATE=WORTH OF A PARTICULAR CROP AT NTH YEAR
         WRITE(2,11)
 11      FORMAT(12X,'CO',13X,'SM',13X,'AN',13X,'CROP',11X,'PRICE',10X,'SO
        1',14X,'RATE')
         WRITE(2,12) CO,SM,AN,CROP,PRICE,SO,RATE
 12      FORMAT(6X,7E15.5/)
         DO 2 I=1,20
         READ(6,3) DRAW(I),RC(I)
 3       FORMAT(2F10.5)
 2       CONTINUE
         DO 200 I=1,20
 200     D(I)=SO+DRAW(I)
C        CALCULATE THE MARKET PRICE OF THE CROP AT THE END OF EACH YEAR
C        THE NUMBER OF YEARS OF THE COMPENSATION IS EQUAL TO 25
C        THE RATE CAN BE 10,15, OR 20 PERCENT
         SUM=0.
         DO 13 N=1,25
 13      SUM=SUM+1./((1.+RATE)**N)
         DO 4 I=1,20
  4      COST(I)=PAI*RC(I)**2*D(I)*(CO+SM*D(I)**AN/(AN+1))+PAI*RC(I)**2
         1*CROP*PRICE*SUM
         WRITE(2,14)
 14      FORMAT(42X,'DEPTH(I)',7X,'RC(I)',10X,'COST(I)')
         DO 44 I=1,20
         WRITE(2,5) D(I),RC(I),COST(I)
 44      CONTINUE
 5       FORMAT(37X,3E15.6)
         WRITE(2,55)
 55      FORMAT(2X,'********************************************
         1***************************************************')
         STOP
         END
C*********************************************************************************
```