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# PARAMETERISATION OF HYDROGEOLOGICAL FACTORS IN GROUND WATER STUDY

SATISH CHANDRA
DIRECTOR

STUDY GROUP

G C MISHRA
A G CHACHADI

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

1985-86

CONTENTS

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $E_1(x)$ | - | exponential integral |
| $Q$ | - | constant pumping rate per unit time period |
| $Q_A(n)$ | - | water withdrawn from aquifer storage during time step n |
| $Q_I$ | - | initial pumping rate |
| $Q_i(n)$ | - | contribution of the $i^{th}$ aquifer during time step n |
| $Q_p(n)$ | - | pumping rate during time step n |
| $Q_w(n)$ | - | water withdrawn from well storage during time step n |
| $r_c$ | - | radius of the well casing |
| $r_w$ | - | radius of the well screen |
| $S_F$ | - | drawdown at the well for which pumping rate will be zero |
| $S_{iw}(n)$ | - | drawdown in the piezometric surface at the well point in the $i^{th}$ aquifer at the end of time step n |
| $S_w$ | - | drawdown at the well at time t after on set of pumping |
| $S_w(n)$ | - | drawdown at the well face at the end of time step n |
| $t$ | - | time after pumping commenced |
| $t_p$ | - | duration of pumping |
| $T$ | - | transmissivity |

$T_i$ - transmissivity of the $i^{th}$ aquifer

$\phi$ - storage coefficient

$\phi_i$ - storage coefficient of the $i^{th}$ aquifer

$\beta_i$ - hydraulic diffusivity = $T_i/\phi_i$ of the $i^{th}$ aquifer

$\partial_{rwi}(I)$ - discrete kernel coefficient

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## ABSTRACT

Walton has presented a relationship of transmissivity with specific capacity for wells having negligible storage. These graphs are used for estimation of transmissivity provided storage coefficient is known a priori. In the present report similar graphs have been presented considering well storage and variation of pumping rate with drawdown. The following cases have been considered: Case 1 - the pumping rate is independent of drawdown and is constant, Case 2- the pumping rate is a linear function of drawdown.

Using discrete kernel approach a set of type curves for a two aquifer system separated by an aquiclude has been presented. Use of the type curves for parameter estimation has been demonstrated using synthetic drawdown data. It has been shown that these type curves can provide a fairly accurate means for determining transmissivity and storage coefficient of individual aquifer from pump test data conducted in a well open to two aquifers.

## 1.0 INTRODUCTION

### 1.1 Determination of Transmissivity Using Specific Capacity

The aquifer parameters like transmissivity (T) and storage coefficient ($\phi$) are usually determined by aquifer test that is by observing the performance of aquifer in response to a long period of pumping at a given rate.

In many cases, especially during reconnaissance type of ground water investigations and for water balance studies it may not be practical or feasible to construct test wells and conduct the time consuming aquifer tests for estimation of hydrogeological parameters. Also, some of the modern quantitative techniques such as those for which electric analog models or mathematical models are contemplated, a sufficiently large number of T and $\phi$ values are required. In all such cases, quick and approximate methods may have to be resorted to, for the determination of hydrogeological parameters. These properties can be estimated with reasonable accuracy by some of the indirect methods based on analysis of water level fluctuations, specific capacity data of wells, and well logs etc.

In this report transmissivity vs specific capacity relationship for known values of storativity has been developed similar to that of Walton (1970) taking well storage into consideration. It is found that some times when a centrifugal pump is used the pumping rate depends upon the drawdown. The pumping rate may be either a linear or a non-linear function of the drawdown. The specific capacity and transmissivity graphs have been developed for wells having storage, incorporating the effect of drawdown on the pumping rate.

## 1.2 Determination of Transmissivity and Storage Coefficient for a Multiaquifer System

The solution of unsteady flow to a well open to a single aquifer permits determination of the formation constants, transmissivity and storativity of that aquifer by means of pumping test. Theis, Jacob's and Chow's methods are widely used for determination of aquifer parameters of a single water bearing stratum. In a borehole it is common to identify a number of aquifers. Water wells under favourable hydrogeological conditions are generally constructed tapping more than one water bearing stratum so as to have dependable yield. Wells which are open to two are more water bearing stratum which have different hydraulic properties and which are not closely connected except by the well itself are referred to as multi-aquifer wells. In the present report the inverse problem of finding the aquifer parameters by comparing the observed drawdowns at the pumping well which taps two aquifers with a set of type curves has been dealt with.

## 2.0 REVIEW

### 2.1 Transmissivity Specific Capacity Relationship

The theoretical specific capacity of a well discharging at a constant rate in a homogenous, isotropic, nonleaky artesian aquifer of infinite area extent is given by the following expression (Walton, 1962) :

$$\frac{Q}{s_w} = \frac{4\pi T}{2.30 \log_{10} (2.25 \, Tt/r_w^2 \, \phi)}$$

where,

$s_w$ = drawdown in a 100 percent efficient pumped well in metres,

$r_w$ = radius of the pumped well in metres,

$Q/s_w$ = specific capacity in $m^3$/day per metre of drawdown,

$Q$ = rate of discharge in $m^3$/day,

$T$ = transmissivity in $m^2$/day

$\phi$ = dimensionless storage coefficient, and

$t$ = time after pumping started in days.

The above equation assumes that : 1) the production well has full penetration and the well is uncased in the entire depth of aquifer, 2) the well loss is negligible, and 3) the effective radius of the production well has not been affected during drilling and development of the production well and is equal to the nominal radius of the production well. The storage coefficient value can be estimated either from well log data or from study of water level data. As the specific capacity varies with the logarithm of $1/\phi$ large error in assumed storativity value results in comparatively small error in transmissivity estimated using the above relation.

The relationship between the specific capacity and transmissivity for artesian and water table conditions has been given for different durations of pumping (Walton,1962). These graphs can be used to obtain rough estimates of the transmissivity from specific capacity data provided approximate value of storage coefficient is known.

As seen from the specific capacity equation the value $Q/s_w$ varies with the logarithm of $1/r_w^2$ . Therefore, large increase in the radius of a well result in comparatively small changes in the specific capacity values. Specific capacity decreases with the period of pumping because the drawdown continuously increases with time as the cone of influence of the well expands till the steady state conditions are arrived at. For this reason it is important to state the duration of the pumping period at which a specific capacity is computed.

## 2.2 Multiaquifer Well

Water wells are generally constructed tapping more than one aquifer in order to have dependable yield. There has been a growing interest in recent years on the analysis of flow to a multiaquifer well. A solution for unsteady flow to a well tapping two confined aquifers having different potentiometric surfaces has been obtained by Papadopulos (1966). The solution obtained by Papadopulos can't be used for determining formation constants of the individual aquifer as the observed response curves has to be compared with a large number of type curves for all possible combination of the various parameters. However, no type curves and numerical results have been given by Papadopulos. Using integral transform technique unsteady flow to a multiaquifer well open to two aquifers has also been analysed by Khader and Veerankutty (1975) who have presented numerical results for contribution of individual aquifer to the total discharge of a well. But the type curves required for identification of aquifer parameters have not been developed by them. Using discrete kernel approach, the analysis of unsteady flow to a well tapping two aquifers separated by an aquiclude has been carried out by Mishra et. al. (1985) for a well having negligible storage. The discrete kernel approache is amenable to develop type curves for multiaquifer well.

## 3.0 PROBLEM DEFINITICN AND METHODOLOGY

### 3.1 Relation Between Transmissivity and Specific Capacity of a Well Having Storage

#### 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 the drawdown. It is necessary to determine the drawdown in piezometric surface at the well face and variation of specific capacity with time during pumping.

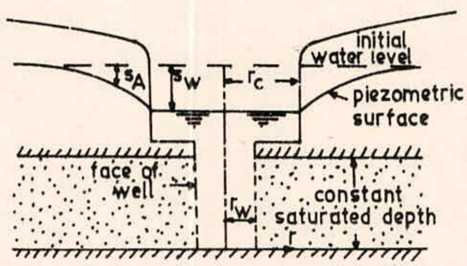


FIGURE 1. SCHEMATIC CROSS SECTION OF A LARGE-DIAMETER WELL

### 3.1.2 Methodology

The following assumptions have been made in the analysis:

1. At any time the drawdown in the aquifer at the well face is equal to that in the well.
2. 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 the 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 Figure 2. Piece wise linear approximation can be made to represent the relationship between discharge and drawdown. However, in the present analysis a single linear relationship has been assumed to be valid for the entire range of drawdown. The pumping rate is expressed by

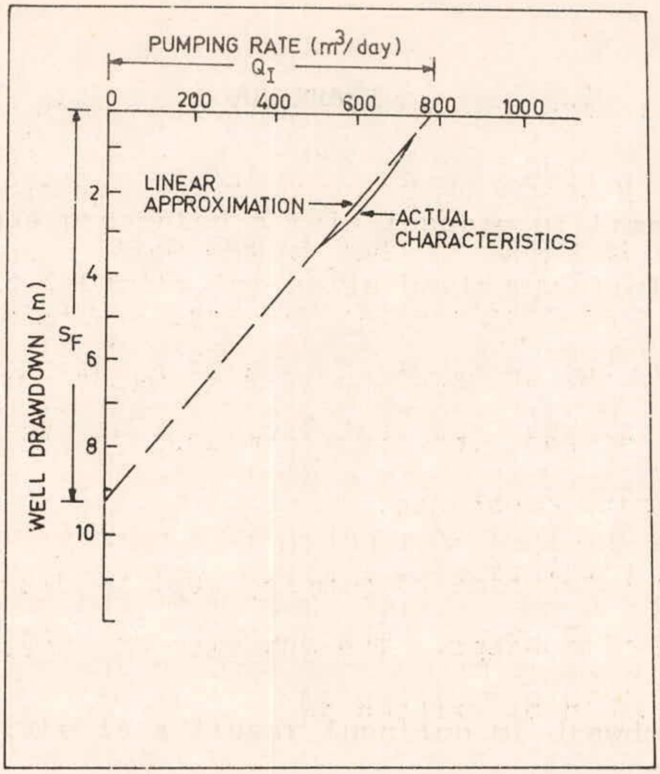


FIGURE 2. A TYPICAL VARIATION OF ABSTRACTION RATE WITH DRAWDOWN

$$Q_P(n) = (1 - S_W(n) / S_F)\, Q_I \qquad \ldots(2)$$

in which

$S_W(n)$ is the drawdown at the well face at the end of time step n. $S_F$ and $Q_I$ have been explained in the figure. 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 $\gamma$. $Q_W(\gamma)$ 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

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

or

$$Q_A(n) + Q_W(n)\ (1 + \frac{Q_I}{S_F \pi r_c^2}) = \left[ 1 - \frac{1}{S_F \pi r_c^2} \sum_{\gamma=1}^{n-1} Q_W(\gamma) \right] Q_I \ldots(5)$$

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

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

where

$$\partial_{rw}\ (N) = \frac{1}{4\pi T} \left[ E_1\ (\frac{\phi r_w^2}{4TN}) - E_1 (\frac{\phi r_w^2}{4T(N-1)}) \right] \qquad \ldots(7)$$

$$E_1(X) = \int_X^{\infty} \frac{e^{-Y}}{Y}\, dY$$

$T$ = transmissivity of the aquifer

$\phi$ = storage coefficient, and

$N$ = an integer

$\partial_{rw}(N)$ = are known as discrete kernel coefficients.

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

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

Rearranging, the following relation is obtained.

$$\partial_{rw}(1)\, Q_A(n) - Q_W(n)\, \frac{1}{\pi r_c^2} = \frac{1}{\pi r_c^2} \sum_{\gamma=1}^{n-1} Q_W(\gamma)$$

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

$Q_A(n)$ and $Q_w(n)$ can be solved in succession starting from time step one using the two linear algebraic equations (5) and (9). 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

$$S_r(n) = \sum_{\gamma=1}^{n} Q_A(\gamma)\, \partial_r\,(n - \gamma + 1) \qquad \ldots(10)$$

where,

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

$S_W(n)$ can be evaluated either using equation (3) or equation (6) and specific capacity has been obtained dividing $Q_p(n)$ by drawdown at the well point.

## 3.2 Development of Type Curves for Multiaquifer System

### 3.2.1 Problem definition

A schematic cross-section of a well tapping two aquifers which are separated by an aquiclude is shown in Figure 3. Each of the aquifers is homogeneous, isotropic, and infinite in areal extent. Prior to the pumping the aquifers are assumed to be at rest condition. The radius of the well screen is $r_w$. Drawdowns in the piezometric surface are caused by discharge from respective aquifers, due to a uniform rate of pumping from the well. The drawdowns are measured at the well point. It is required to find the aquifer parameters $T_1, Q_1$ and $T_2, Q_2$ making use of the observed drawdown.

### 3.2.2 Methodology

The following procedure has been adopted to develop the type curves. The assumptions made in the analysis are :

i) The radius of the well is small and hence the well storage is neglected.

ii) At any time the drawdowns in both the aquifers at well face are same but vary with time.

iii) The time parameter is discrete. Within each time step, the abstraction rates of water derived from each of the aquifers are separate constants.

When the two aquifers are tapped by a single well and

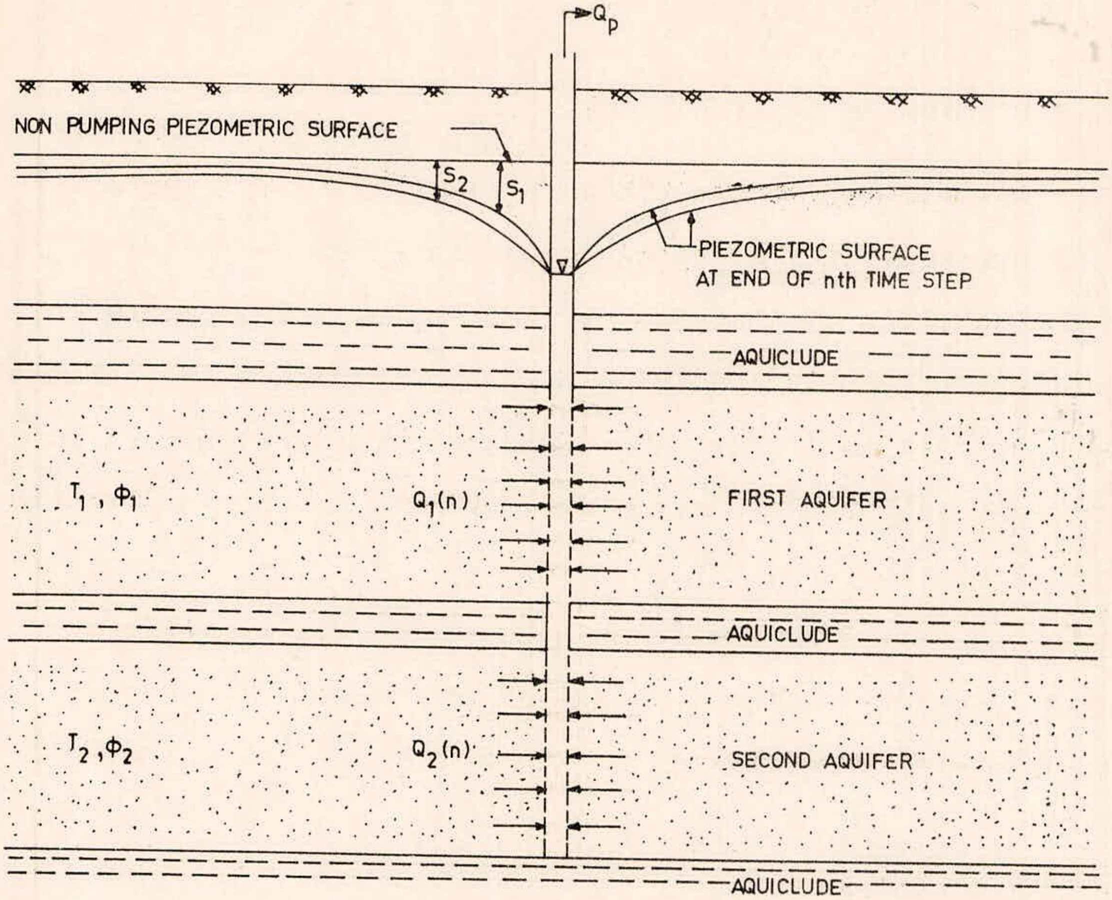


FIGURE 3. SCHEMATIC SECTION OF A WELL TAPPING TWO CONFINED AQUIFERS SEPARATED BY AN AQUICLUDE

the well is pumped, there is contribution from each aquifer to the pumping through the respective well screens. Let $Q_1(n)$ and $Q_2(n)$ be the contributions from aquifer 1 and 2 respectively at time step n. At any time the algebraic sum of the abstractions from both aquifers will be equal to the pumping rate. Hence,

$$Q_1(n) + Q_2(n) = Q_P \qquad \text{... (11)}$$

The drawdown at the well face at the end of time step n in aquifer 1 is given by ( Morel Seytoux, 1975)

$$S_{1w}(n) = \sum_{\gamma=1}^{n} Q_1(\gamma)\ \partial_{rw1}\ (n - \gamma + 1) \qquad \text{... (12)}$$

where,

$$\partial_{rw1}(m) = \frac{1}{4\pi T_1}\left[E_1\ (\frac{r_w^2}{4\beta_1 m}) - E_1(\frac{r_w^2}{4\beta_1(m-1)})\right] \qquad \text{... (13)}$$

and

$$\beta_1 = T_1/\phi_1 .$$

Similarly the drawdown at the well face at the end of time step n in aquifer 2 is given by

$$S_{2w}(n) = \sum_{\gamma=1}^{n} Q_2(\gamma)\partial_{rw2}\ (n - \gamma + 1) \qquad \text{...(14)}$$

where,

$$\partial_{rw2}(m) = \frac{1}{4\pi T_2}\left[E_1\ (\frac{r_w^2}{4\beta_2 m}) - E_1(\frac{r_w^2}{4\beta_2(m-1)})\right] \qquad \text{...(15)}$$

and $\beta_2 = T_2/\phi_2$ .

$\beta_1$ and $\beta_2$ are the hydraulic diffusivity of the 1st and 2nd aquifer respectively. Since $S_{1w}(n) = S_{2w}(n)$, therefore, from Equations (12) and (14).

$$\sum_{\gamma=1}^{n} Q_1(\gamma)\partial_{rw1}(n-\gamma+1) = \sum_{\gamma=1}^{n} Q_2(\gamma)\partial_{rw2}(n-\gamma+1) \qquad \text{...(16)}$$

Rearranging,

$$Q_1(n)\partial_{rw1}(1) - Q_2(n)\partial_{rw2}(1)$$

$$= \sum_{\gamma=1}^{n-1} Q_2(\gamma)\partial_{rw2}(n-\gamma+1) - \sum_{\gamma=1}^{n-1} Q_1(\gamma)\partial_{rw1}(n-\gamma+1) \qquad \ldots(17)$$

Using Equations (11) and (17) the contribution of first aquifer to pumping is found to be

$$\frac{Q_1(n)}{Q_P} = \frac{1}{1+(\frac{T_2}{T_1})\frac{\partial'_{rw1}(1)}{\partial'_{rw2}(1)}}\left[1-(\frac{T_2}{T_1})\cdot\frac{1}{\partial'_{rw2}(1)}\sum_{\gamma=1}^{n-1}\frac{Q_1(\gamma)}{Q_P}\partial'_{rw1}(n-\gamma+1)\right.$$

$$\left.+\frac{1}{\partial'_{rw2}(1)}\sum_{\gamma=1}^{n-1}(1-\frac{Q_1(\gamma)}{Q_P})\partial'_{rw2}(n-\gamma+1)\right] \qquad \ldots(18)$$

in which

$$\partial'_{rw2}(n) = \left[E_1(\frac{\phi_1 r_w^2}{4T_1 n}) - E_1(\frac{\phi_1 r_w^2}{4T_1(n-1)})\right]$$

and

$$\partial'_{rw2}(n) = \left[E_1(\frac{\phi_2 r_w^2}{4T_2 n}) - E_1(\frac{\phi_2 r_w^2}{4T_2(n-1)})\right] = \left[E_1(\frac{\phi_2}{\phi_1}\cdot\frac{T_1}{T_2}\cdot\frac{\phi_1 r_w^2}{4T_1 n})\right.$$

$$\left.- E_1(\frac{\phi_2}{\phi_1}\frac{T_1}{T_2}\frac{\phi_1 r_w^2}{4T_1(n-1)})\right]$$

$\frac{Q_1(n)}{Q_P}$ can be found in succession starting from time step 1.

$\frac{Q_1(n)}{Q_P}$ can be expressed as a function of $\partial'_{rw1}(n)$, $\partial'_{rw2}(n)$.

$\frac{T_1}{T_2}$, $\frac{\phi_1}{\phi_2}$ and $\frac{\phi_1 r_w^2}{4T_1 n}$.

The contribution of the second aquifer is given by

$$\frac{Q_2(n)}{Q_P} = 1 - \frac{Q_1(n)}{Q_P} \qquad \ldots(19)$$

Thus $Q_1(n)$ and $Q_2(n)$ can be solved in succession starting from time step one using the Equations (18) and (19) for known values of $T_1$, $T_2$, $\phi_1$, $\phi_2$, $r_w$ and $Q_P$. Knowing $Q_1(n)$ and $Q_2(n)$, the drawdown $S_{ri}(n)$, in the $i^{th}$ aquifer at any distance r from the centre of the well can be found using the relation

$$S_{ri}(n) = \sum_{\gamma=1}^{n} Q_i(\gamma)\,\partial_{ri}(n-\gamma+1) \qquad \ldots(20)$$

where,

$$\partial_{ri}(m) = \frac{1}{4\pi T_i}\left[E_1\left(\frac{r^2}{4\beta_i m}\right) - E_1\left(\frac{r^2}{4\beta_i (m-1)}\right)\right] \qquad \ldots(21)$$

The drawdown at the end of time step n at the well point can be expressed as

$$S_w(n) = \sum_{\gamma=1}^{n} Q_2(\gamma)\,\partial_{rw2}(n-\gamma+1) \qquad \ldots(22)$$

Since $Q_2(\gamma) = Q_P - Q_1(\gamma)$, therefore,

$$S_w(n) = \sum_{\gamma=1}^{n}\left[Q_P - Q_1(\gamma)\right]\partial_{rw2}(n-\gamma+1) \qquad \ldots(23)$$

Breaking the summation into two parts

$$S_w(n) = \sum_{\gamma=1}^{n-1}\left[Q_P - Q_1(\gamma)\right]\partial_{rw2}(n-\gamma+1) + \left[Q_P - Q_1(n)\right]\partial_{rw2}(1) \qquad \ldots(24)$$

Replacing $Q_1(n)$ by the expression given at Equation (18) and simplifying

$$\frac{\frac{S_w(n)}{Q_P}}{4\pi T_1} = \sum_{\gamma=1}^{n-1}\left[1 - \frac{Q_1(\gamma)}{Q_P}\right]\left(\frac{T_1}{T_2}\right)\partial'_{rw2}(n-\gamma+1) + \left(\frac{T_1}{T_2}\right)\partial'_{rw2}(1)$$

$$- \left[\frac{T_1}{T_2}\,\frac{\partial'_{rw2}(1)}{1+\left(\frac{T_2}{T_1}\right)\frac{\partial'_{rw1}(1)}{\partial'_{rw2}(1)}}\right]\left[1-\left(\frac{T_1}{T_2}\right)\frac{1}{\partial'_{rw2}(1)}\sum_{\gamma=1}^{n-1}\frac{Q_1(\gamma)}{Q_P}\partial'_{rw1}(n-\gamma+1)\right.$$

$$\left. + \frac{1}{\partial'_{rw2}(1)}\sum_{\gamma=1}^{n-1}\left(1 - \frac{Q_1(\gamma)}{Q_P}\right)\partial'_{rw2}(n-\gamma+1)\right] \qquad \ldots(25)$$

Thus for a given value of $T_1/T_2, \phi_1/\phi_2$, the right hand side of Equation (25) is only a function of $\phi_1 r_w^2/4T_1 n$

Therefore,

$$\frac{\dfrac{S_w(n)}{Q_P}}{4\pi T_1} = W\,(U_1(n)\,) \qquad \ldots(26)$$

where $W(U_1(n))$ is the right hand side of Equation(25) and can be regarded as well function for a two aquifer system and

$$U_1(n) = \frac{\phi_1\ r_w^2}{4\ T_1\ n}.$$

Taking the logarithm, Equation (26) reduces to

$$\log_{10} S_w(n) = \log_{10}\left(\frac{Q_P}{4\pi T_1}\right) + \log_{10} W(U_1(n))$$

From the expression of $U_1(n)$

$$\log_{10}(n) = \log_{10}\left(\frac{\phi_1\ r_w^2}{4\ T_1}\right) + \log_{10}\left(\frac{1}{U_1(n)}\right)$$

Therefore, the variation of $W(U_1(n))$ with $\frac{1}{U_1(n)}$ when plotted on double log paper will match with the log-log plot of $S_W(n)$ with n.

## 4.0 RESULTS

### 4.1 Relationship between Transmissivity and Specific Capacity of Well Having Storage

The discrete kernel coefficients, $\partial_{rw}(n)$, have been generated using equation(7) for known values of transmissivity, storage coefficient and radius of the well screen. The exponential integral, $E_1(.)$, which appears in equation(7) has been evaluated making use of the polynomial and rational approximations given by Gautschi and Cahill (1964). After generating the discrete kernel, $Q_A(n)$ and $Q_W(n)$ are solved using equations (5) and (9) for known values of $m, Q_I$ and $S_F$. The drawdown at the well face is then obtained with the help of equation(3). The variation of $S_W(t)/(Q/4\pi T)$ with $4Tt/(\phi r_w^2)$ for m equal to 5,10 and 20 is shown in figure 4 for $r_w/r_c = 1$ and for different values of $\phi$ for a constant abstraction rate Q. $S_W(t)$ is the drawdown at the well face at time t and $S_W(t)/(Q/4\pi T)$ can be regarded as well function for a large diameter well. The type curves in figure 4 contain the response of an aquifer during the abstraction as well as the recovery phase. Each of the recovery curves is characterised by a non-dimensional time factor, $4Tt_p/(\phi r_w^2)$, at which it leaves the time drawdown curve of the abstraction phase. The non-dimensional time factor can be used to check the accuracy of the aquifer parameters determined by curve matching. The time draw-down curve which comprises the response of the aquifer during abstraction

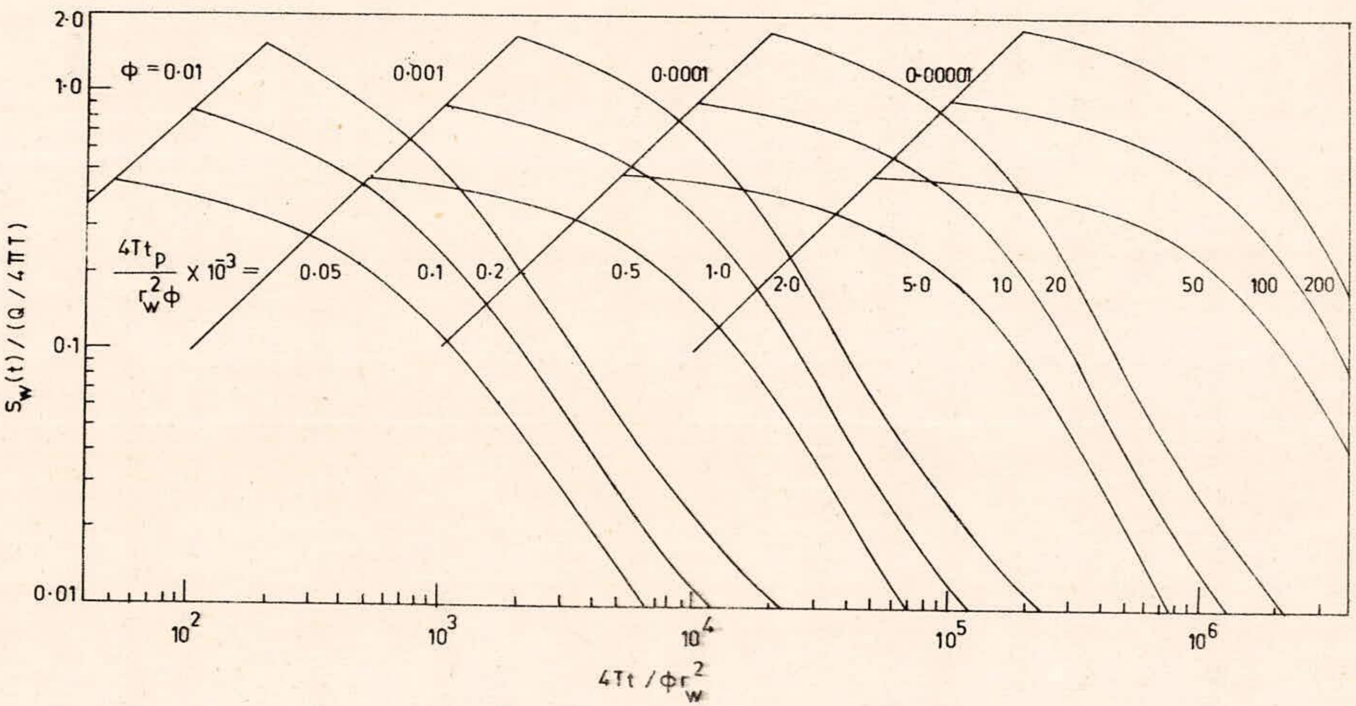


FIGURE 4. FAMILY OF TYPE CURVE : $\frac{S_W(t)}{Q/4\pi T}$ VERSUS $\frac{4Tt}{\phi r_w^2}$ FOR $r_w/r_c=1$

as well as recovery will only match uniquely with one of the type curves.

Results for variable abstraction rate have been presented for a particular case. The values of $S_F$ and $Q_I$ adopted correspond to an actual pumping test. The values of $Q_P(n)$, $Q_W(n)$, and $S_W(n)$ are presented in Table 1a. For average abstraction rate, the corresponding values of drawdown, abstraction from well storage have been given in the Table 1b. There is difference in the drawdown values and average situation can not substitute the variable abstraction case.

The specific capacity values have been determined for known values of transmissivity, storage coefficient, pumping rate and well dimensions for different durations of pumping. Figures 5(a) - 5(g) show the relation of specific capacity with transmissivity for a constant pumping rate while Figures 6(a) - 6(g) show the relation of specific capacity with transmissivity for a linear variation of discharge with drawdown. These graphs can be used to find the approximate value of transmissivity using specific capacity value at a well.

## 4.2 Determination of Transmissivity and Storage Coefficient for a Multiaquifer System

With assumed values of $T_1, \phi_1, T_2, \phi_2$ and $r_w$ the discrete kernels are generated and $Q_1(n)/Q_p$ values are solved in succession starting from time step 1 using Equation(18). Then the drawdown $S_w(n)$ at various times have been calculated at the well face. The variations of well function, $S_w(n)/(\frac{Q_P}{4\pi T_1})$, with

TABLE 1a. Aquifer and Well Storage Contribution and Drawdown Under Time Variant Pumping

($T=2.1875 m^2/10$ min., $\phi = .001$, $r_w = r_c = 5.4$m,

$Q_I = 9.44 m^3/10$ min., $S_F = 1.8$ m, m=18)

| Time step n | $Q_A(n)$ | $Q_W(n)$ | $Q_P(n)$ | $S_W(n)$ |
|---|---|---|---|---|
| 1 | .4951 | 8.4645 | 8.9596 | .0923 |
| 2 | .8756 | 7.6461 | 8.5217 | .1758 |
| 4 | 1.4593 | 6.3042 | 7.7635 | .3203 |
| 6 | 1.8936 | 5.2408 | 7.1344 | .4402 |
| 8 | 2.2273 | 4.3818 | 6.6091 | .5403 |
| 10 | 2.4875 | 3.6809 | 6.1684 | .6243 |
| 12 | 2.6923 | 3.1048 | 5.7970 | .6951 |
| 14 | 2.8541 | 2.6288 | 5.4829 | .7550 |
| 16 | 2.9823 | 2.2339 | 5.2162 | .8058 |
| 18 | 3.0840 | 1.9050 | 4.9890 | .8491 |
| 19 | 2.8566 | -2.8566 | 0.0 | .8179 |
| 20 | 2.6789 | -2.6789 | 0.0 | .7887 |
| 22 | 2.3922 | -2.3922 | 0.0 | .7350 |
| 24 | 2.1596 | -2.1596 | 0.0 | .6866 |
| 26 | 1.9627 | -1.9627 | 0.0 | .6427 |
| 28 | 1.7923 | -1.7923 | 0.0 | .6027 |
| 30 | 1.6426 | -1.6426 | 0.0 | .5661 |
| 32 | 1.5100 | -1.5100 | 0.0 | .5324 |
| 34 | 1.3916 | -1.3916 | 0.0 | .5014 |
| 36 | 1.2852 | -1.2852 | 0.0 | .4728 |

TABLE 1b. Aquifer and Well Storage Contribution and Drawdown Under Constant Pumping

($T=2.1875 m^2/10$ min., $\phi=0.001$, $r_w=r_c=5.4$ m, $Q=7.2812 m^3/10$ min., $m=18$)

| Time Step (n) | $Q_A(n)$ | $Q_W(n)$ | $S_W(n)$ |
|---|---|---|---|
| 1 | .4023 | 6.8789 | .0750 |
| 2 | .7312 | 6.5500 | .1465 |
| 4 | 1.2845 | 5.9968 | .2803 |
| 6 | 1.7519 | 5.5293 | .4035 |
| 8 | 2.1602 | 5.1211 | .5175 |
| 10 | 2.5227 | 4.7585 | .6233 |
| 12 | 2.8480 | 4.4332 | .7218 |
| 14 | 3.1420 | 4.1393 | .8137 |
| 16 | 3.4091 | 3.8722 | .8997 |
| 18 | 3.6528 | 3.6284 | .9802 |
| 19 | 3.3645 | -3.3645 | .9433 |
| 20 | 3.1447 | -3.1447 | .9092 |
| 24 | 2.5176 | -2.5176 | .7899 |
| 28 | 2.0817 | -2.0817 | .6923 |
| 32 | 1.7495 | -1.7495 | .6108 |
| 36 | 1.4863 | -1.4863 | .5418 |

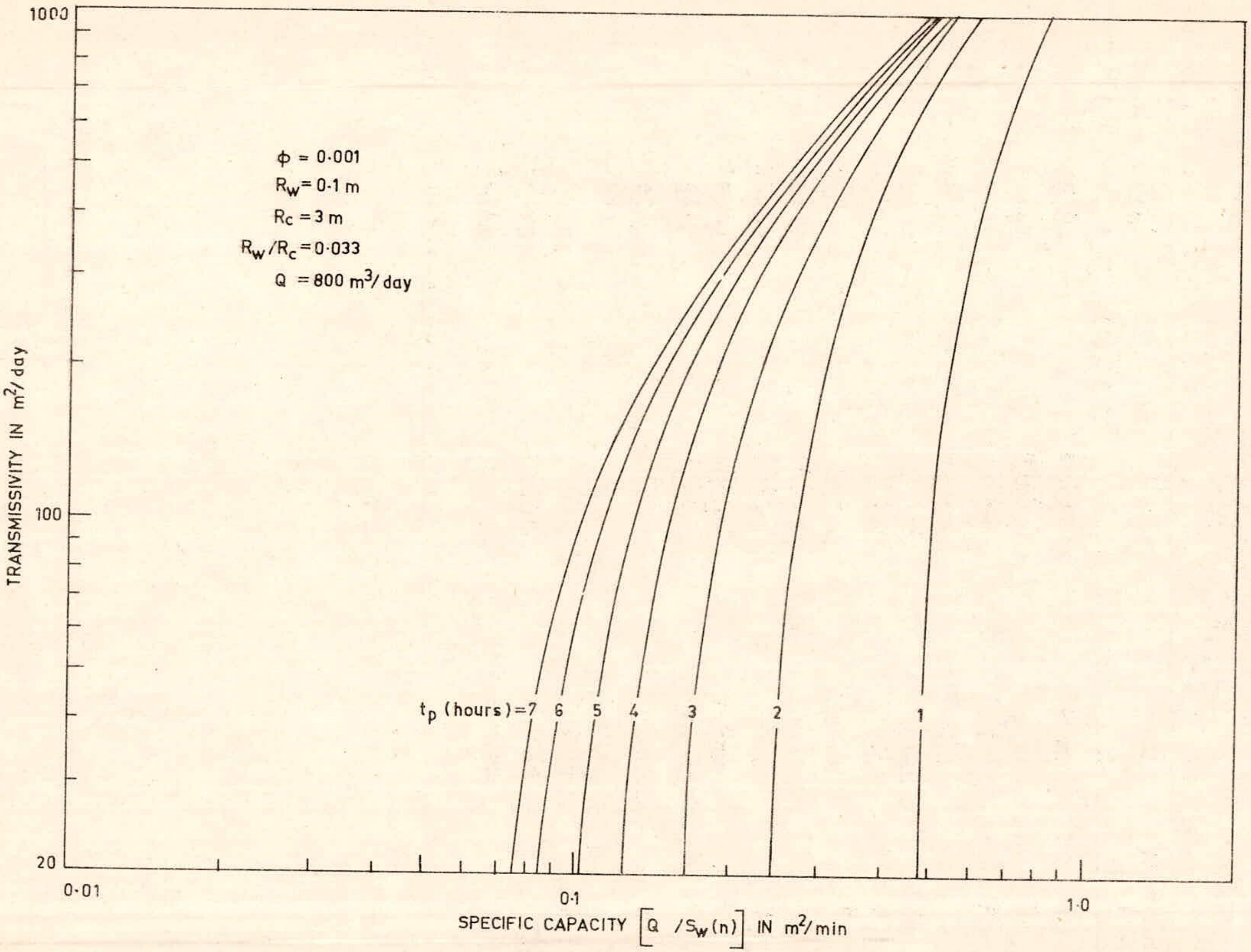


FIGURE 5(a) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP UNDER CONSTANT PUMPING FOR $r_w/r_c$ = 0.033 and $\phi$=.001

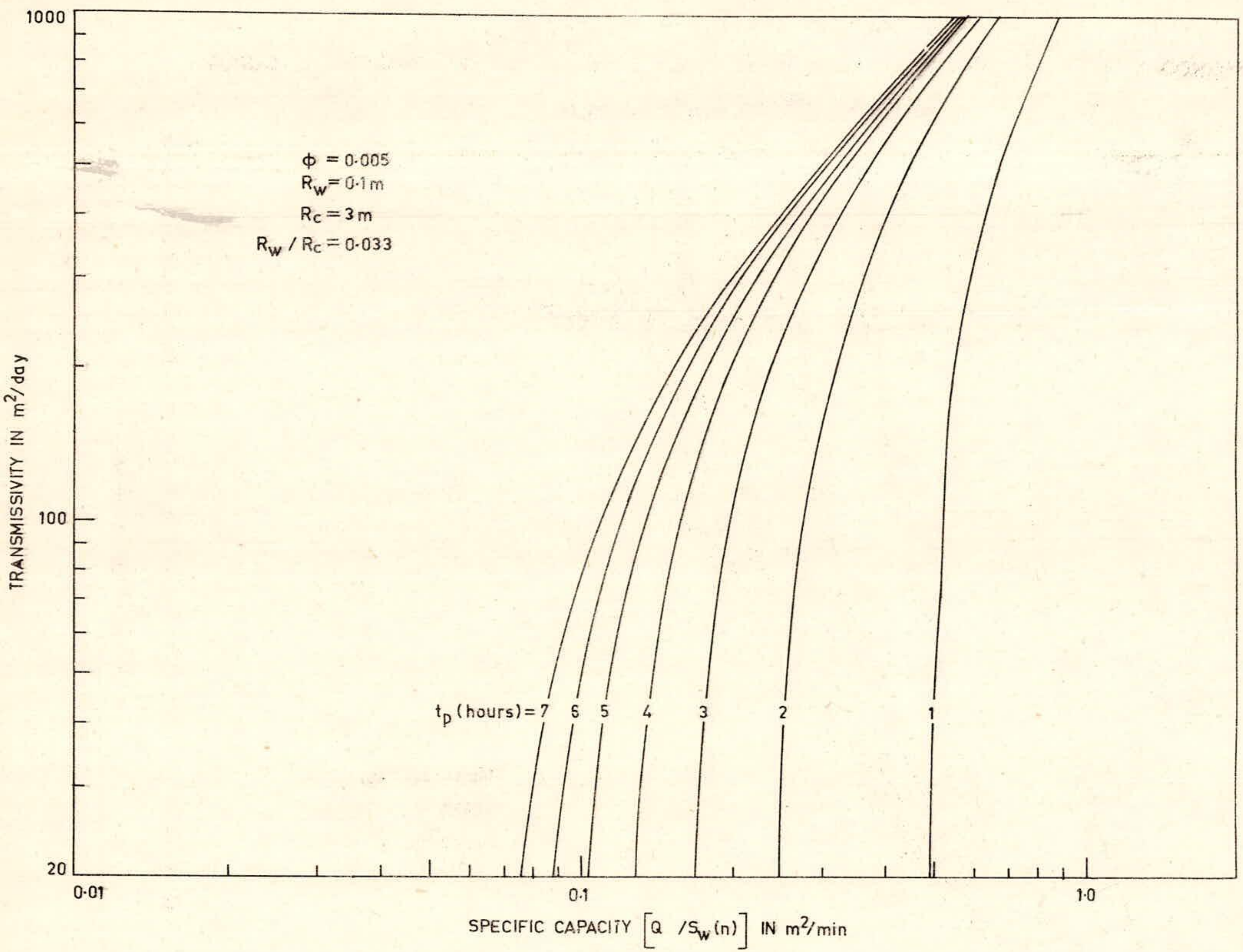


FIGURE 5(b) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP UNDER CONSTANT PUMPING FOR $\frac{r_w}{r_c} = 0.033$ and $\phi = .005$

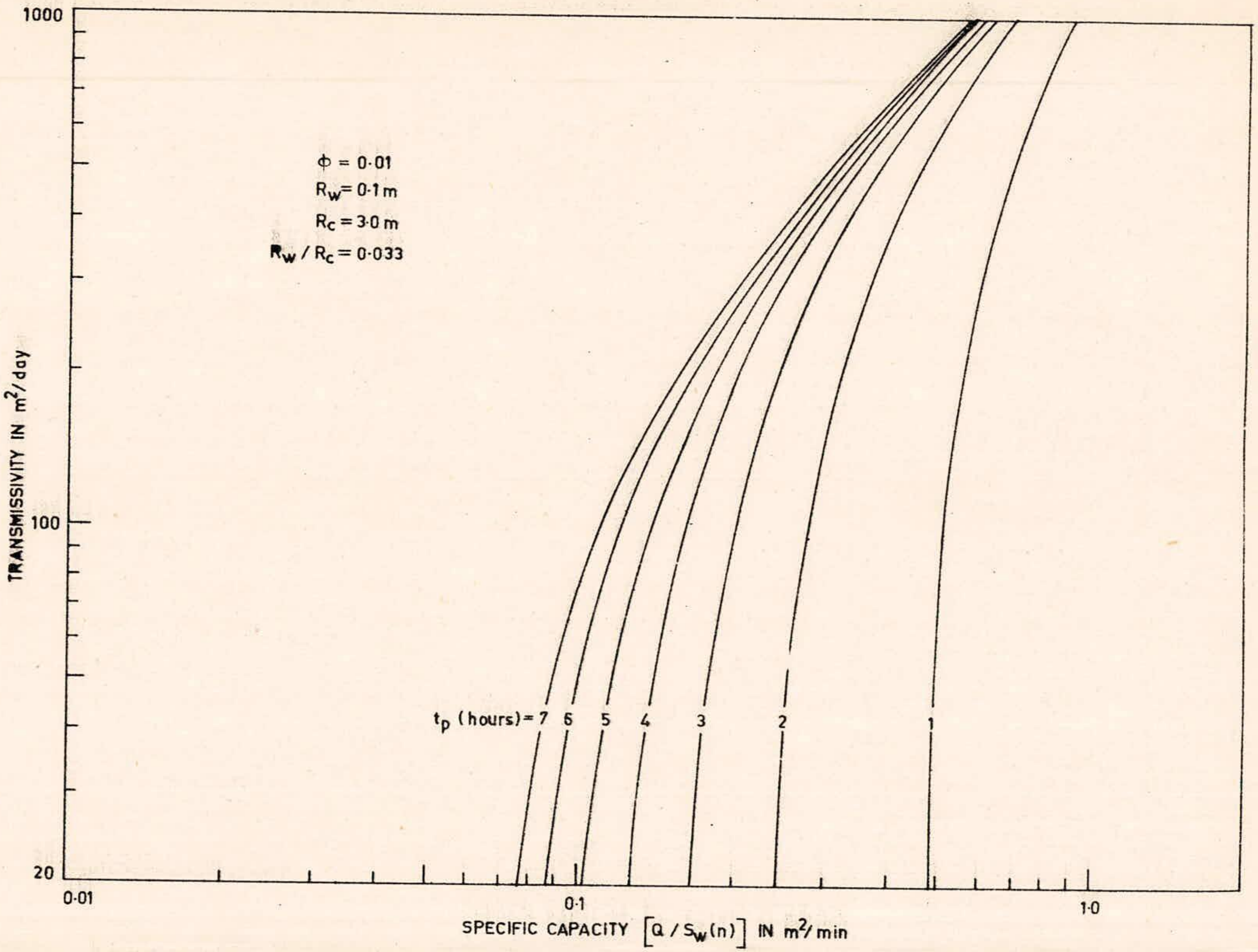


FIGURE 5(c) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP UNDER CONSTANT PUMPING FOR $\frac{r_w}{r_c} = 0.033$ and $\phi=0.01$

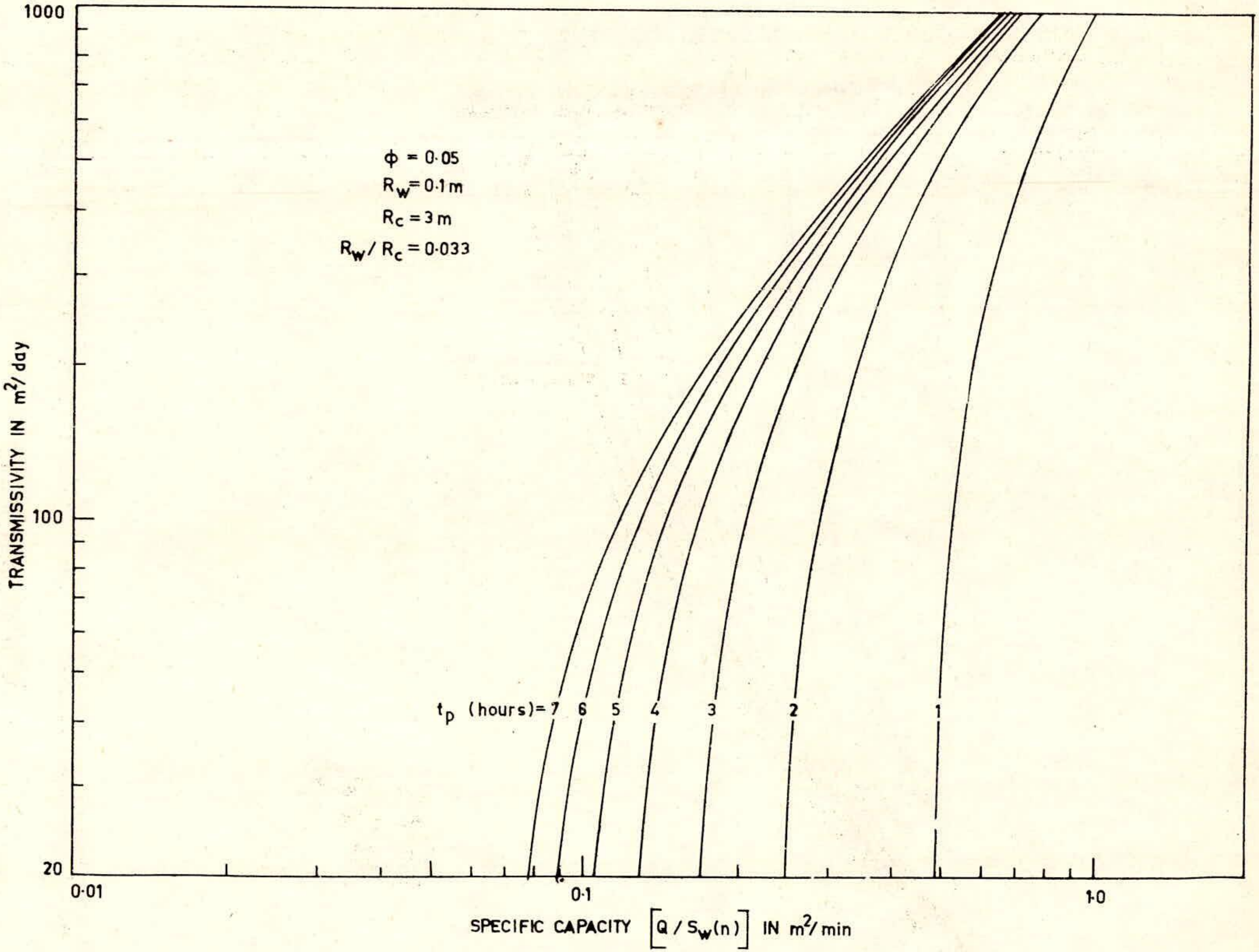


FIGURE 5(d) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP UNDER CONSTANT PUMPING FOR $r_w/r_c$ = 0.033 and $\phi$ =0.05

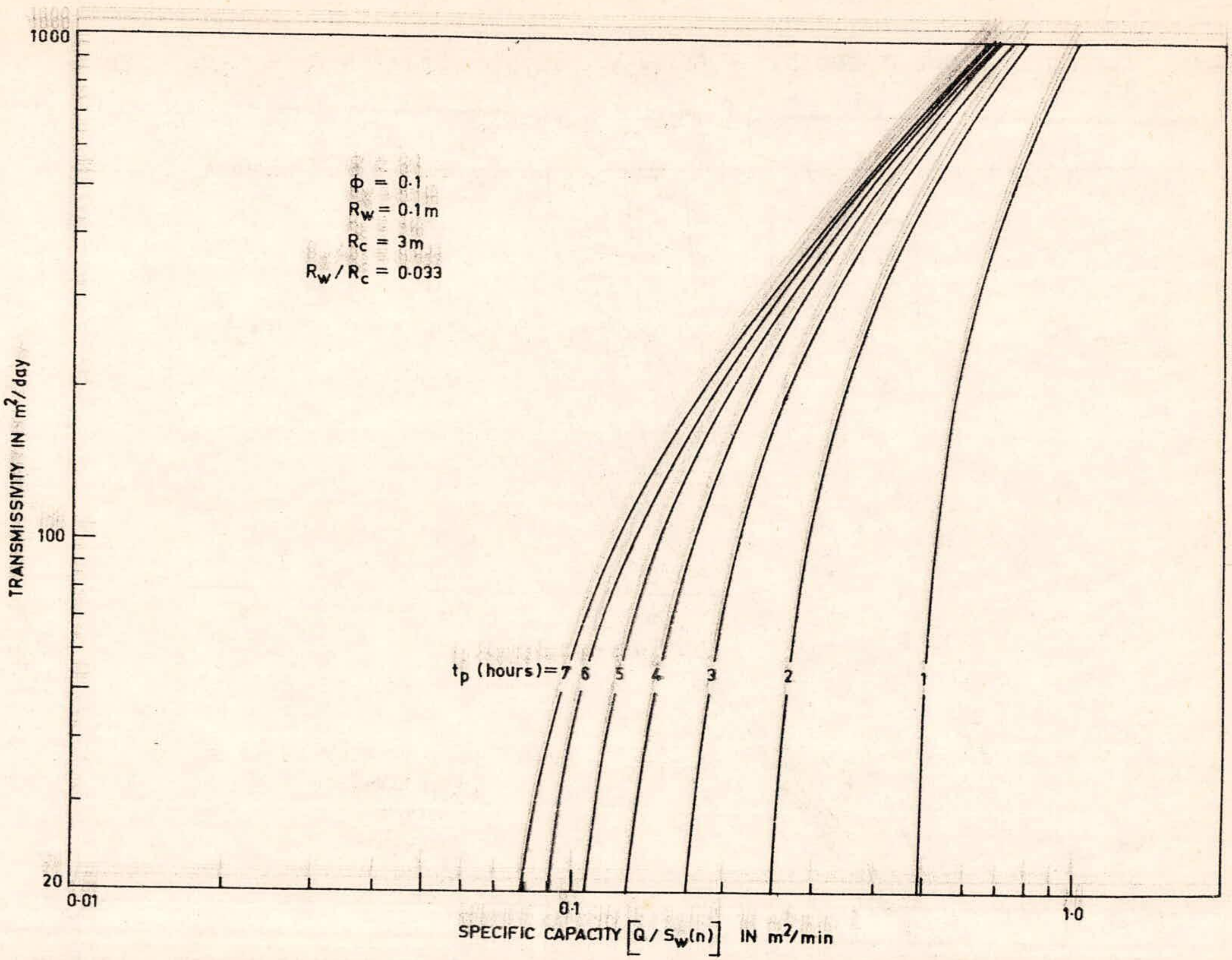


FIGURE 5(e) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP UNDER CONSTANT PUMPING FOR $r_w/r_c = 0.033$ and $\phi=0.1$

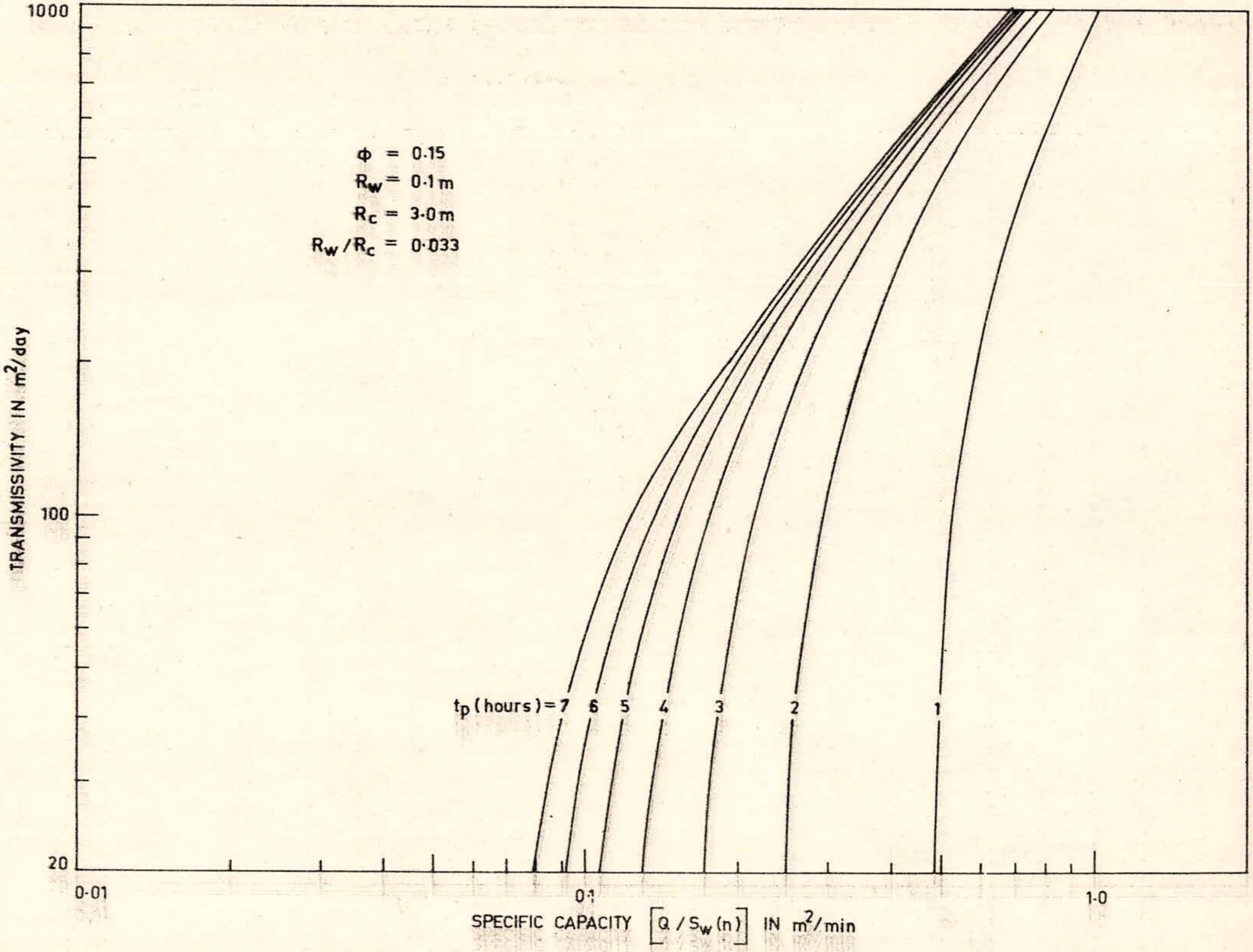


FIGURE 5(f) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP UNDER CONSTANT PUMPING FOR $r_w/r_c$ =0.033 and $\phi$=0.15

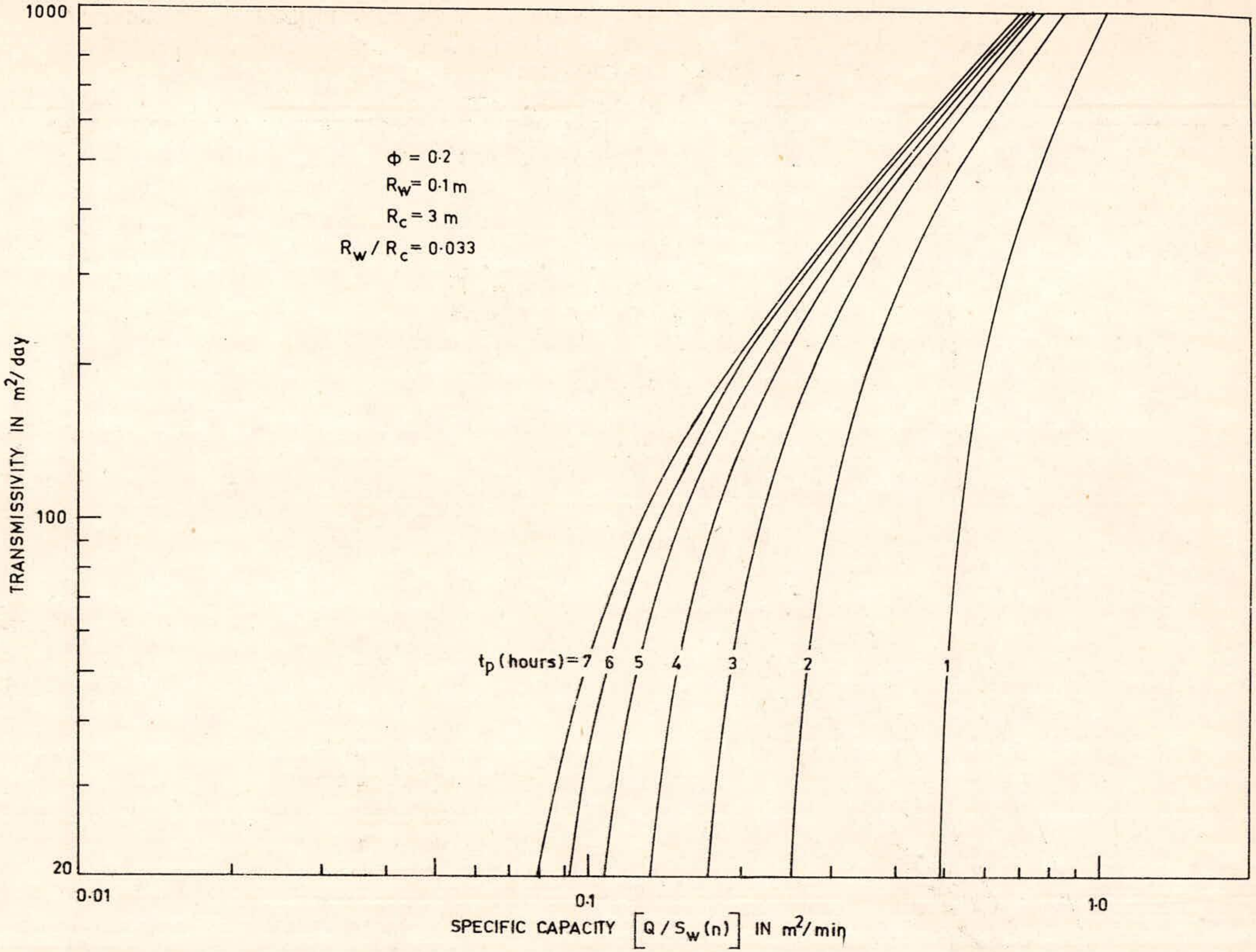


FIGURE 5(g) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP UNDER CONSTANT PUMPING FOR $r_w/r_c = 0.033$ and $\phi = 0.2$

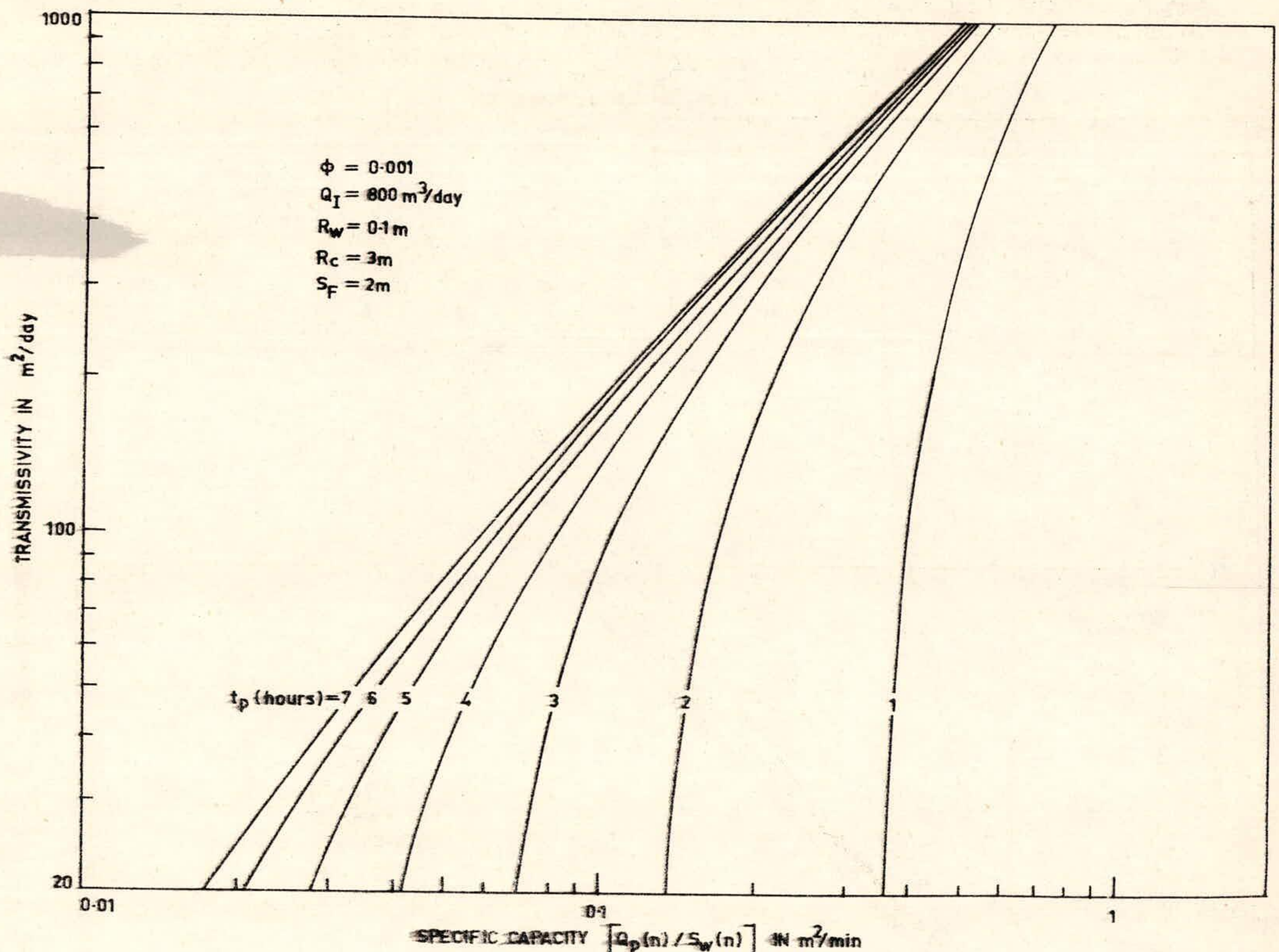


FIGURE 6(a) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP WHEN PUMPING RATE VARIES LINEARLY WITH DRAWDOWN FOR $r_w/r_c=.033$ and $\phi=.001$

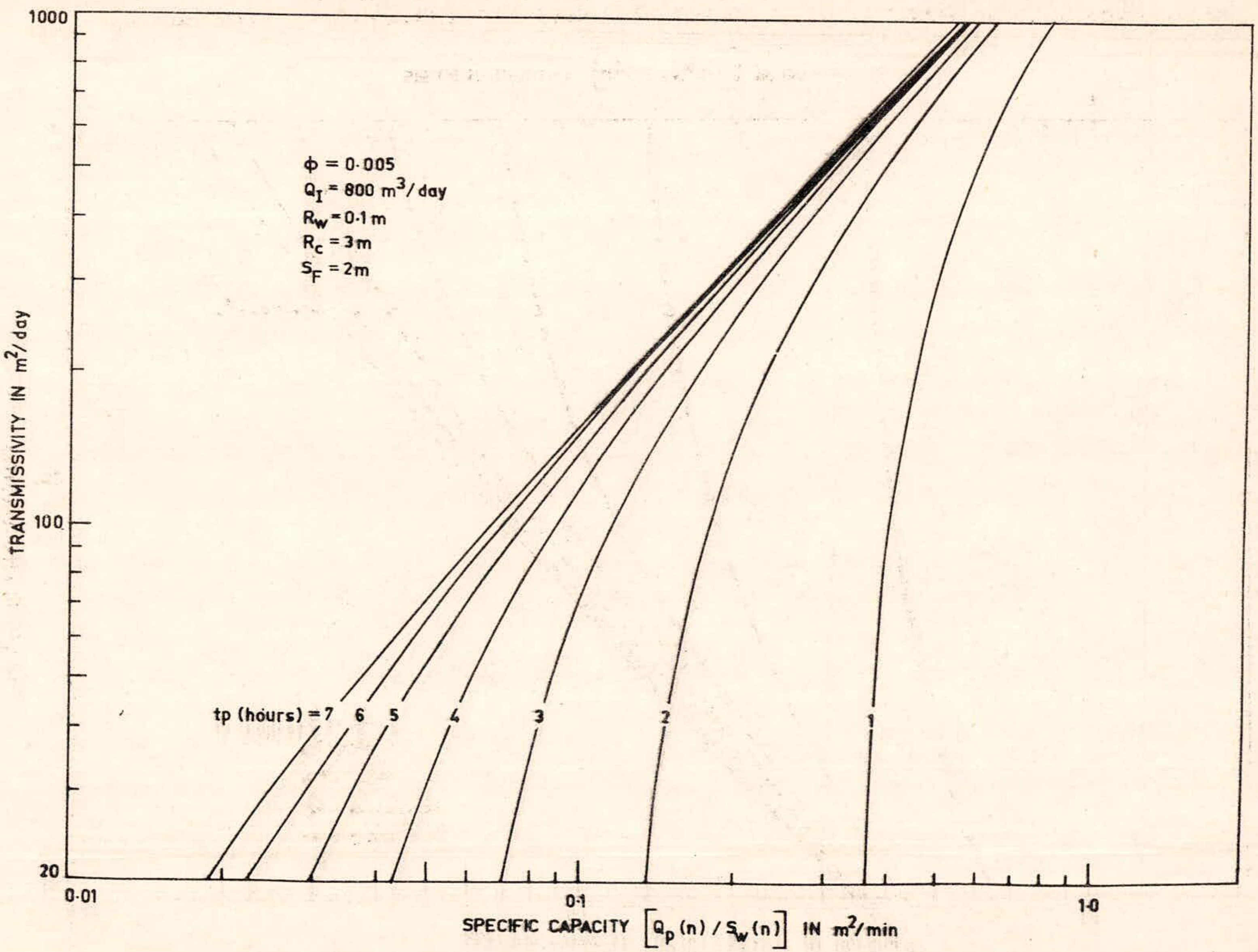


FIGURE 6(b) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP WHEN PUMPING RATE VARIES LINEARLY WITH DRAWDOWN FOR $r_w/r_c = .033$ and $\phi = 0.005$

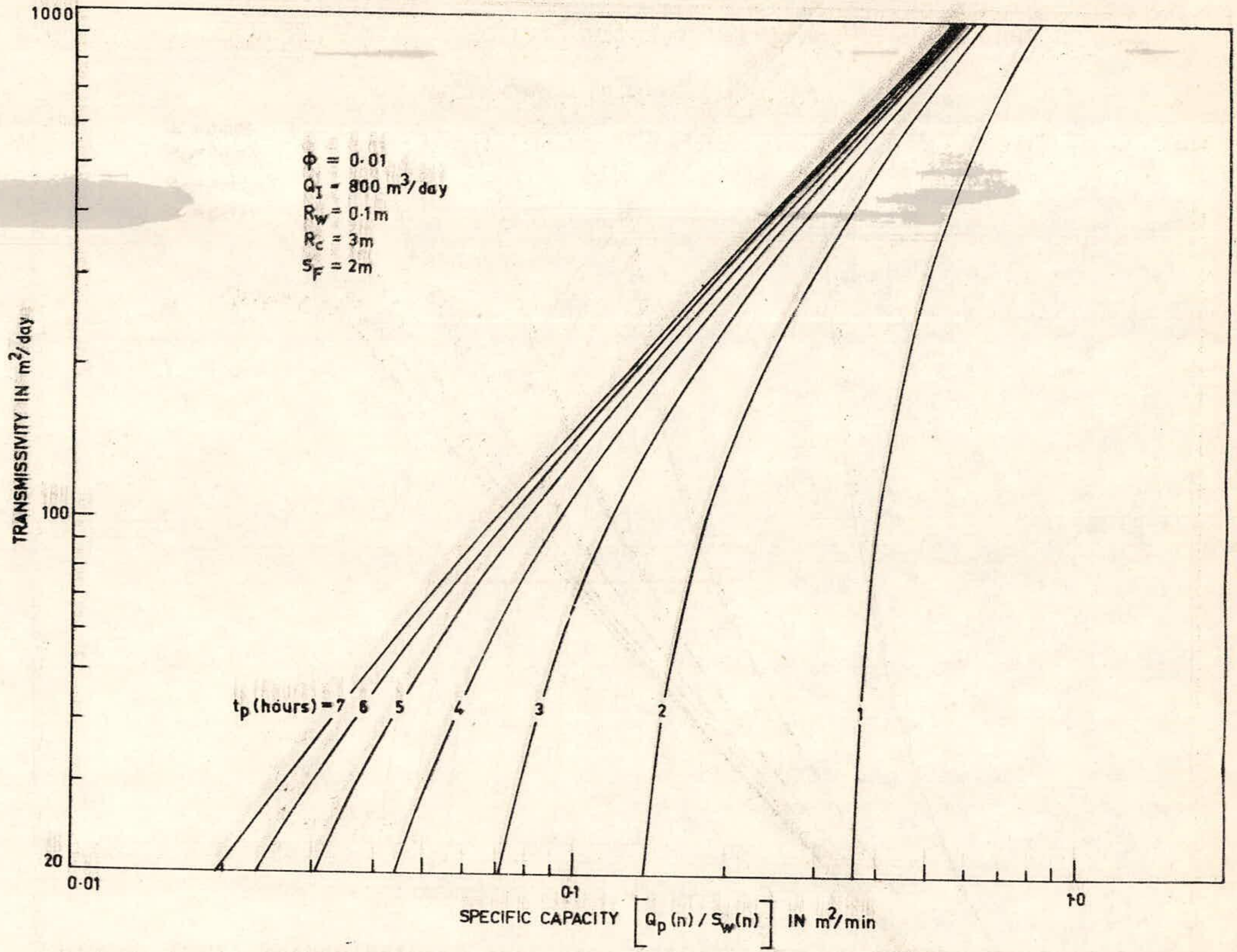


FIGURE 6(c) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP WHEN PUMPING RATE VARIES LINEARLY WITH DRAWDOWN FOR $r_w/r_c=.033$ and $\phi=0.01$

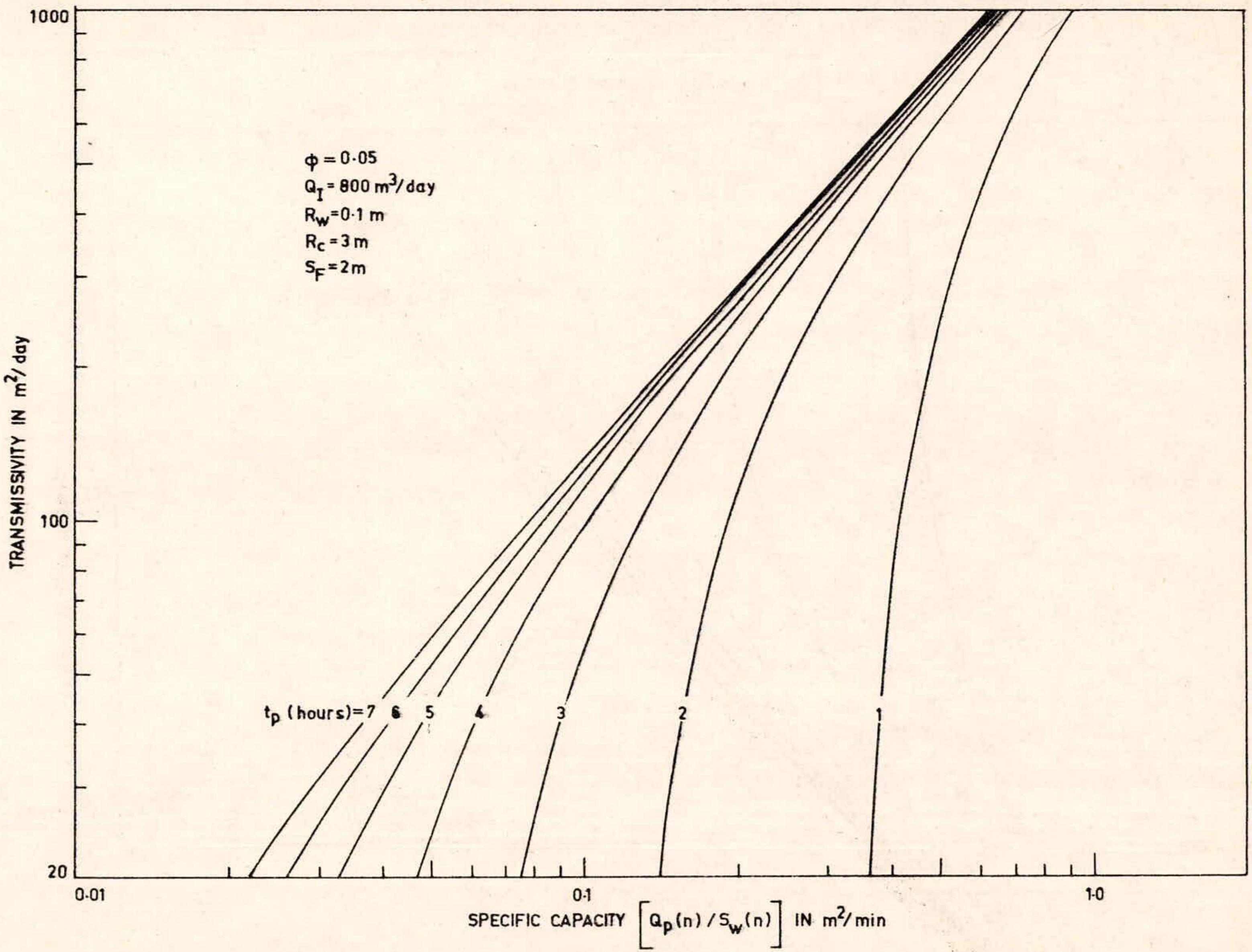


FIGURE 6(d) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP WHEN PUMPING RATE VARIES LINEARLY SITH DRAWDOWN FOR $r_w/r_c$=.033 and $\phi$ =0.05

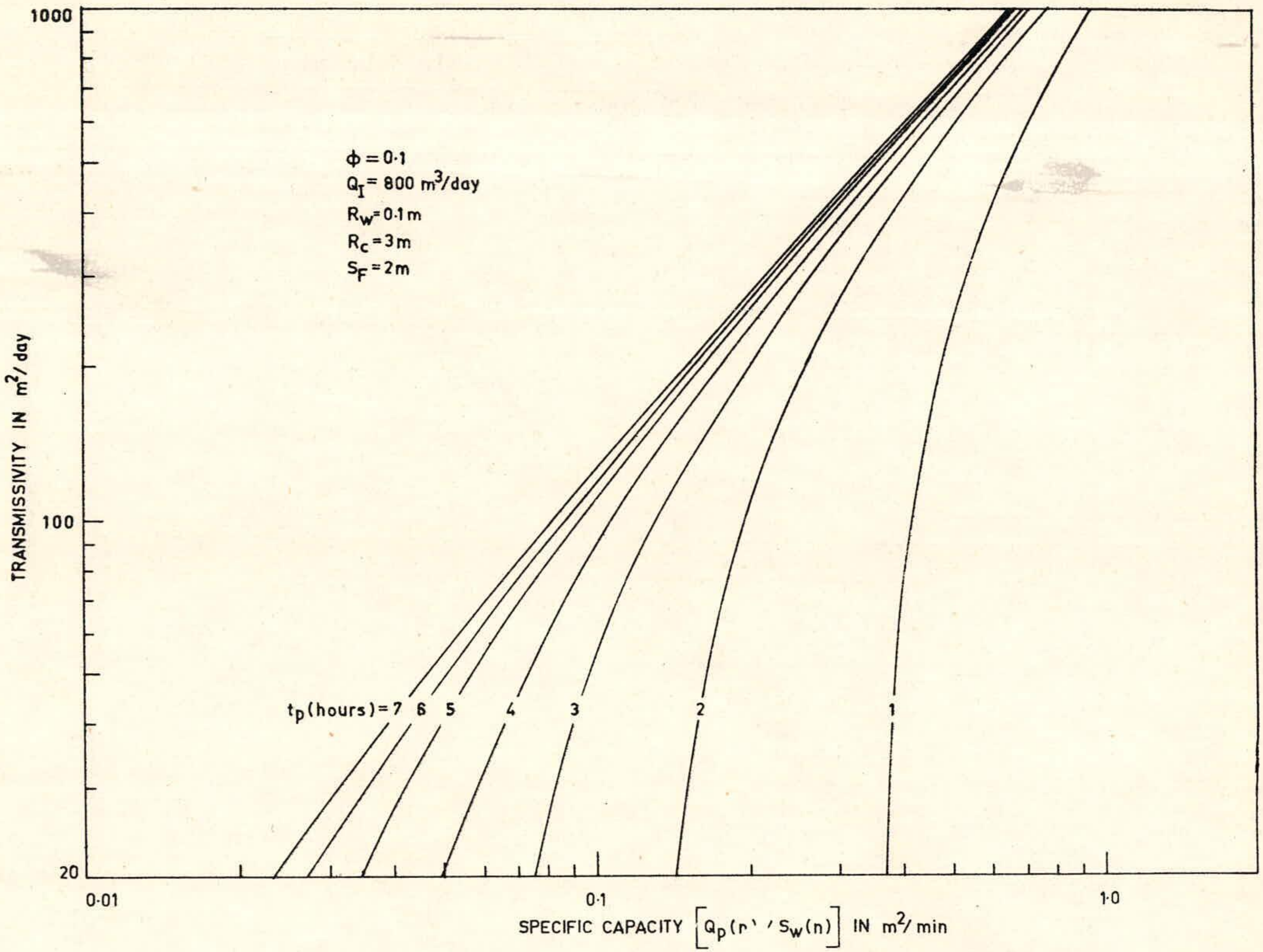


FIGURE 6(e) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP WHEN PUMPING RATE VARIES LINEARLY WITH DRAWDOWN FOR $r_w/r_c = .033$ and $\phi = 0.1$

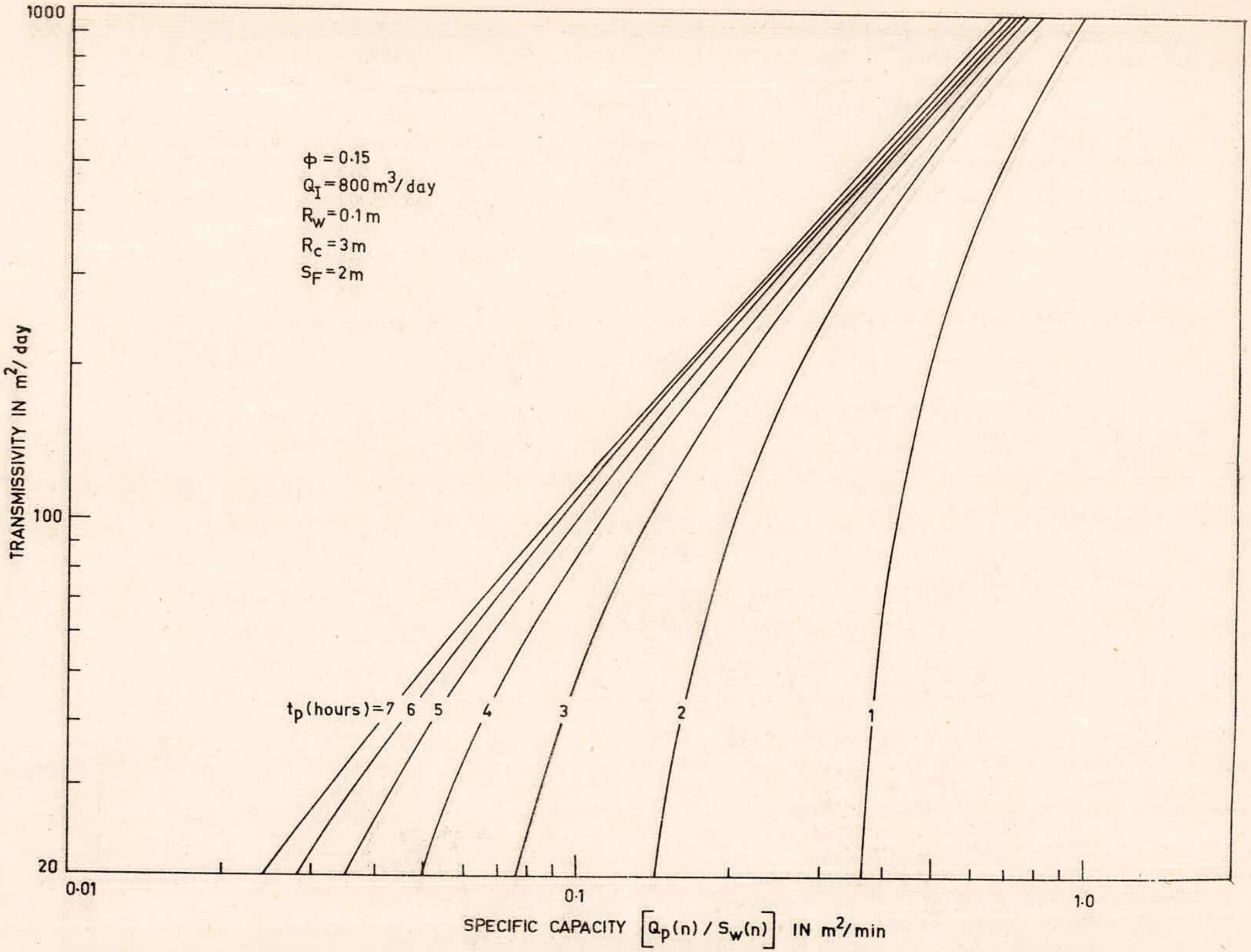


FIGURE 6(f) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP WHEN PUMPING RATE VARIES LINEARLY WITH DRAWDOWN FOR $r_w/r_c$=.033 and $\phi$ =0.15

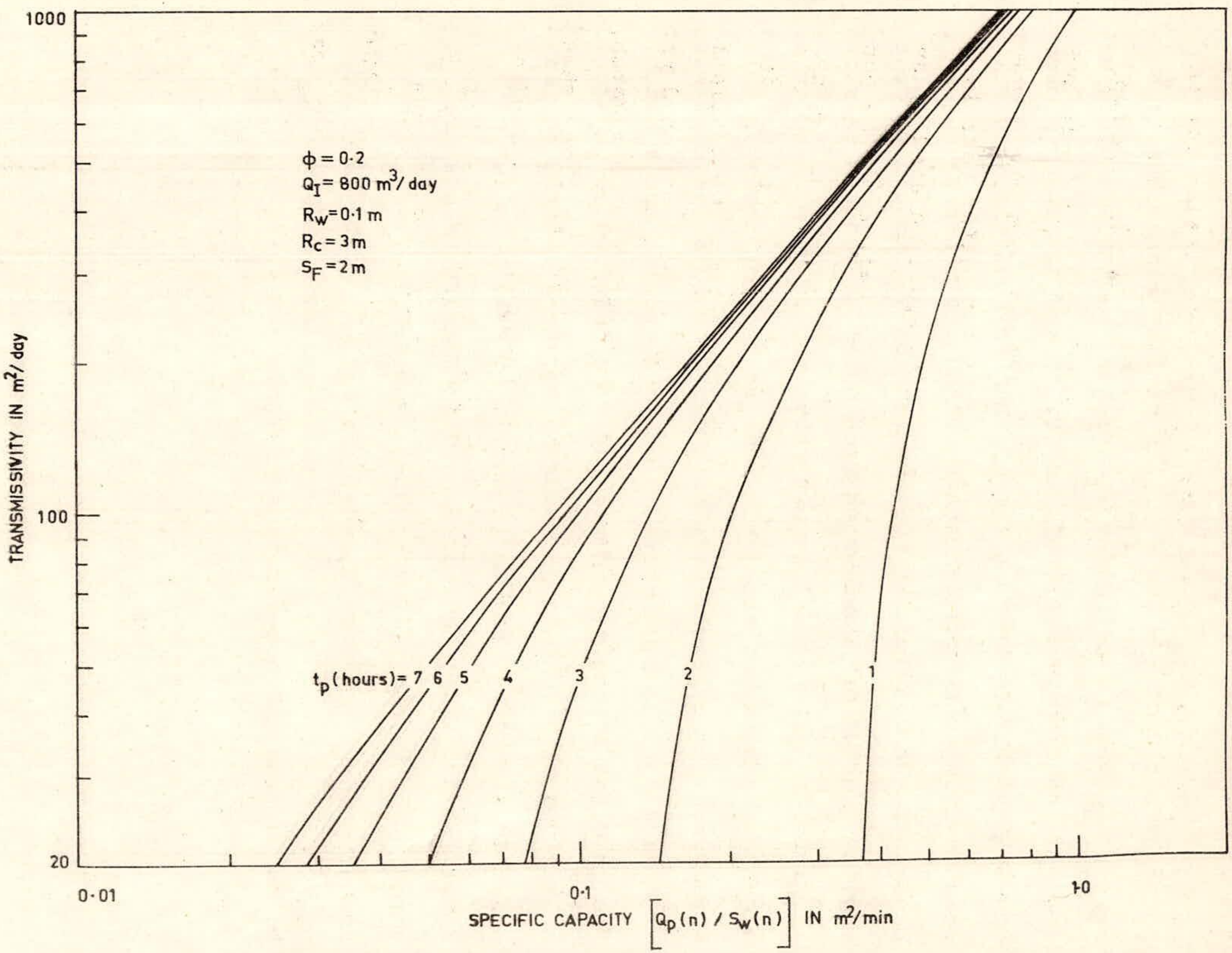


FIGURE 6(g) TRANSMISSIVITY SPECIFIC CAPACITY RELATIONSHIP WHEN PUMPING RATE VARIES LINEARLY WITH DRAWDOWN FOR $r_w/r_c = .033$ and $\phi = 0.2$

the non-dimensional time factor $\frac{4T_1 n}{\phi_1 r_w^2}$ are plotted for the adopted values of $\frac{T_1}{T_2}$ and $\frac{\phi_1}{\phi_2}$. In similar manner the type curves have been plotted for $\frac{T_1}{T_2}$ ranging from 0.1 to 10 and for $\frac{\phi_1}{\phi_2}$ ranging from 0.00001 to 10,000 and have been presented in Figures 7(a) through 7(e). When an aquifer test is conducted in a two aquifer system which are separated by an aquiclude the drawdown at the abstraction well could be observed and a graph of drawdown vs time could be plotted as shown in Figure 8. The time drawdown curve should be plotted in a log-log paper having the scale same as that of the available type curve. The drawdown vs time curve could be matched with one member of the type curves. While searching for a match, the abscissa of the type curve and time drawdown curve should be kept parallel. Once a matching has been identified( as shown in Figure 8), the $T_1/T_2$ and $\phi_1/\phi_2$ values, a set of $W(U_1(t))$, and $U_1(t)$ and corresponding S and t values are noted. The values of $T_1$ and $\phi_1$ will be given by $T_1 = (Q_p/4\pi S)W(U_1(t))$ and $\phi_1 = \frac{4T_1 t}{r_w^2 U_1(t)}$. Once $T_1$ and $\phi_1$ are estimated, $T_2$ and $\phi_2$ can be known from the noted ratios of $T_1/T_2$ and $\phi_1/\phi_2$.

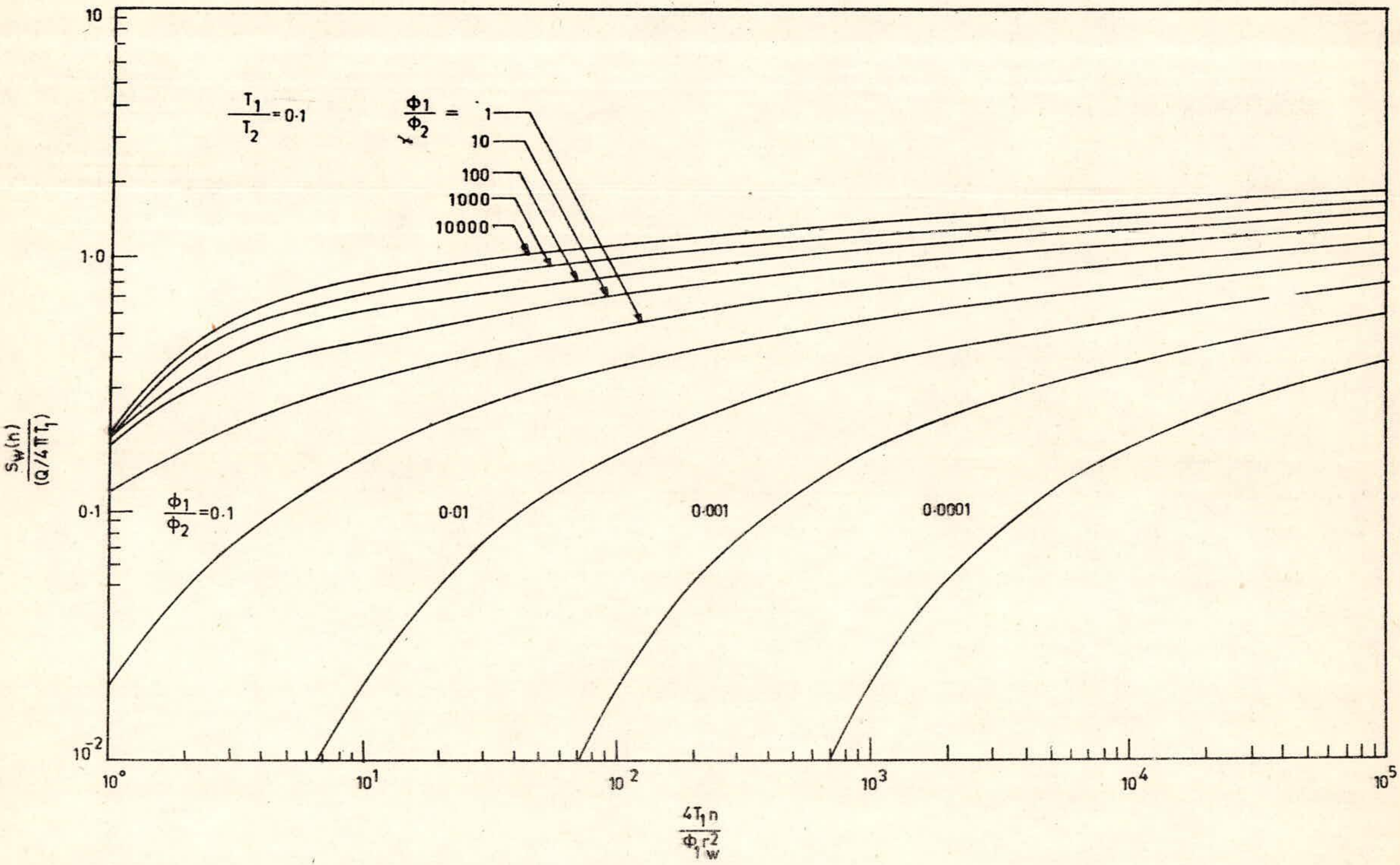


FIGURE 7(a) MULTIAQUIFER TYPE CURVE FOR $T_1/T_2 = 0.1$

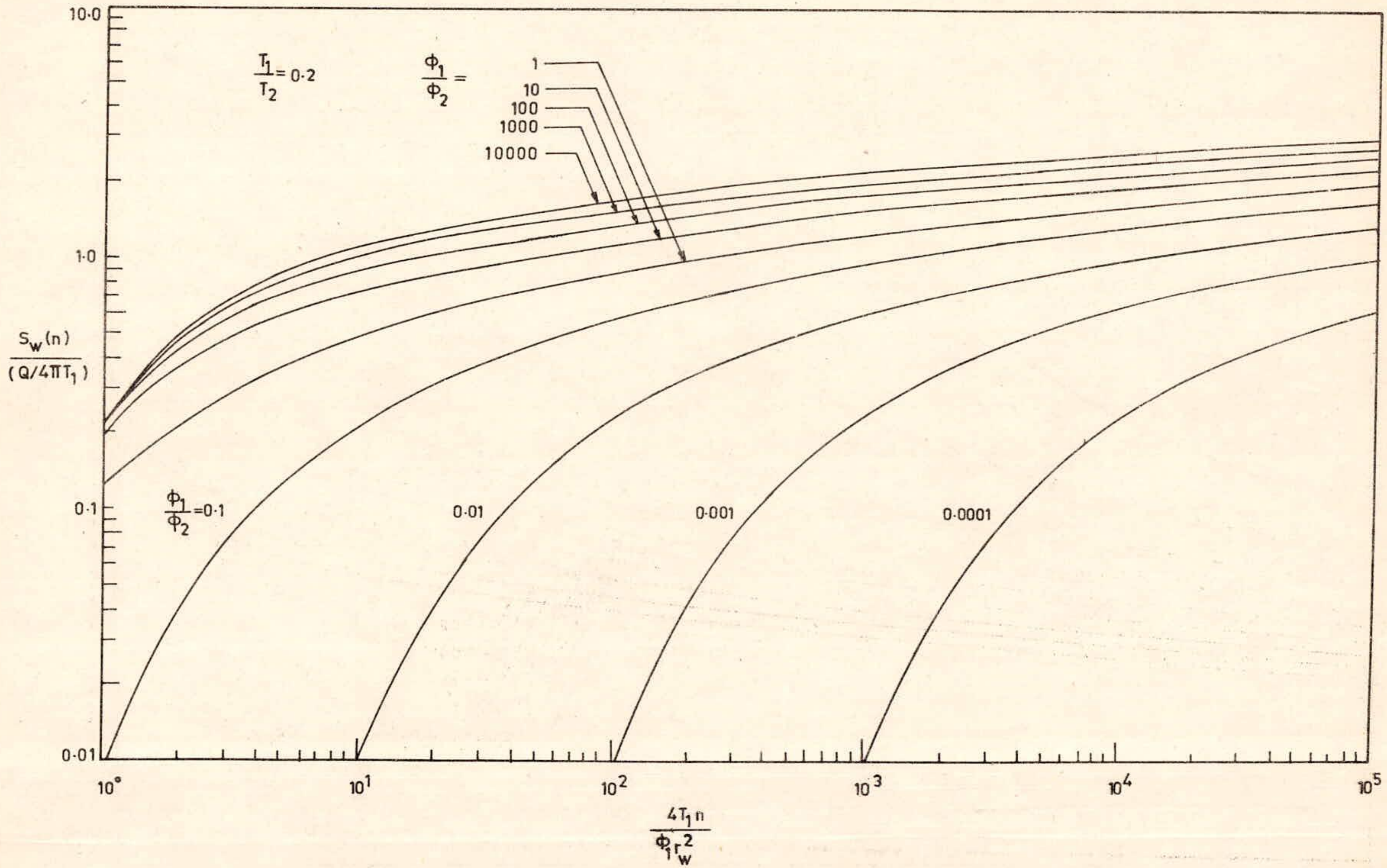


FIGURE 7(b) MULTIAQUIFER TYPE CURVE FOR $T_1/T_2 = 0.2$

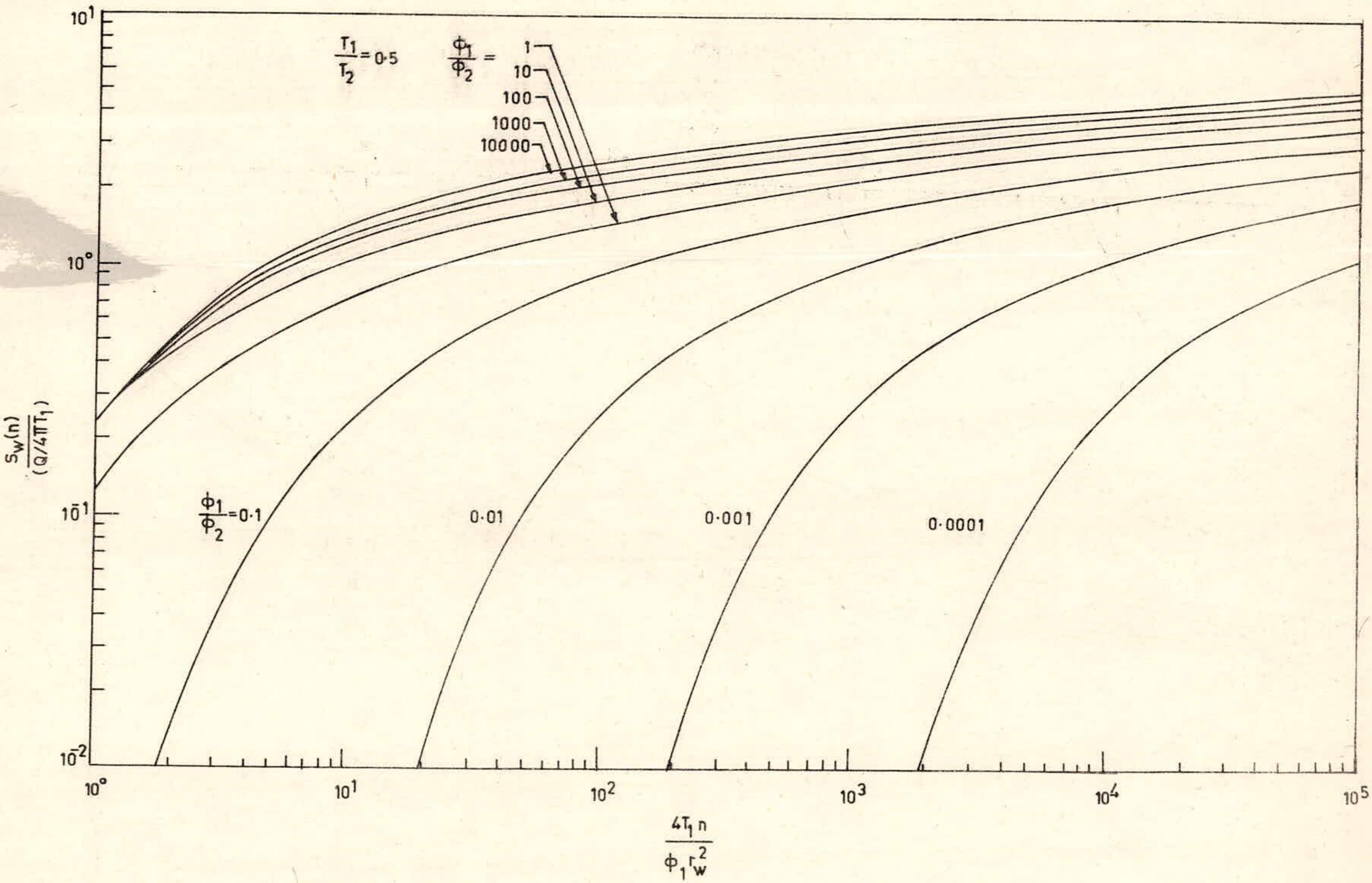


FIGURE 7(c) MULTIAQUIFER TYPE CURVE FOR $T_1/T_2 = 0.5$

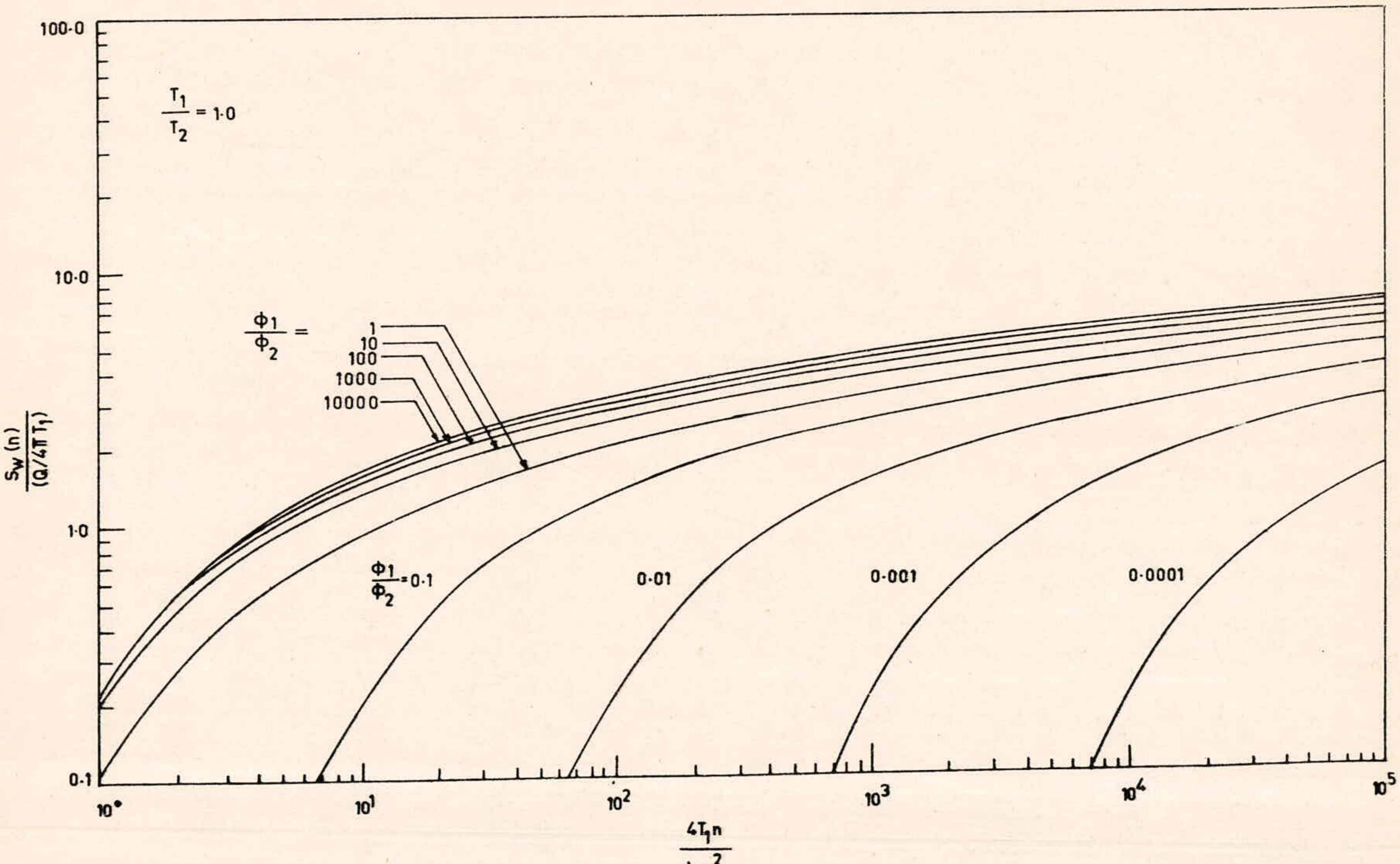


FIGURE 7(d) MULTIAQUIFER TYPE CURVE FOR $T_1/T_2 = 1.0$

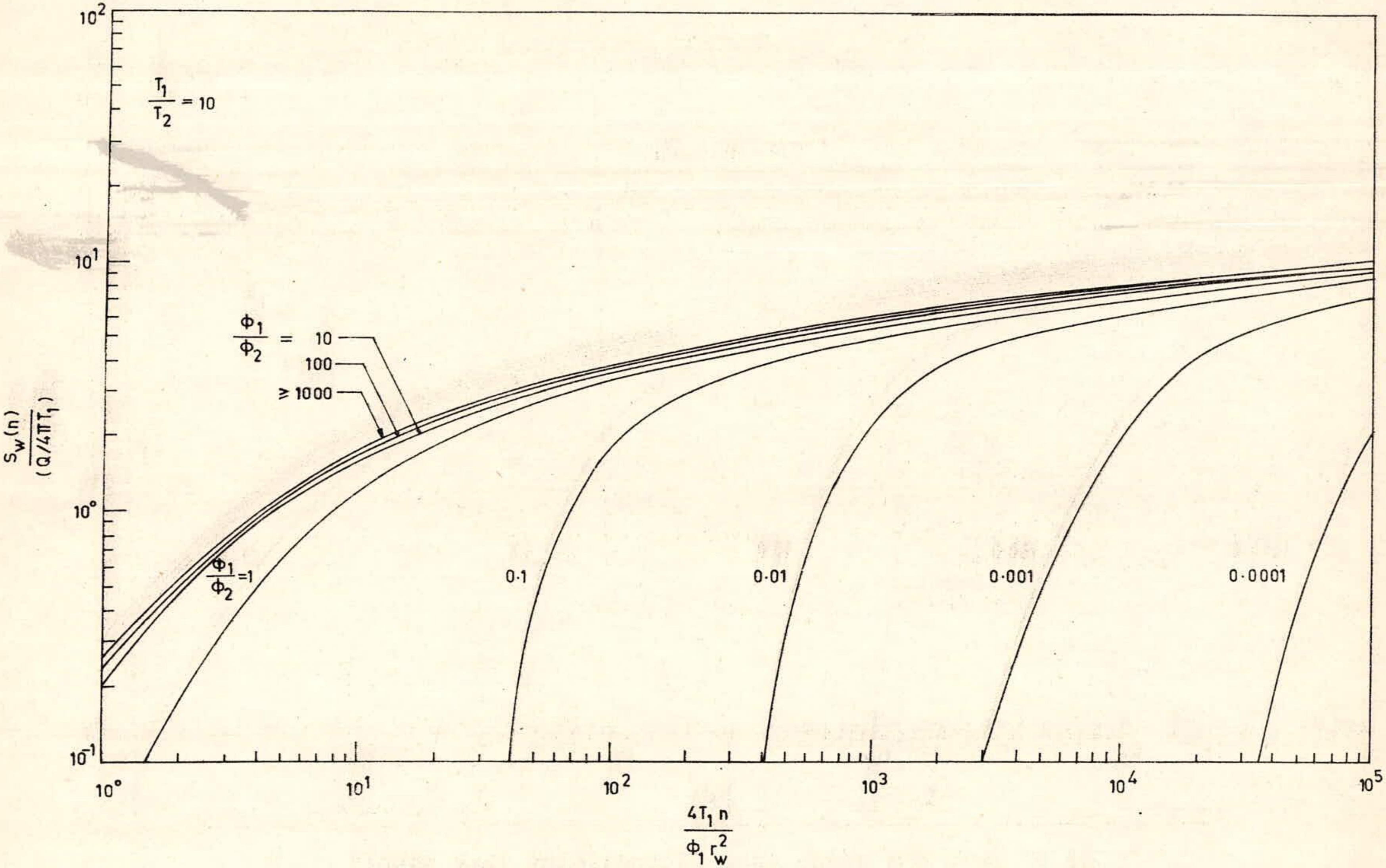


FIGURE 7(e) MULTIAQUIFER TYPE CURVE FOR $T_1/T_2 = 10$

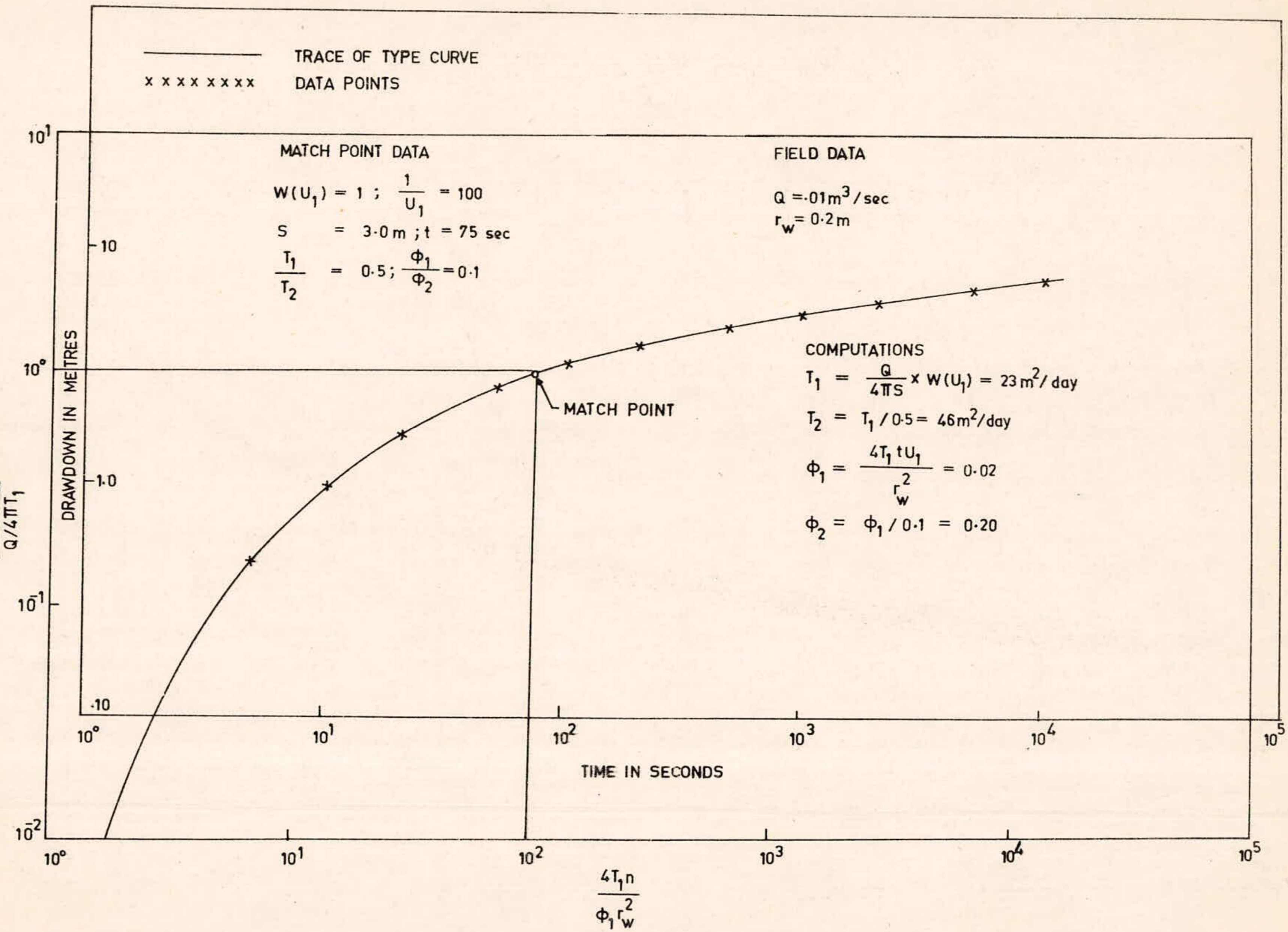


FIGURE 8 TYPE CURVE MATCHING FOR MULTIAQUIFER SYSTEM

## 5.0 CONCLUSIONS

Unsteady flow to a large-diameter well induced by time variant pumping has been analyzed by discrete kernel approach. Tractable analytical expressions have been derived for determination of aquifer contribution, well storage contribution and drawdown at any point in the aquifer. The variations of transmissivity with specific capacity have been presented for different values of storage coefficients considering well storage. Results have been presented for the cases when the pumping rate is independent of time and is a constant and when the pumping rate is linear functions of drawdown. These graphs can be used for quick determination of transmissivity when the storage coefficient is known a priori.

A set of type curves for a two aquifer system separated by an aquiclude has been presented. Using variation of drawdown at the abstraction well during an aquifer test conducted in the multiaquifer system the parameters of each layer can be estimated using these type curves.

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