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RETENTION OF GROUNDWATER RECHARGE BENEATH A SPREADING BASIN

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LIST OF SYMBOLS

a, b	-	dimensions of recharge basin
h, h_o	-	height of water level above datum
$\bar{h}$	-	weighted mean of the depth of saturation during the period of flow
k	-	coefficient of permeability
K	-	response corresponding to a unit step excitation
n, m	-	integers
P	-	total number of wells
Q_i	-	rate of withdrawal from the i^{th} pumping well
$Q_{RO}(t)$	-	quantity of water left the zone with radius R upto time t
$Q_{RR}(t)$	-	quantity of water retained in the zone with radius R upto time t
Q_R	-	quantity of water recharged
R	-	radial distance from the centre of the recharge basin
r_w	-	radius of the injection well
r_i	-	distance of the i^{th} pumping well from observation point
s	-	drawdown
T_i	-	transmissivity of the i^{th} aquifer
t	-	time
ϕ_i	-	coefficient of storativity of the i^{th} aquifer
β_i	-	hydraulic diffusivity of the i^{th} aquifer
$E_i(\cdot)$	-	an exponential integral

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ABSTRACT

Artificial recharge of groundwater is becoming increasingly important in groundwater management. Artificial recharge has been defined as the process of replenishing groundwater through various methods designed specifically for that purpose. These methods are: Direct-Surface, Direct-Subsurface and Indirect Techniques. Among the direct surface techniques, basin method is most favoured method of recharge and among direct subsurface techniques, recharge wells are generally used. Water table evolution due to recharge from basins having finite width and finite or infinite length have been analysed by various investigators. In the present report methods have been suggested to assess the water recharged from a basin or through an injection well. The methods of assessment are based on monitoring of the water table rise consequent to recharge. Analytical methods have also been developed to assess the volume of recharged water available in a region at different times after the on set of recharge.

1.0 INTRODUCTION

It has been recognized that aquifers are more than sources of water but storage reservoirs that require proper management for efficient use. With respect to management, aquifers may be classified as reservoir for long-term storage artificially produced and water quality control tools through use of the filtering characteristics of aquifers especially in respect of the artificial recharge of waste water. Artificial recharge may be viewed as an augmentation of the natural movement of surface water into underground formation by some method of construction, by surface spreading of water or by artificially changing natural conditions.

The purpose of artificial recharge of groundwater has been

i) to reduce, stop or even reverse declining level of ground water,

ii) to protect underground fresh water in coastal aquifer against salt water intrusion from the ocean,

iii) to store surface water, including flood or other surface water, imported water and reclaimed waste water for future use,

iv) to improve water quality by removing suspended solids by filteration through ground, and

v) to store water to reduce cost of pumping and piping.

There are two aspects associated with assessment of artificial recharge. They are assessment of the water actually recharged and availability of the recharged water with space and time. In this report methodology has been developed to predict quantity of water recharged and to evaluate the temporal and spatial variation of the recharged water.

2.0 REVIEW

2.1 Method of Artificial Recharge

Artificial recharge is performed by surface spreading, sub-surface injection and by induced infiltration from surface waters. Direct-surface recharge techniques are among the simplest, oldest, and most widely applied method of artificial recharge. In these methods, water moves from land surface to the aquifer by percolating through the soil. Field studies of spreading techniques have shown that, of the many factors governing the amount of water that will enter the aquifer, the area of recharge and length of time that the water is in contact with the soil are the most important. Direct-surface methods can be grouped into several categories such as: flooding, ditch and furrow, basins, stream channel modification, and over-irrigation.

2.1.1 Flooding

Recharge by flooding can be done only on land having a 1 to 3 percent slope. The objective is to spread water over a large area in a thin film that travels slowly down hill without disturbing the soil. The water is spread over the land surface from several distribution points to obtain an even application. Embankments or ditches may bound the system to localize infiltration or to protect adjacent land. Excess water may be collected at the systems topographic low point for disposal.

The biggest problem with the flooding technique is containments. Other problems are related to large area required and evaporation. The method's greatest advantage is the relatively low cost of construction and maintenance.

2.1.2 Ditch and Furrow Systems

In this method, a source stream provides recharge water that is passed through closely spaced, shallow, flat-bottomed ditches or furrows. Most ditch-and-furrow systems have one of three patterns: lateral, dendritic, or contour (see Fig.1).

Lateral Systems

These characteristically have one or more main supply canals from which smaller ditches protrude at right angles. Gates at the head of these systems control flow rates. Furrow depth depends on topography but rarely exceeds that necessary to maintain a uniform velocity with maximum wetted surface. Most systems divert stream water into main canals, pass the water through a series of lateral furrows, and collect runoff in a canal further downslope that routes the water back to the source stream.

Dendritic Systems

These divert flow from a main canal to a series of successively smaller ditches and gates control the flow to each series of ditches. The bifurcation of ditches continues until virtually all water has infiltrated; terminal collection ditches are optional.

Contour Systems

These spread water through a ditch or ditches that follow the contour of the land. A switchback is made wherever the ditch approaches the limit of the spreading area. In effect, the ditch traverses the spreading area repeatedly and, at the lowest point, returns the water to the source stream.

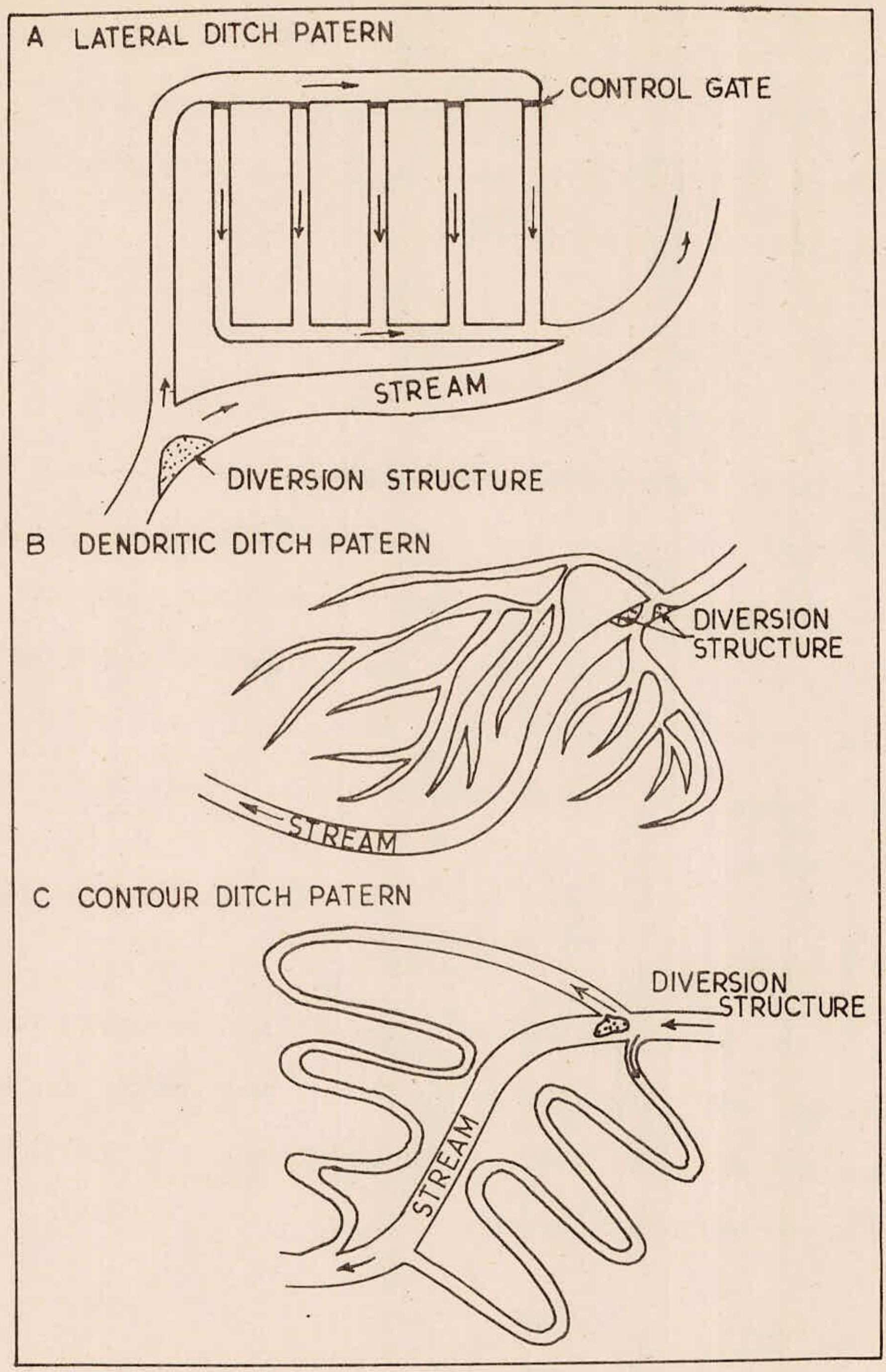

FIG. 1 TYPICAL DITCH & FURROW SYSTEMS(A) LATERAL (B) DENDRITIC (C) CONTOUR (ARROWS INDICATE DIRECTION OF FLOW)

The ditch-and-furrow system is particularly advantageous where recharge water contains high loads of suspended sediment. Generally, system flow rates are sufficient to carry a large percentage of foreign materials through the system and back into the source stream.

2.1.3 Basins

Basins are probably the most favoured method of recharge because they allow efficient use of space and require only simple maintenance. Basins are either excavated or are enclosed by dikes or levees. Basin geometry is flexible, allowing construction to be adapted to the terrain. Basins may be constructed individually, such as in small drainage areas to collect urban runoff, or in series for infiltration of stream or stormwater, as shown in Figure 2. Use of multiple basins for infiltration of stream water provides several advantages: the storage capability allows a longer time for recharge, the upstream basins act as clarifiers for those below, and the ability to bypass the basins permits periodic maintenance (such as scrapping) to restore infiltration rates. In flat areas, basins are more costly to construct because natural landform containments cannot be used; basins in such areas are commonly long, straight, and narrow and are constructed side by side.

The advantages of basins include:

1. Expected flows can generally be accommodated by constructing basins of appropriate size.
2. Intermittent floodwater can be stored for later infiltration.
3. Clogging can be easily mitigated through basin construction techniques or operational procedures.
4. Land is used efficiently.

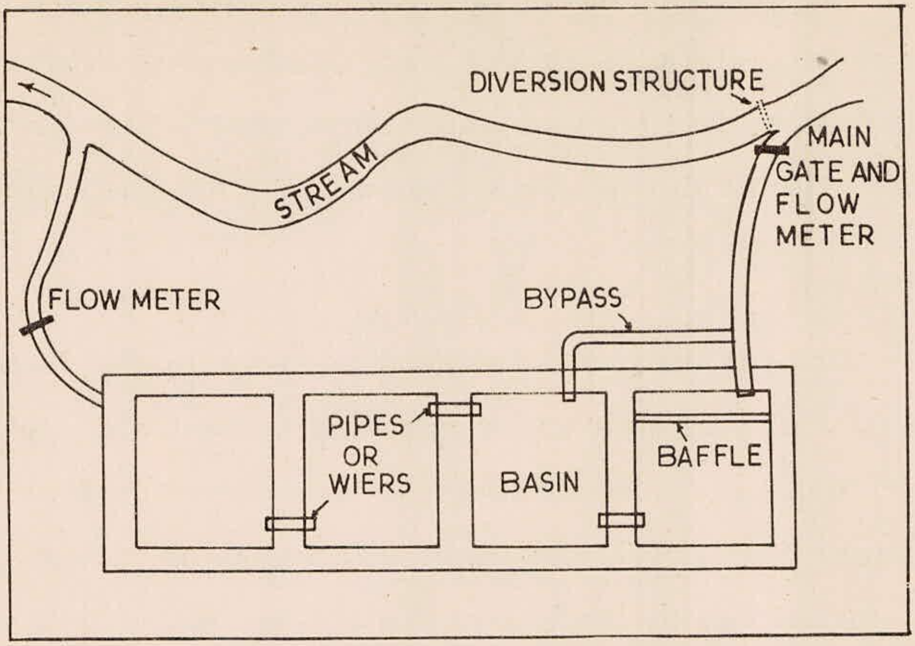

FIG.2 A SERIES OF RECHARGE BASINS RECEIVING STREAM WATER

2.1.4 Stream Channel Modification

Stream channel modification entails construction of check dams across stream flood plains. Above the dams, basin like impoundments enhance recharge by increasing the wetted area and driving head while detaining water for recharge, below the dams, recharge is enhanced through exposure of more than just the original stream channel to water (Fig.3). Because stream water flowing at velocities greater than the stream bed infiltration rate is essentially lost, upstream reservoirs can be constructed to dispense water in accordance with stream bed infiltration capacity.

Dredging flowing channels also increases the infiltration efficiency, and widening, leveling, increase the wetted area as well as infiltration rate.

Most stream channel modification structures are temporary and

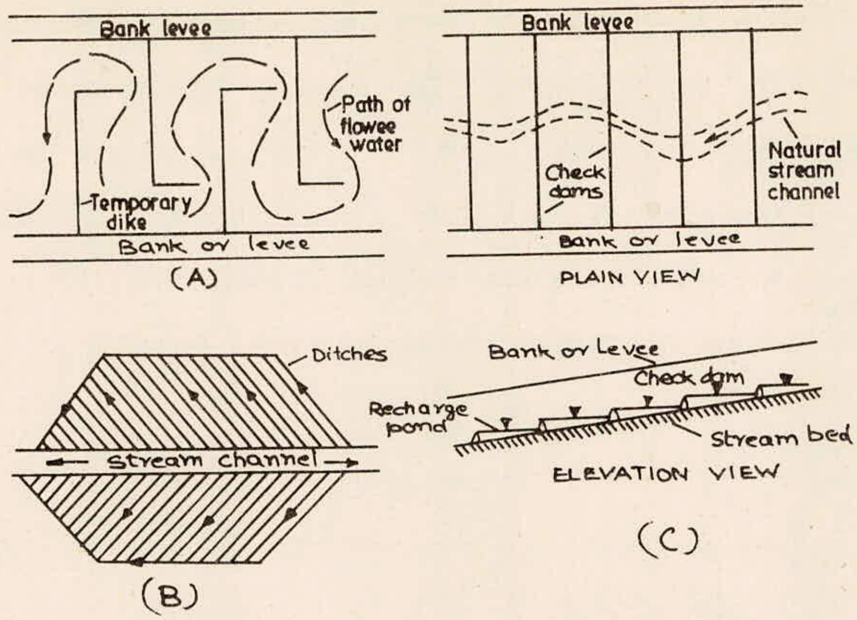

FIG.3 RECHARGE BY STREAM CHANNEL MODIFICATION (A) DIVERSION, (B) DITCHES, (C) CHECK DAM

are designed to increase recharge only seasonally. Many are destroyed by floods. Nevertheless, stream channel modification is effective wherever suitable because construction costs are relatively low, maintenance is inexpensive, and the procedure rarely conflicts with other land uses.

2.1.5 Overirrigation

When irrigation water is applied during nongrowing seasons, the groundwater is artificially recharged. Methods of irrigation are similar to those of artificial recharge and include overland flow, ditch-and-furrow systems, sub-irrigation, flooding, and spray systems. Because overirrigation is usually created by excess surface water, one of the first four techniques described is usually employed. Implementation costs are minimal because the water distribution works have already been constructed.

2.2 Direct-Subsurface Recharge

Direct-subsurface recharge is achieved when water is conveyed and emplaced directly into an aquifer. Direct-subsurface recharge generally is used when a semipermeable confining stratum separates the source of recharge water from the aquifer requiring replenishment. Techniques of direct-subsurface recharge include injection of water into (1) natural openings in the aquifer, (2) pits or shafts, (3) wells (see Fig.4)

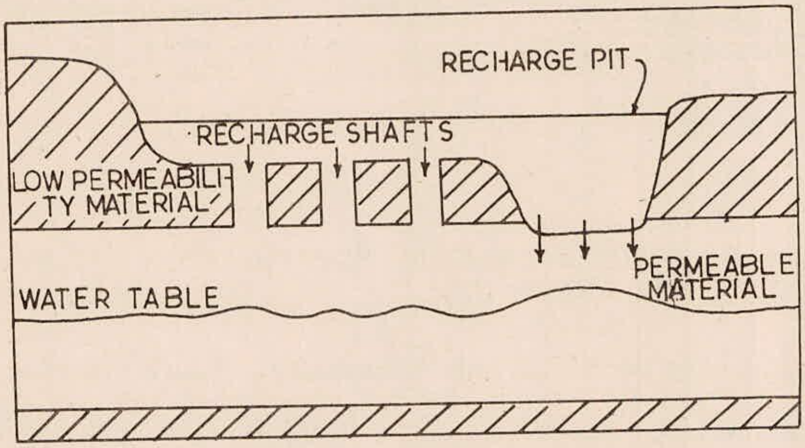

FIG.4 RECHARGE PITS AND SHAFTS

In all methods of subsurface recharge, the quality of the recharge water is of primary concern because the water enters the aquifers without the filtration or oxidation that occur when water percolates through the unsaturated zone. All direct-subsurface methods of recharge use structures that occupy much less land than is required for surface methods.

2.2.1 Natural Openings

Natural openings, such as those caused by fracturing or solution in cavernous limestones or other soluble rock, can act as a drain beneath an impounded body of water or as the extension of a pipeline delivering water to it. Depending on the source of water and size, configuration, and location of the openings, maintenance, protection, and improvement may not be necessary. Although this type of recharge system is relatively inexpensive, un-favourable terrain and geologic conditions may preclude its use.

2.2.2 Pits and Shafts

Where a semipervious confining layer is at or near land surface, the aquifer(s) below must be recharged through deep pits or shafts penetrating that layer. Pits are variable in dimension, their depth generally is dependent on the thickness of the confining unit. The steep sides of pits minimize the opprotunity for clogging, which occurs mainly at the pit bottom. Costs of construction and maintenance are high compared to surface techniques, especially if comparatively small quantities of water are to be applied.In some areas, these costs can be avoided by use of abandoned gravel pits or quarries.

Shafts are deeper than pits and smaller in diameter. They are either constructed by hand with draglines or are drilled or bored. They can be filled with coarse material or simply lined. As with all subsurface techniques, shaft walls and fill materials are succeptible to clogging by suspended solids or biologic activity. Shafts are particularly difficult to maintain. Although similar in operation to large-diameter wells, shafts that terminate above a static water table cannot be redeveloped by pumping. Rest periods and chemical treatment are generally the only means of restoring infiltration capacity and are often only partly successful. Badly clogged shaft fill material must be removed and replaced with clean fill. Because of high construction and maintenance costs, pits and shafts have limited application.

2.2.3 Wells

Recharge wells, commonly called injection wells, are generally used to replenish groundwater when an aquifer is deep and separated from the surface by materials of low permeability. If injection wells are installed in unconsolidated material, the upper section of the well is cased and the screen is placed directly in the aquifer or surrounded by an artificial gravel pack. Typically a concrete seal is constructed at the point where the well passes into the aquifer to prevent injection pressures from forcing water upward around the casing. For a consolidated aquifer overlain by impermeable consolidated deposits, casing and screens may not be required. Wells are also used to recharge unconfined aquifers where the available land is limited. Recharge wells are not limited to replenishining just one aquifer, nor does the recharge water need to be derived from a surface source. Recharge wells can be constructed to supply water to two or more aquifers simultaneously (Fig.5) and, where hydraulic conditions permit, can be used as passive connectors between adjacent aquifers separated by impermeable material (Fig.6).

In addition to the primary purpose of replenishing potential aquifers, recharge wells have also been used to recharge groundwater used for air conditioning and to add freshwater to coastal aquifers experiencing saltwater intrusion. Injection well design depends on the recharge purpose, the amount of water to be injected and the acceptance rate of the aquifer. The latter is a function of hydraulic gradient, aquifer permeability, and length and type of screen. Because the contact area between well screen and aquifer is small, gravel packs surrounding the screen are

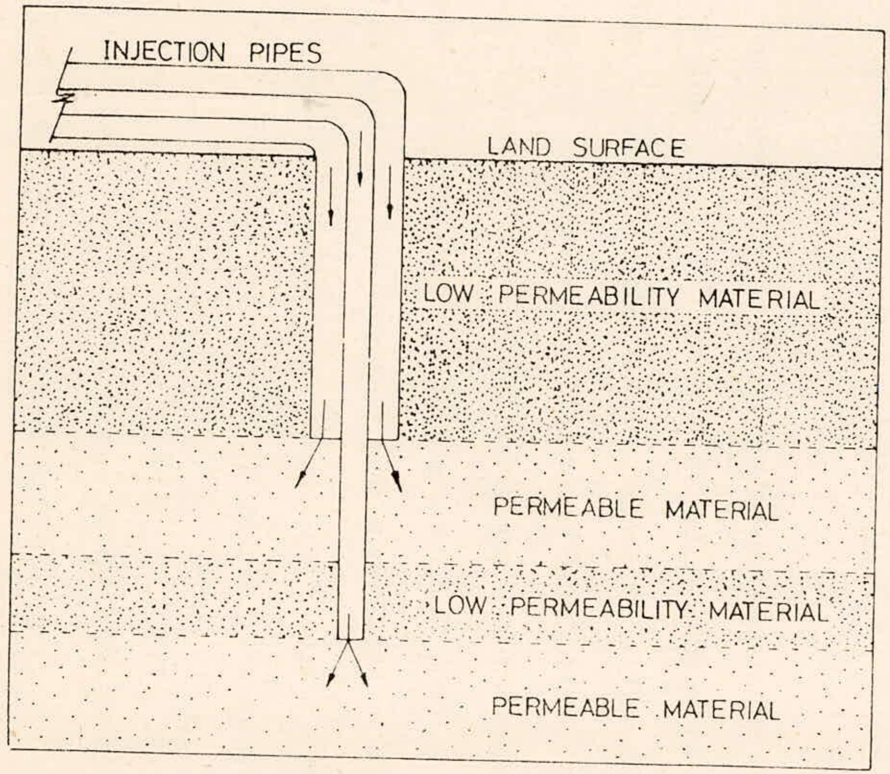

FIG.5 MULTIAQUIFER RECHARGE WELL

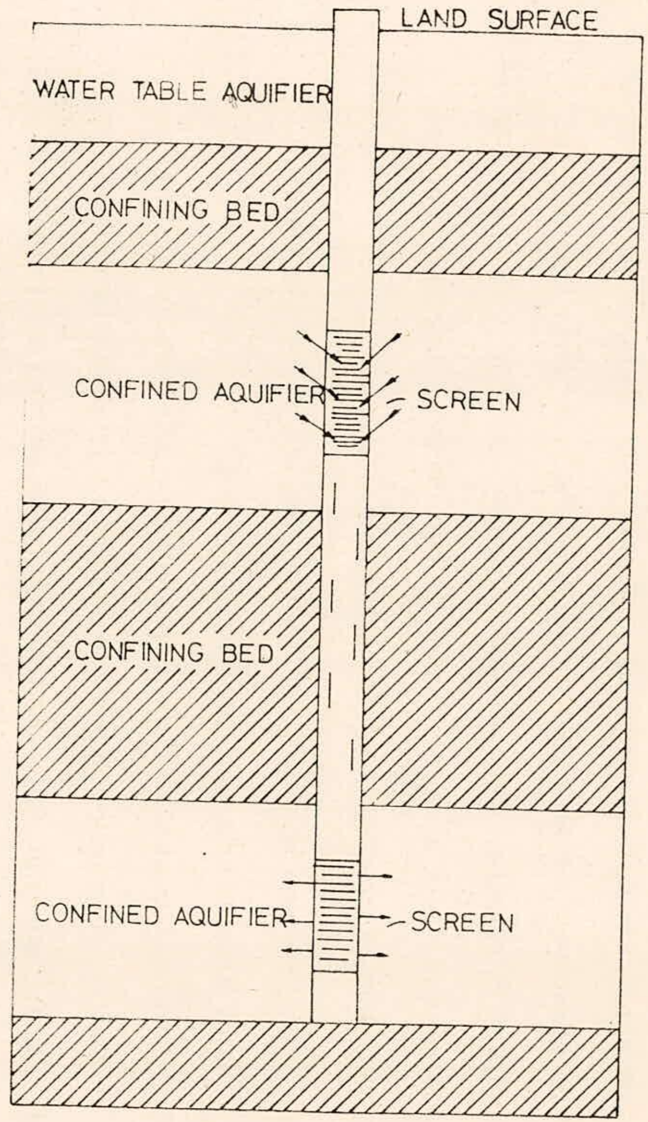

FIG.6 CONNECTOR WELL USE IN AQUIFER RECHARGE

generally used to increase the effective well diameter.

Recharge well performance can be severely hindered by the accumulation of suspended solids and biologic and chemical impurities, as well as by dissolved air and gases and entrained air from turbulence. Most clogging effects can be avoided by proper treatment of the recharge water beforehand, but to correct once it has occured requires various well redevelopment procedures, which include:

1. Pumping and surging the well to remove inorganic material and loosely attached organic material.
2. Adding biocides and oxidizing agents to eliminate organic matter stemming from bacteria and their waste products.
3. Using specific chemical treatments to remove encrustation caused by chemical precipitation.

2.3 Induced Recharge

Direct methods of artificial recharge described above involve the conveyance of surface water to some point where it enters the ground. Distinguished from these methods is the method of induced recharge, accomplished by withdrawing groundwater at a location adjacent to a river or lake so that lowering of the groundwater level will induce water to enter the ground from the surface source. The schematic cross sections of a river valley in Fig.7 show flow patterns with and without induced infiltration from a stream. On the basis of this definition, wells located directly adjacent to and fed largely by surface water serve as means of artificial recharge.

Induced infiltration where supplied by a perennial stream ensures a continuing water supply even though overdraft condition may exist in nearby areas supplied only by natural recharge. The method has proved effective in unconsolidated formations of permeable sand and gravel hydraulically connected between stream and aquifer. The amount of water induced into the aquifer depends on the rate of pumping, permeability, type of well, distance from surface stream, and natural groundwater movement. It is important that the velocity of the surface stream be sufficient to prevent silt deposition from sealing the streambed.

Studies of water quality have shown that induced recharge can furnish water free of organic matter and pathogenic bacteria. Because surface water commonly is less mineralized than groundwater, water obtained by induced infiltration, being a mixture of two water sources, possesses a higher quality than natural groundwater.

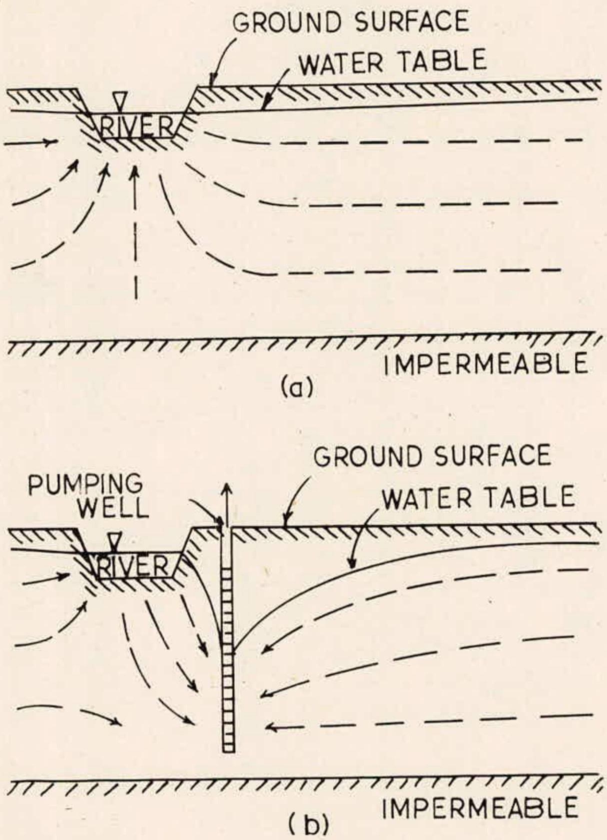

FIG.7 INDUCED RECHARGE RESULTING FROM A WELL PUMPING NEAR A RIVER (a) NATURAL FLOW PATTERN, (b) FLOW PATTERN WITH PUMPING

2.4 Assessment of Artificial Recharge

A typical curve of recharge rate versus time is shown in Fig.8. The initial decrease is attributed to dispersion and swelling of soil particles after wetting; the subsequent increase accompanies elimination of entrapped air by solution in passing water; the final gradual decrease results from microbial growths clogging the soil pores. Long-term recharge rates vary widely; Table 1 summarizes representative rates obtained for basins in the United States. A study of artificial recharge projects in California indicated that natural ground slope can serve as a convenient guide for estimating long-time rates. For alluvial soils in the slope range of 0.1 to 10 percent, the long-time infiltration rate W in metres per day is given by

$$W = 0.65 + 0.56i$$

Where i is the natural ground slope in percent. Individual rates were found to vary within a factor of 2 of this estimate.

TABLE 1 Representative Spreading Basin Recharge Rates (Todd,1980)

Location	Rate, m/day
Santa Cruz River, Arizona	0.3-1.2
Los Angeles County, California	0.7-1.9
Madera, California	0.3-1.2
San Gabriel River, California	0.6-1.6
San Joaquin Valley, California	0.1-0.5
Santa Ana River, California	0.5-2.9
Santa Clara Valley, California	0.4-2.2
Tulare County, California	0.1
Ventura County, California	0.4-0.5
Des Moines, Iowa	0.5
Newton, Mass.	1.3
East Orange, N.J.	0.1
Princeton, N.J.	Less than 0.1
Long Island, N.Y	0.2-0.9
Richland, Washington	2.3

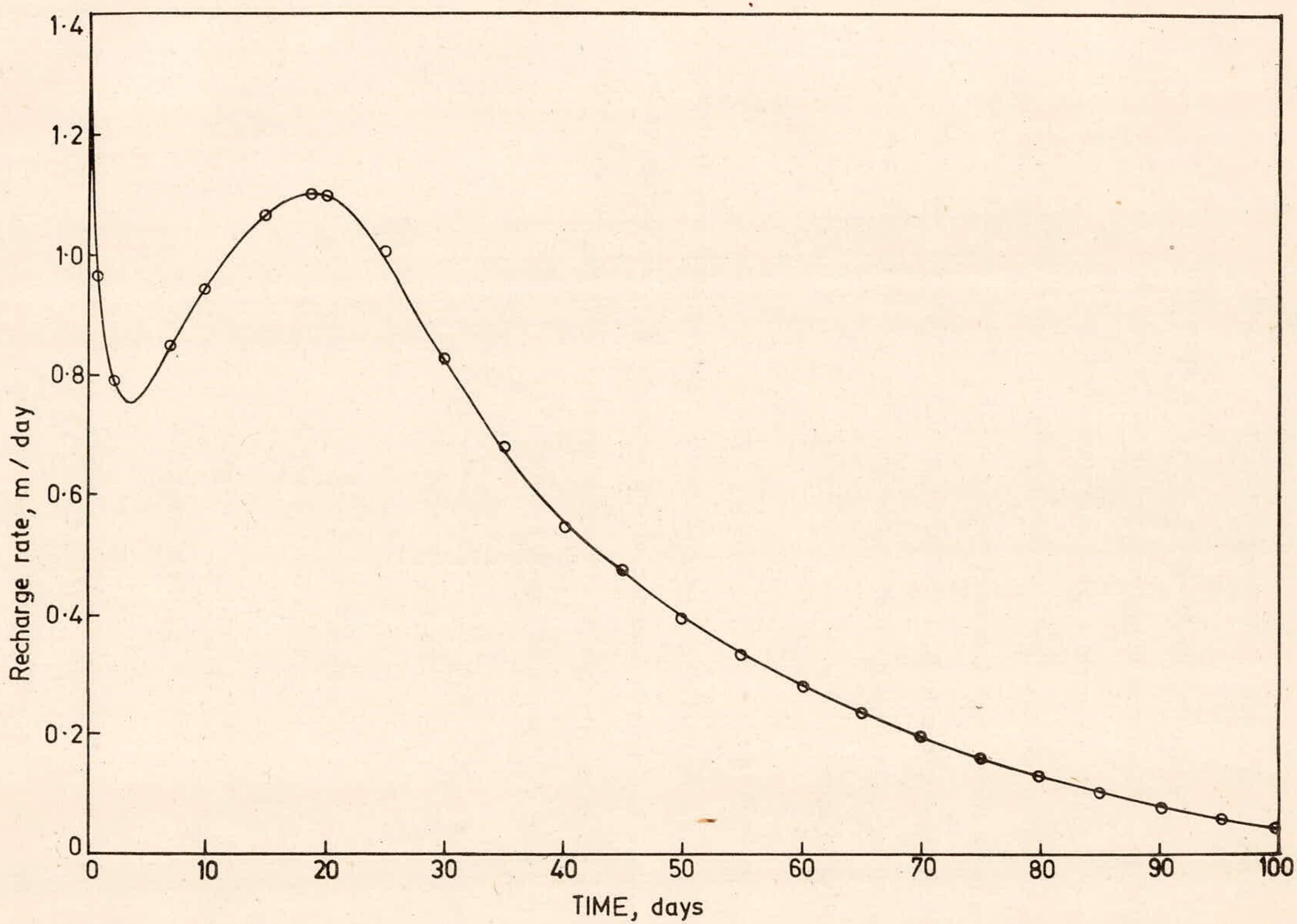

FIG.8 TYPICAL TIME VARIATION OF RECHARGE RATE FOR WATER SPREADING ON UNDISTURBED SOIL

3.0 STATEMENT OF THE PROBLEM

3.1 Assessment of Water Recharged by Basin Method

Schamatic section and plan view of a spreading basin and the groundwater abstraction structures are shown in Figure 9. Water is recharged through the basin during a certain period of time. The groundwater is withdrawn through abstraction wells as shown in the figure. Continuous monitoring of groundwater level is done at an observation well. It is required to find the quantity of groundwater recharged through the basin and its distribution in space and time using groundwater level data.

3.1.1 Methodology

Hantush (1967) developed the following approximate analytical expression for the rise and fall of the water table in an infinite unconfined aquifer in response to uniform percolation from a rectangular spreading basin in absence of pumping wells:

$$h^2 = h_0^2 + \left(\frac{w\bar{h}t}{2\phi}\right) \{F[\frac{(a+x)}{2\sqrt{(k\bar{h}\ t/\phi)}}, \frac{(b+y)}{2\sqrt{(k\bar{h}\ t/\phi)}}]$$

$$+ F[\frac{(a+x)}{2\sqrt{(k\bar{h}\ t/\phi)}}, \frac{(b-y)}{2\sqrt{(k\bar{h}\ t/\phi)}}]$$

$$+ F[\frac{(a-x)}{2\sqrt{(k\bar{h}\ t/\phi)}}, \frac{(b+y)}{2\sqrt{(k\bar{h}\ t/\phi)}}]$$

$$+ F[\frac{(a-x)}{2\sqrt{(k\bar{h}\ t/\phi)}}, \frac{(b-y)}{2\sqrt{(k\bar{h}\ t/\phi)}}]\}$$

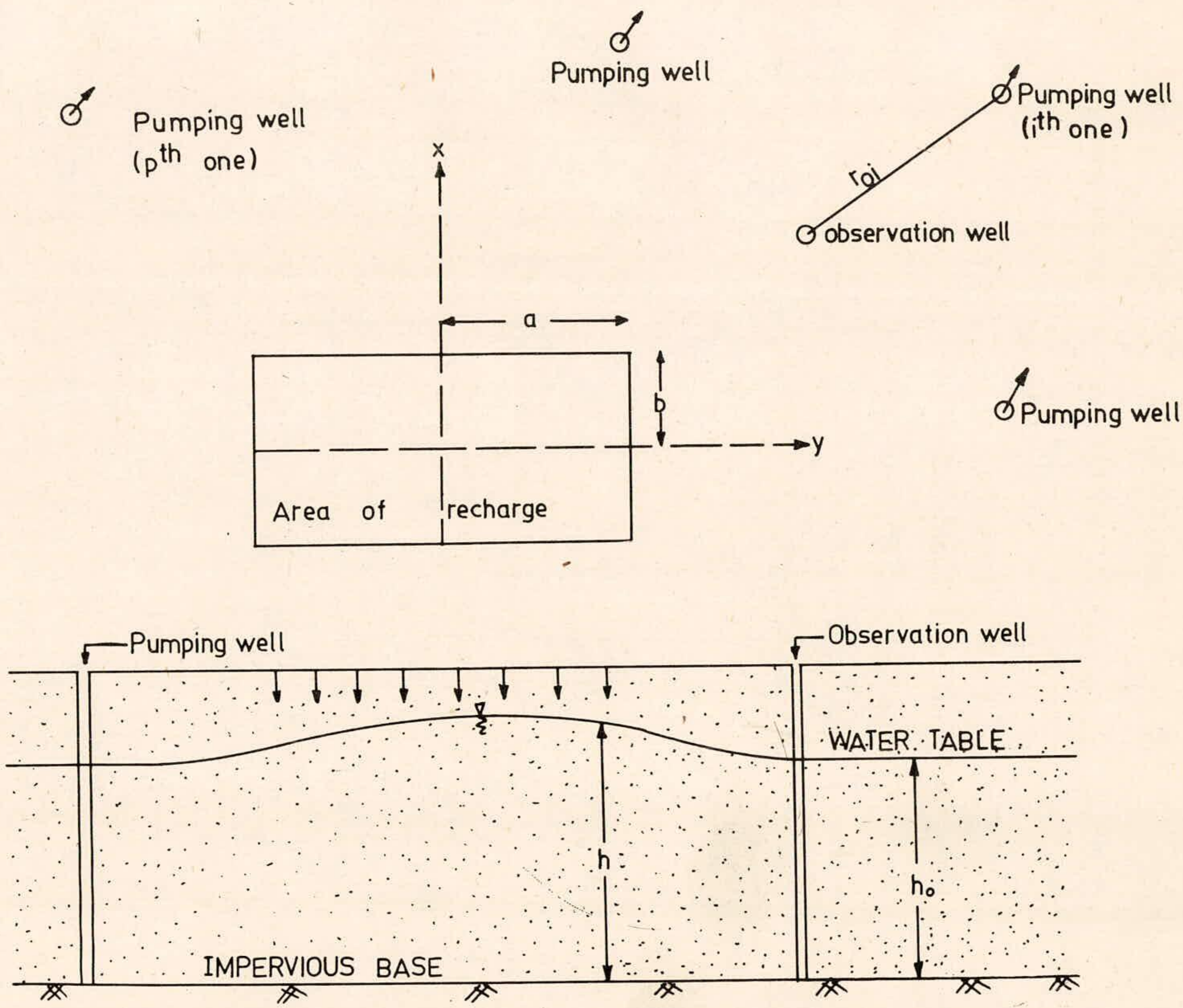

FIG.9 SCHEMATIC PLAN AND SECTION OF A SPREADING BASIN

$$h^2 = h_0^2 + (\frac{w\bar{h}t}{2\phi}) [f(x,y,t)]$$

in which,

$\bar{h}$ = weighted mean of the depth of saturation during the period of flow

w = constant rate of percolation

a = dimension of the rectangular strip

b = dimension of thr rectangular strip

ϕ = storage coefficient of the aquifer

k = coefficient of permeability

t = time

and

$$F(p,q) = \int_0^1 \mathrm{erf}(p/\sqrt{z}).\mathrm{erf}(q/\sqrt{z})dz$$

$$\mathrm{erf}(X) = \frac{2}{\sqrt{\pi}} \int_0^X e^{-u^2} du, \qquad \mathrm{erf}(\infty) = 1$$

$$\text{Let } \bar{h} = \frac{h+h_0}{2}$$

The rise in water table is given by

$$s(x,y,t) = \frac{w\bar{h}t}{2\phi(h+h_0)} f(x,y,t)$$

$$= \frac{w\bar{h}t}{4\phi(\frac{h+h_0}{2})} f(x,y,t)$$

$$= \frac{wt}{4\phi} f(x,y,t)$$

For continuous recharge at unit rate, the water table rise is given by

$$s(x,y,t) = \frac{t}{4\phi} f(x,y,t) = K(x,y,t)$$

If recharge takes place for one unit time, and no recharge after that, the rise at the end of n^{th} unit time step, $\delta_b(x,y,n)$, is given by

$$\delta_b(x,y,n) = K(x,y,n) - K(x,y,n-1),$$

$$\delta_b(x,y,1) = K(x,y,1).$$

If the recharge varies with time, the rise due to recharge alone at the end of n^{th} time step is given by

$$s(x,y,n) = \sum_{\gamma=1}^{n} W(\gamma)\, \delta_b(x,y,n-\gamma+1).$$

in which $W(\gamma)$ is the recharge rate during γ^{th} unit time step.
Decline in water table rise at the observation well due to pumping is given by

$$\sum_{i=1}^{P} \sum_{\gamma=1}^{n} Q_i(\gamma)\, \delta_{wi}(n-\gamma+1)$$

in which

P is the total number of wells,

$$\delta_{wi}(m) = \frac{1}{4\pi T}\left[E_1\left(\frac{r_i^2}{4\beta m}\right) - E_1\left(\frac{r_i^2}{4\beta(m-1)}\right)\right]$$

and

r_i = distance of the r^{th} pumping well from observation point.

The resultant water table rise is given by

$$s(x,y,n) = \sum_{\gamma=1}^{n} W(\gamma)\, \delta_b(x,y,n-\gamma+1) - \sum_{i=1}^{P} \sum_{\gamma=1}^{n} Q_i(\gamma)\, \delta_{wi}(n-\gamma+1)$$

Splitting the summation into two parts and rearranging

$$W(n) = \frac{s(x,y,n) - \sum_{\gamma=1}^{n-1} W(\gamma)\, \delta_b(x,y,n-\gamma+1) + \sum_{i=1}^{P} \sum_{\gamma=1}^{n} Q_i(\gamma)\, \delta_{wi}(n-\gamma+1)}{\delta_b(x,y,1)}$$

Thus, knowing $s(x,y,n)$, $W(\gamma)$ can be found in succession staring from time step 1 for known withdrawal rates, $Q_i(\gamma)$.

After knowing the quantities of water recharged by the basin at different time, its spatial and temporal availability in the aquifer can be assessed as follows:

Let it be required to ascertain the amount of water available within a radial distance of 'R' from the centre of the basin at time t. For large value of r, the basin can be regarded as a point source.

If continuous recharge takes place at unit rate per unit time the drawdown at a distance R from the point source is given by

$$s(R,t) = \frac{1}{4\pi T} \int_{\frac{R^2}{4\beta t}}^{\infty} \frac{e^{-u}}{u}\, du$$

and the gradient of water table is given by

$$\frac{\partial s(R,t)}{\partial r} = - \frac{1}{2\pi T} \frac{e^{-\frac{R^2}{4\beta t}}}{R}$$

The quantity of water leaving the zone with radius R is

$$q_{RO}(t) = - 2\pi R T \left. \frac{\partial s}{\partial r} \right|_R$$

Replacing the expression of $\left.\frac{\partial s}{\partial r}\right|_R$ and simplifying

$$q_{RO}(t) = e^{-\frac{R^2}{4\beta t}}$$

The quantity of water which has left the zone of radius R upto time t can be expressed as

$$Q_{RO}(t) = \int_0^t e^{-\frac{R^2}{4\beta c}} \, dc$$

$$= te^{-\frac{R^2}{4\beta t}} - \frac{R^2}{4\beta} E_i(\frac{R^2}{4\beta t})$$

in which,

$$E_i(\frac{R^2}{4\beta t}) = \text{an exponential integral} = \int_{\frac{R^2}{4\beta t}}^{\infty} \frac{e^{-u}}{u} \, du$$

The quantities of water retained is

$$Q_{RR}(t) = t - te^{-\frac{R^2}{4\beta t}} + \frac{R^2}{4\beta} E_i(\frac{R^2}{4\beta t})$$

If recharge at unit rate takes place for unit time and no recharge there after, the cumulative flows which has left the zone with radius R at the end of time step n can be expressed as

$$\delta_{CQRO}(n) = Q_{RO}(n) - Q_{RO}(n-1)$$

$$= n\, e^{-\frac{R^2}{4\beta n}} - \frac{R^2}{4\,\beta} E_i(\frac{R^2}{4\beta n}) - (n-1)e^{-\frac{R^2}{4\beta(n-1)}}$$

$$+ \frac{R^2}{4\beta} E_i(\frac{R^2}{4\beta(n-1)})$$

$$\delta_{CQRO}(1) = e^{-\frac{R^2}{4\beta}} - \frac{R^2}{4\beta} E_i(\frac{R^2}{4\beta})$$

Similarly the cumulative quantity of water which is retained in the zone with radius R at the end of time step n is

$$\delta_{CQRR}(n) = 1 - ne^{-\frac{R^2}{4\beta n}} + \frac{R^2}{4\beta} E_i(\frac{R^2}{4\beta n})$$

$$+ (n-1)\, e^{-\frac{R^2}{4\beta(n-1)}} - \frac{R^2}{4\beta} E_i(\frac{R^2}{4\beta(n-1)})$$

$$\delta_{CQRR}(1) = 1 - e^{-\frac{R^2}{4\beta}} + \frac{R^2}{4\beta} E_i(\frac{R^2}{4\beta})$$

If recharge through the basin takes place at a rate $W(\gamma)$ the quantities of water retained within zone of radius R is

$$Q_{RR}(n) = \sum_{\gamma=1}^{n} W(\gamma)\, \delta_{CQRR}(n-\gamma+1)$$

and the quantities which have left up to time n is given by

$$Q_{RO}(n) = \sum_{\gamma=1}^{n} W(\gamma)\, \delta_{CQRO}(n-\gamma+1)$$

3.2 Assessment of Water Recharged from an Injection Well to Individual Aquifer in a Multi-aquifer System

Schematic section of an injection well in a two layer multi-aquifer system is shown in Fig.5. It is required to find the quantity of water going to each of the aquifers during recharge and exchange of flow between the aquifers after the stoppage of recharge. Water is injected at a known rate for a given duration.

3.2.1 Methodology

Let T_1, ϕ_1, be the transmissivity and storage coefficient of the first aquifer and T_2, ϕ_2, be the parameters of the second aquifer. At any time step n the total quantity of water recharged, $Q_R(n)$ is given by

$$Q_R(n) = Q_R(1,n) + Q_R(2,n) \tag{1}$$

where,

$Q_R(1,n)$ = quantity of water recharged to the 1st aquifer, and

$Q_R(2,n)$ = quantity of water recharged to the 2nd aquifer.

Equating the expressions of drawdowns in the first and second aquifer at the well face

$$\sum_{\gamma=1}^{n} Q_R(1,\gamma)\ \delta_1(r_w, n-\gamma+1) = \sum_{\gamma=1}^{n} Q_R(2,\gamma)\ \delta_2(r_w, n-\gamma+1)$$

rewritting,

$$Q_R(1,n)\ \delta_1(r_w,1) - Q_R(2,n)\ \delta_2(r_w,1) = \sum_{\gamma=1}^{n-1} Q_R(2,\gamma)\ \delta_2(r_w, n-\gamma+1) - \sum_{\gamma=1}^{n-1} Q_R(1,\gamma)\ \delta_1(r_w, n-\gamma+1) \tag{2}$$

where,

$$\delta_1(m) = \frac{1}{4\pi T_1}\left[E_1\left(\frac{r_w^2}{4\beta_1 m}\right) - E_1\left(\frac{r_w^2}{4\beta_1(m-1)}\right)\right],$$

$$\delta_2(m) = \frac{1}{4\pi T_2}\left[E_1\left(\frac{r_w^2}{4\beta_2 m}\right) - E_1\left(\frac{r_w^2}{4\beta_2(m-1)}\right)\right],$$

$$\beta_1 = \frac{T_1}{\phi_1},$$

$$\beta_2 = \frac{T_2}{\phi_2}, \text{ and}$$

r_w = radius of injection well.

From equations (1) anu (2)

$$Q_R(2,n) = \frac{1}{1 + \dfrac{\delta_2(r_w,1)}{\delta_1(r_w,1)}}\left[Q_R(n) - \frac{1}{\delta_1(r_w,1)}\left\{\sum_{\gamma=1}^{n-1} Q_R(2,\gamma)\,\delta_2(r_w,n-\gamma+1) - \sum_{\gamma=1}^{n-1} Q_R(1,\gamma)\,\delta_1(r_w,n-\gamma+1)\right\}\right]$$

$$Q_R(1,n) = Q_R(n) - Q_R(2,n)$$

Thus $Q_R(1,n)$, and $Q_R(2,n)$ can be known in succession starting from time step 1.

3.3 Assessment of Recharge Through a Recharge Well Open to a Single Aquifer Using the Water Level Data Recorded at a Nearby Observation Well

Water is recharged through an injection well to a aquifer and the water level rise is monitored in an observation well during recharge. It is required to ascertain the water recharged using the data of observation of water table rise.

3.3.1 Methodology

Recharge studies through a injection well open to a single aquifer have been carried out by many researchers assuming steady state conditions. Solution for estimating recharge under unsteady state condition has been presented below:

Let the drawdown be recorded at an observation well which is located at a distance r from the recharge well. The drawdown at the observation point can be expressed as

$$s(r,n) = \sum_{\gamma=1}^{n} Q_R(\gamma)\ \delta(r,n-\gamma+1)$$

rewritting,

$$s(r,n) = \sum_{\gamma=1}^{n-1} Q_R(\gamma)\ \delta(r,n-\gamma+1) + Q_R(n)\ \delta(n,1)$$

Hence,

$$Q_R(n) = [s(r,n) - \sum_{\gamma=1}^{n-1} Q_R(\gamma)\ \delta(r,n-\gamma+1)]/\delta(r,1)$$

For the first time step

$$Q_R(1) = \frac{s(r,1)}{\delta(r,1)}$$

The recharge $Q_R(n)$ can be assessed in succession starting from time step one. The coefficient $\delta(r,n)$ is given by:

$$\delta(r,n) = \frac{1}{4\pi T} [E_1(\frac{r^2}{4\beta n}) - E_1(\frac{r^2}{4\beta(n-1)})],$$

$$\beta = \frac{T}{\phi}.$$

4.0 RESULTS AND DISCUSSION

Results have been presented with an aim to analyse the dissipation of recharged water in the aquifer in space and time. For this purpose, the recharge basin has been assumed to be a point source. If recharge takes at unit rate perunit time period, the cumulative quantities of water retained within a zone of radius R at the end of n^{th} unit time step is shown in Figs.10(a) through 10(d) for various sets of aquifer parameters and radius R. The cumulative quantities of recharged water retained are represented by the discrete kernel coefficients $\delta_{CQRR}(n)$. Also the cumulative quantities of flow left the circular zone which has a radius R, have been shown in Figs.11(a) through 11(d). The discrete kernel coefficients are the properties of the linear system, using which the response for time variant excitation could be obtained. The dissipation of recharge occurring at variable rate through a recharge basin could be predicted making use of these coefficients. The quantities available within a zone of radius R, is governed by the aquifer parameters and the radius R. It could be seen from Figs.11(a) through 11(d) that the slope of the graph of cumulative flow retained versus time decreases with time indicating that, under continuous recharge, fraction of the recharge water retained decreases with time. With increasing storage coefficient, the cumulative quantities retained upto any particular time

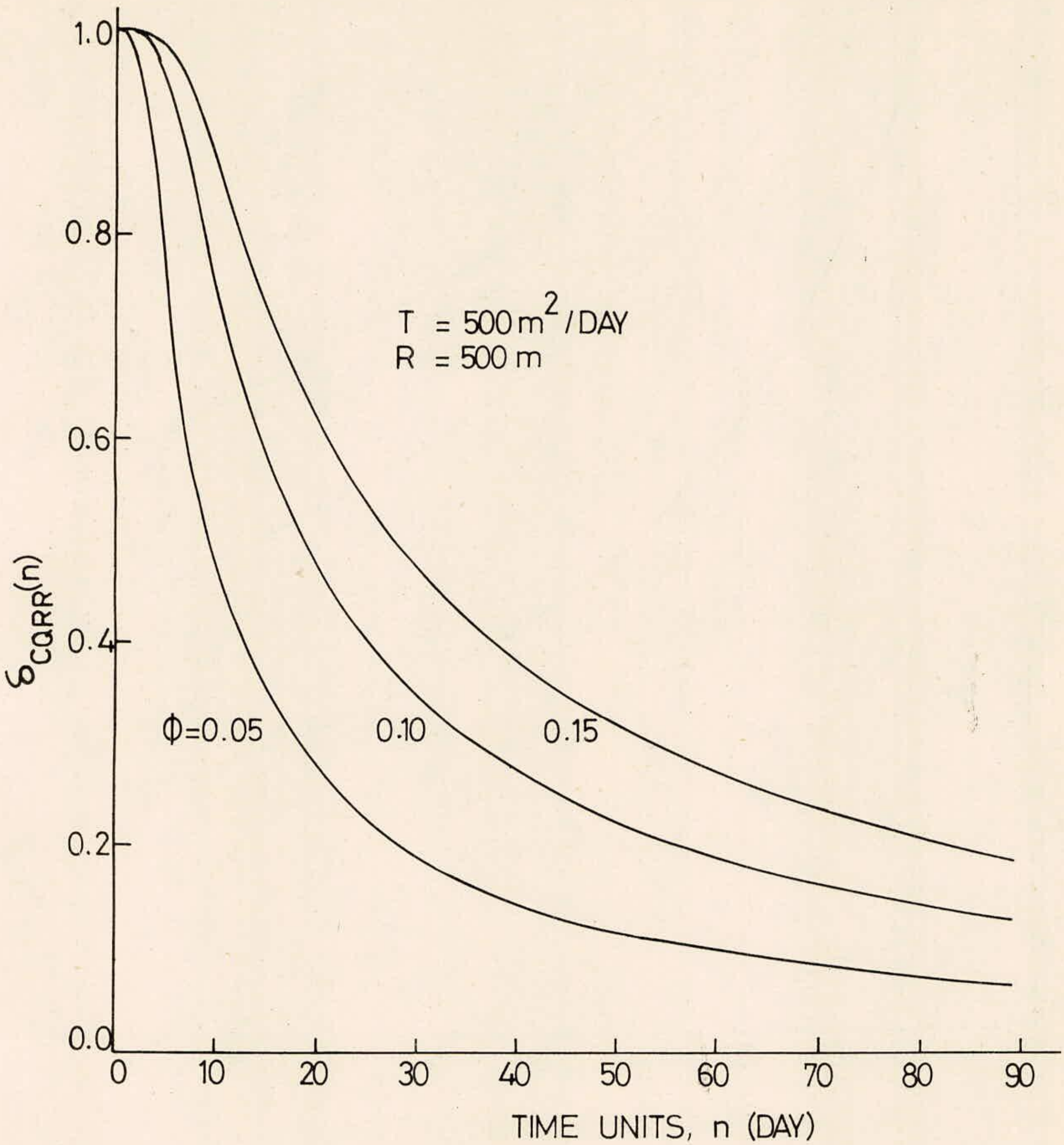

FIG.10(a) VARIATION OF $\delta_{CQRR}(n)$ WITH TIME n FOR
T = 500 m^2/day and R = 500 m

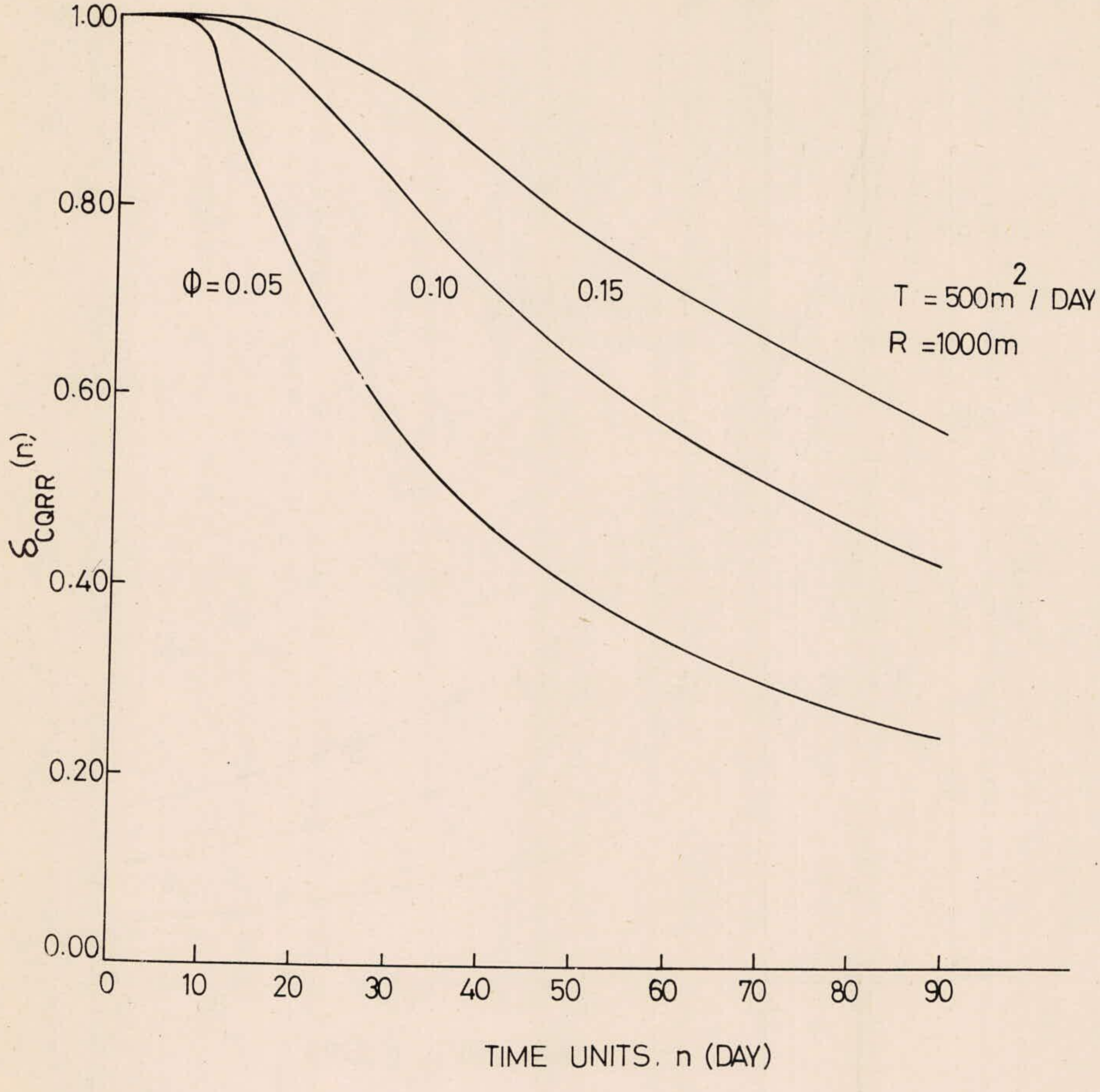

FIG.10(b) VARIATION OF $\delta_{CQRR}(n)$ WITH TIME n FOR $T = 500\ m^2/day$ and $R = 1000\ m$

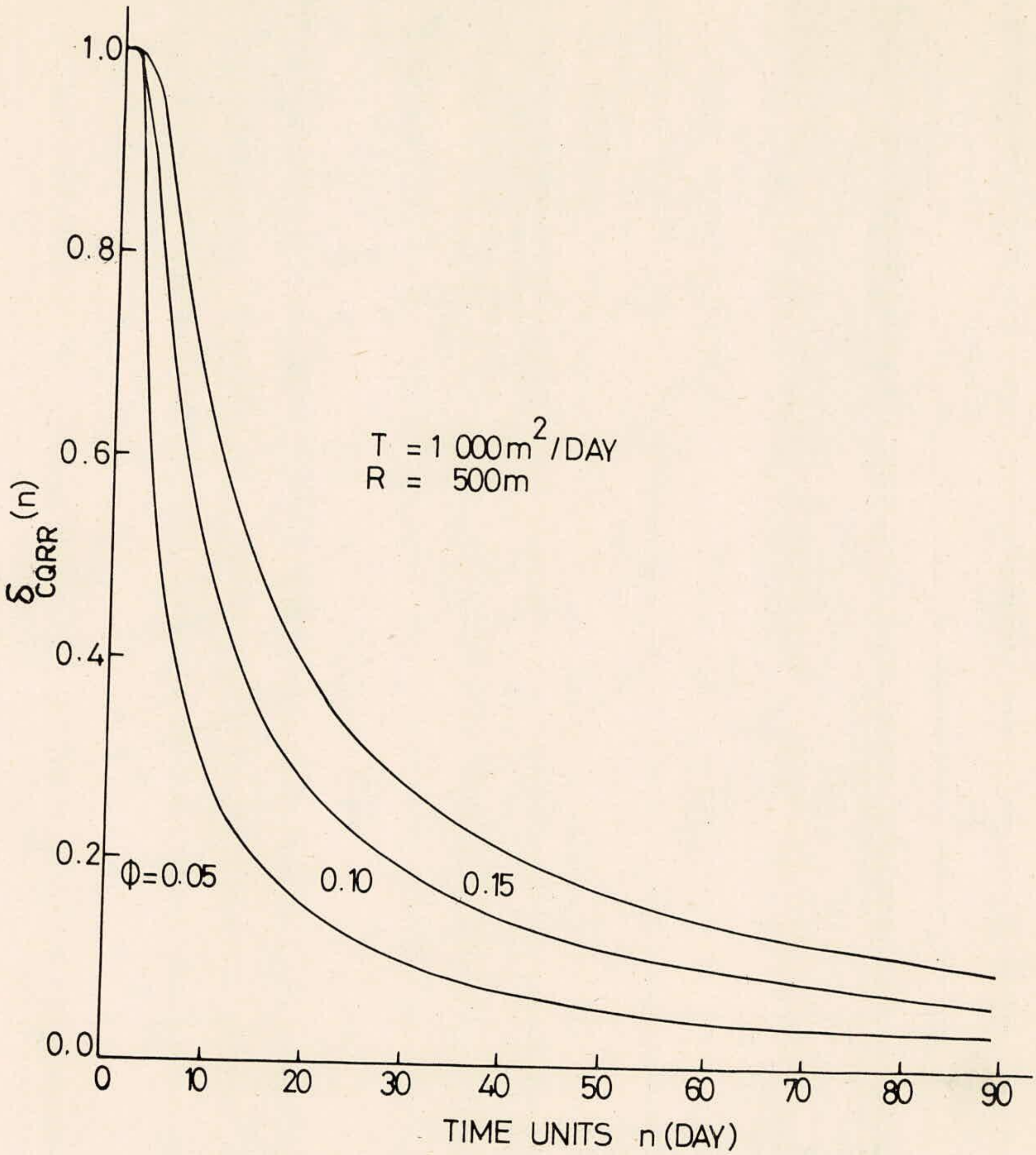

FIG.10(c) VARIATION OF $\delta_{CQRR}(n)$ WITH TIME n FOR $T = 1000\ m^2/day$ and $R = 500\ m$

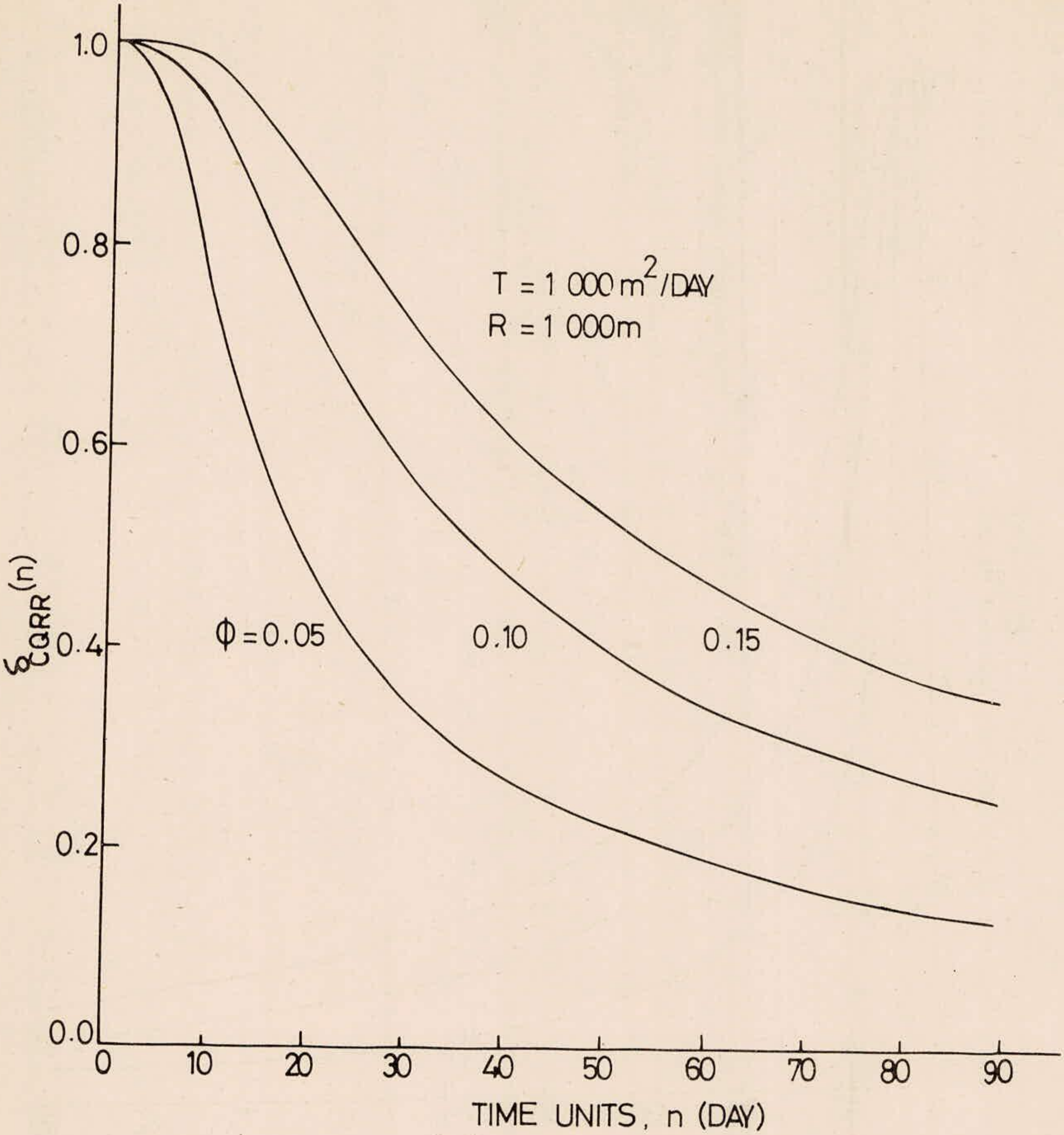

FIG.10(d) VARIATION OF $\delta_{CQRR}(n)$ WITH TIME n FOR T = 1000 m^2/day and R = 1000 m

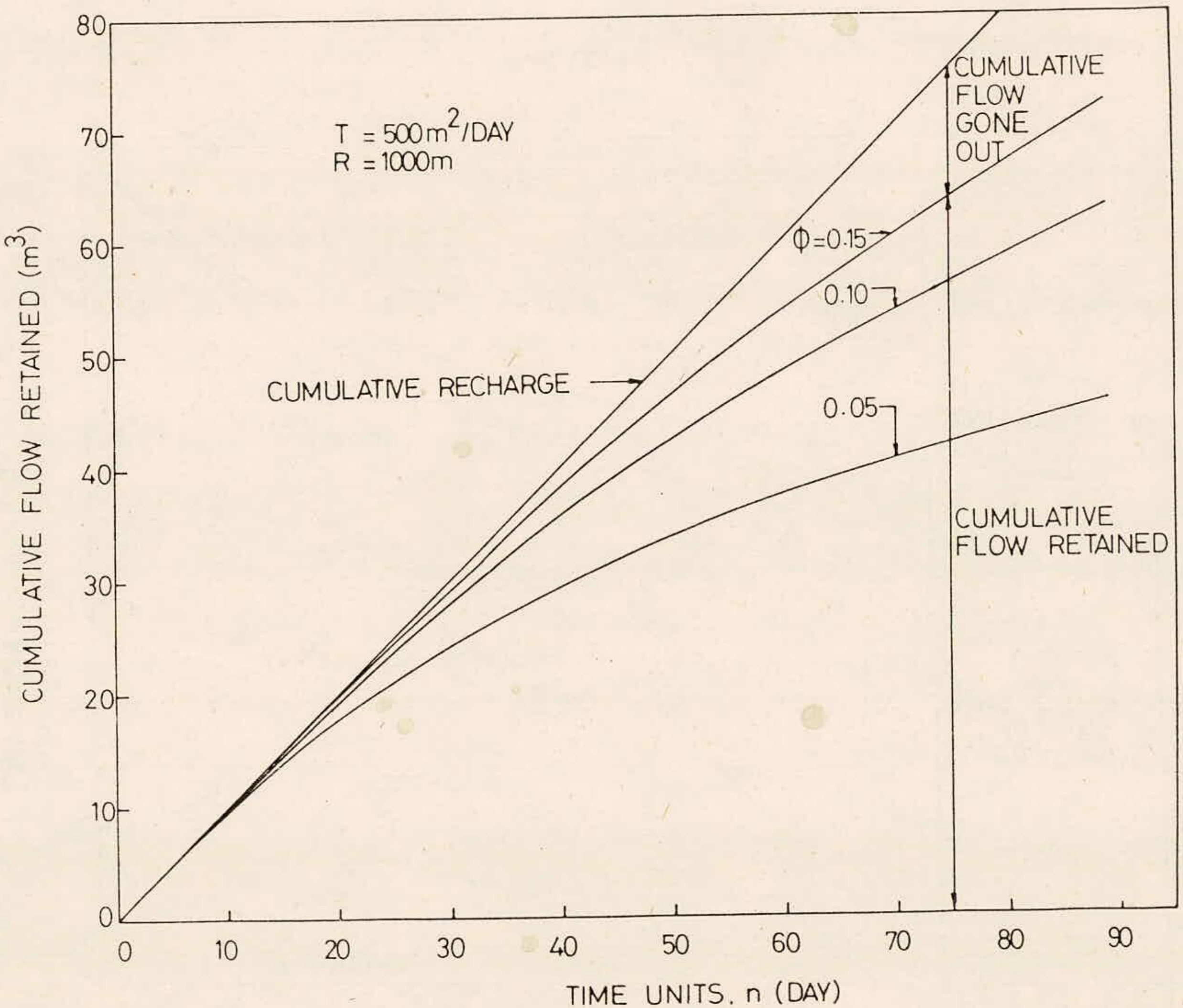

FIG.11(a) VARIATION OF CUMULATIVE FLOW WITH TIME n FOR T = 500 m^2/day and R = 1000 m

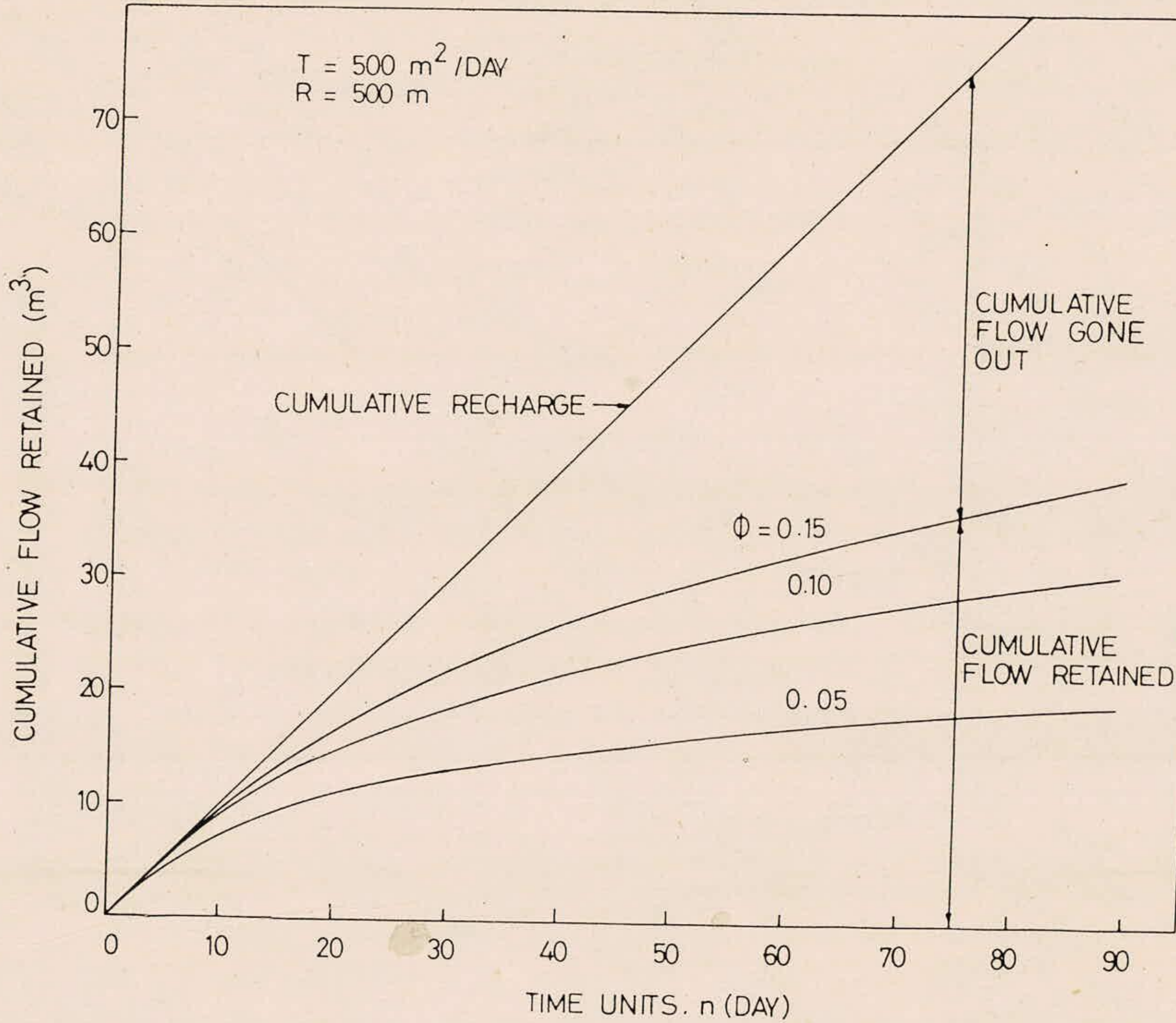

FIG.11(b) VARIATION OF CUMULATIVE FLOW WITH TIME n FOR T = 500 m^2/day and R = 500 m

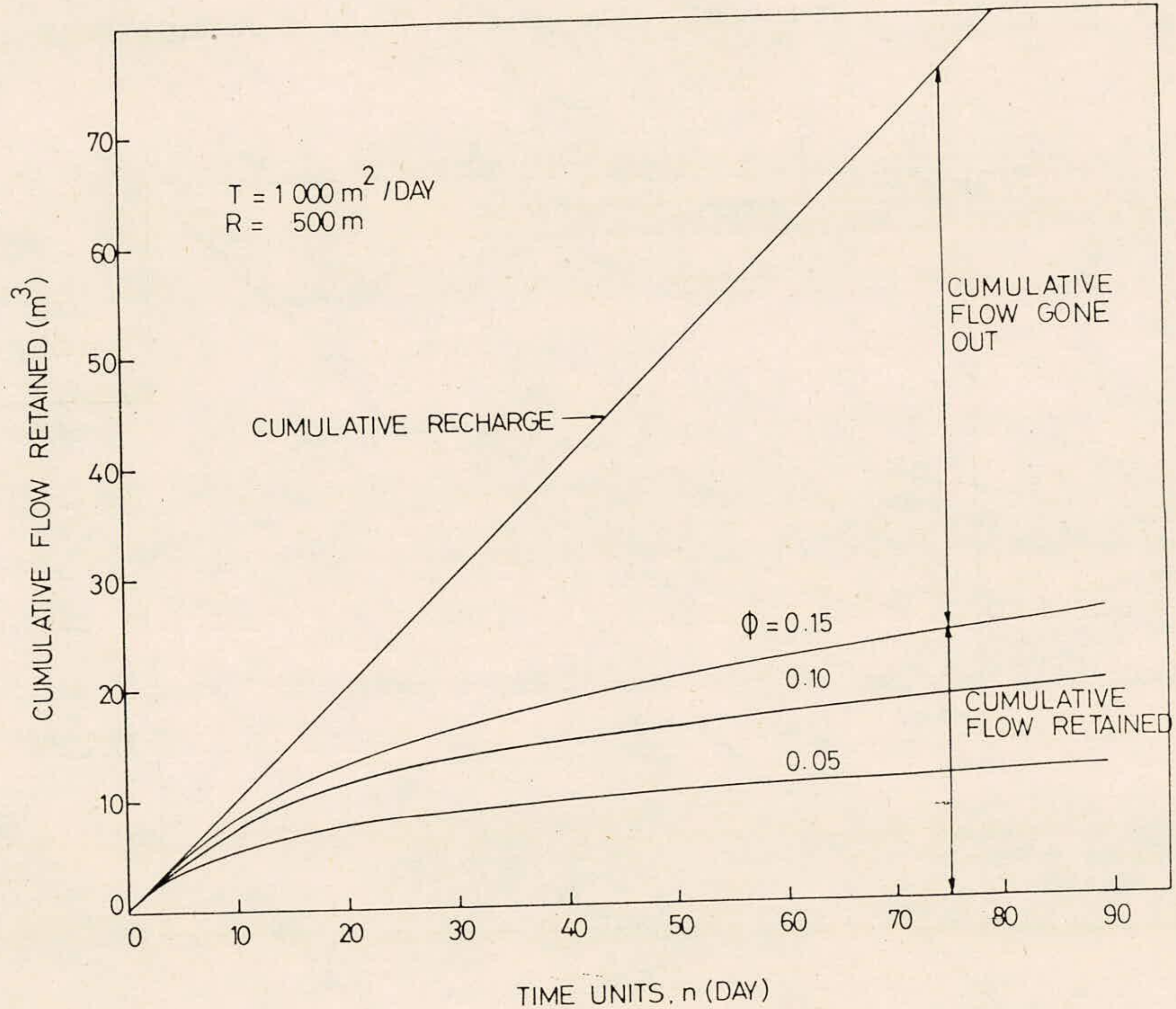

FIG.11(c) VARIATION OF CUMULATIVE FLOW WITH TIME n FOR T = 1000 m^2/day and R = 500 m

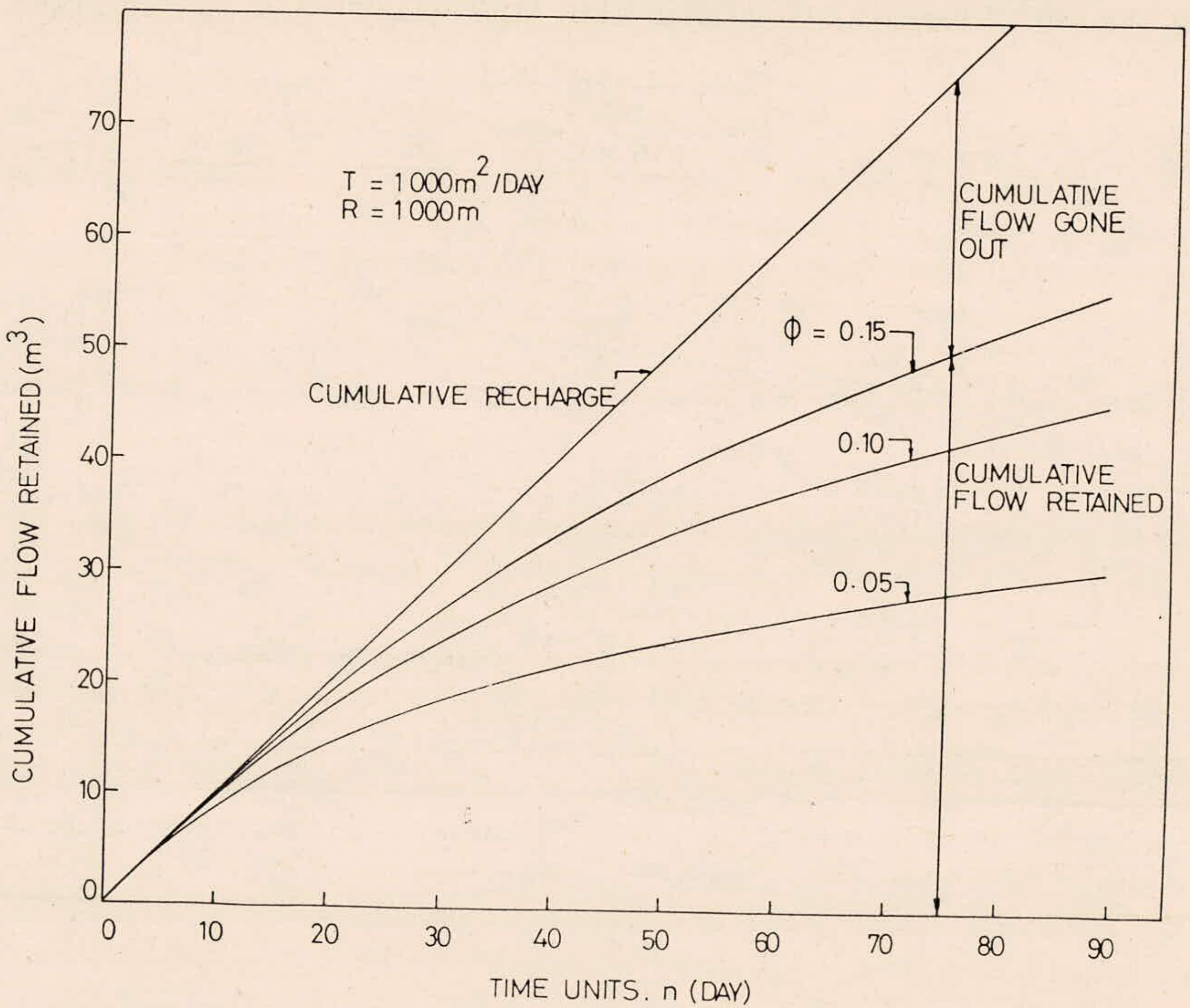

FIG.11(d) VARIATION OF CUMULATIVE FLOW WITH TIME n FOR T = 1000 m^2/day and R = 1000 m increases. For example at the end of 50 days, for R = 1000 m, T = 500 m^2/day, and ϕ = 0.05, the cumulative fraction of water retained = 0.68, where as for ϕ = 0.15, the corresponding cumulative fraction retained is 0.93. As time increases, the cumulative fraction retained decreases. For example at the end of t = 80 days, ϕ = 0.05 and 0.15 the fractions retained are 0.54 and 0.83 respectively.

The dissipation of a typical actual recharge that may occur is next considered. The size of the basin considered is 200 m x 10 m. The variation of recharge rate through unit area with time is shown in Fig.8. If recharge occurs at this rate its dissipation in an aquifer has been studied for various sets of aquifer parameters and values of radius R.

The variation of cumulative recharge, cumulative recharge quantities retained and cumulative recharge quantities left the zone with radious R are presented for T = 1000 m^2/day and R = 2000 m for values of ϕ = 0.05 and 0.1. The recharge through the basin stops at n = 24, i.e. at the end of 120 days. Therefore the slope of cumulative volume of recharge with time has become zero at n = 24 and beyond. It could be seen from Fig.12(a) that the quantities of water available in area with radius R = 2000 m at the end of 73 unit time (i.e. at the end of 365 days) is 1.4 x 10^4 m^3 of water if ϕ = 0.05. The total quantities that has been recharged is 1.05 x $10^5 m^3$. Thus 13.33 fraction of water is available at the end of 365 days. It may be noted that the recharge quantities available will get modified if any abstraction well is there in the area.

The quantities of water going to individual aquifer if water is injected through a multiaquifer recharge well which is open to two aquifers,

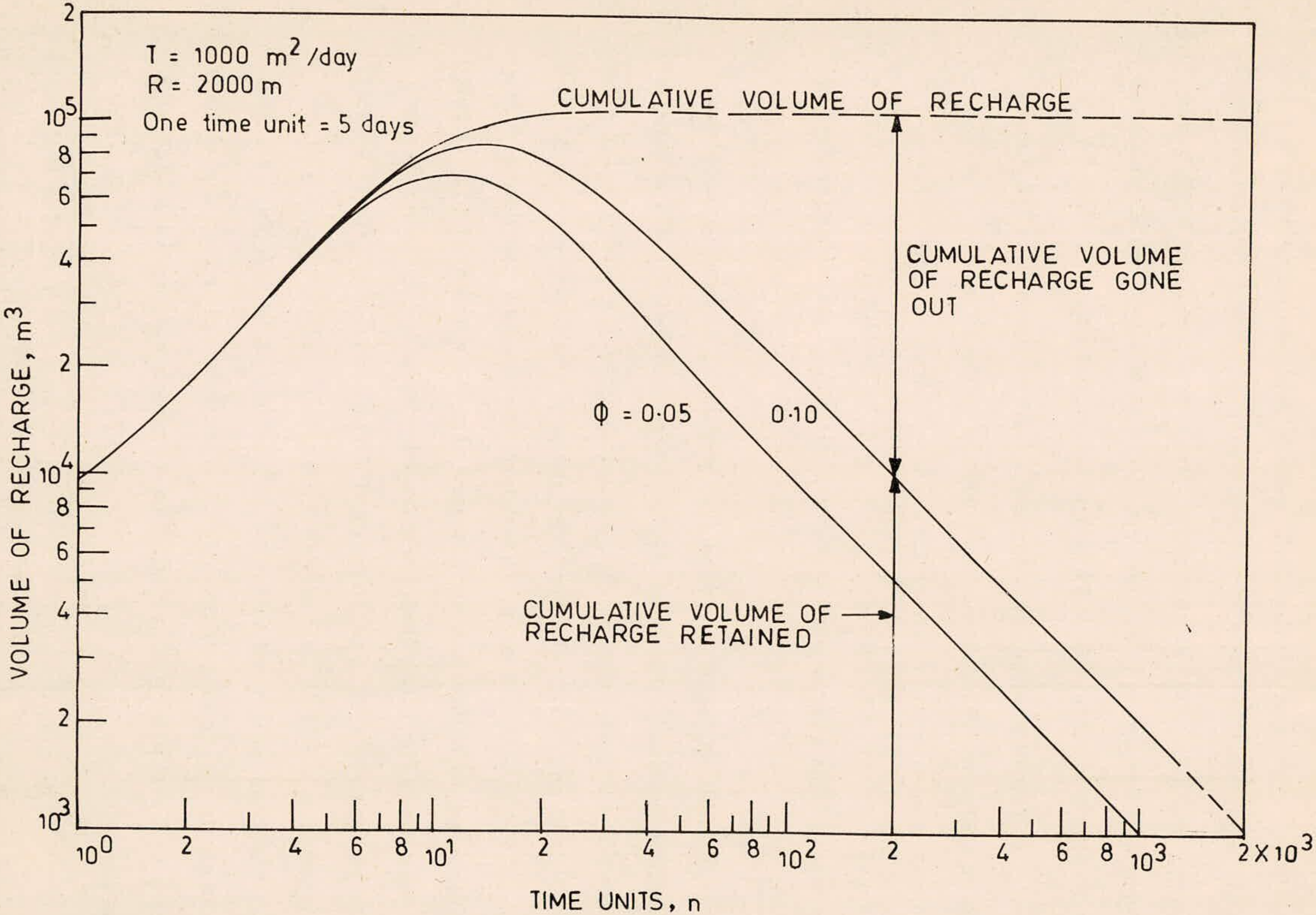

FIG.12(a) VARIATION OF VOLUME OF RECHARGE WITH TIME n FOR T = 1000 m^2/day and R = 2000 m

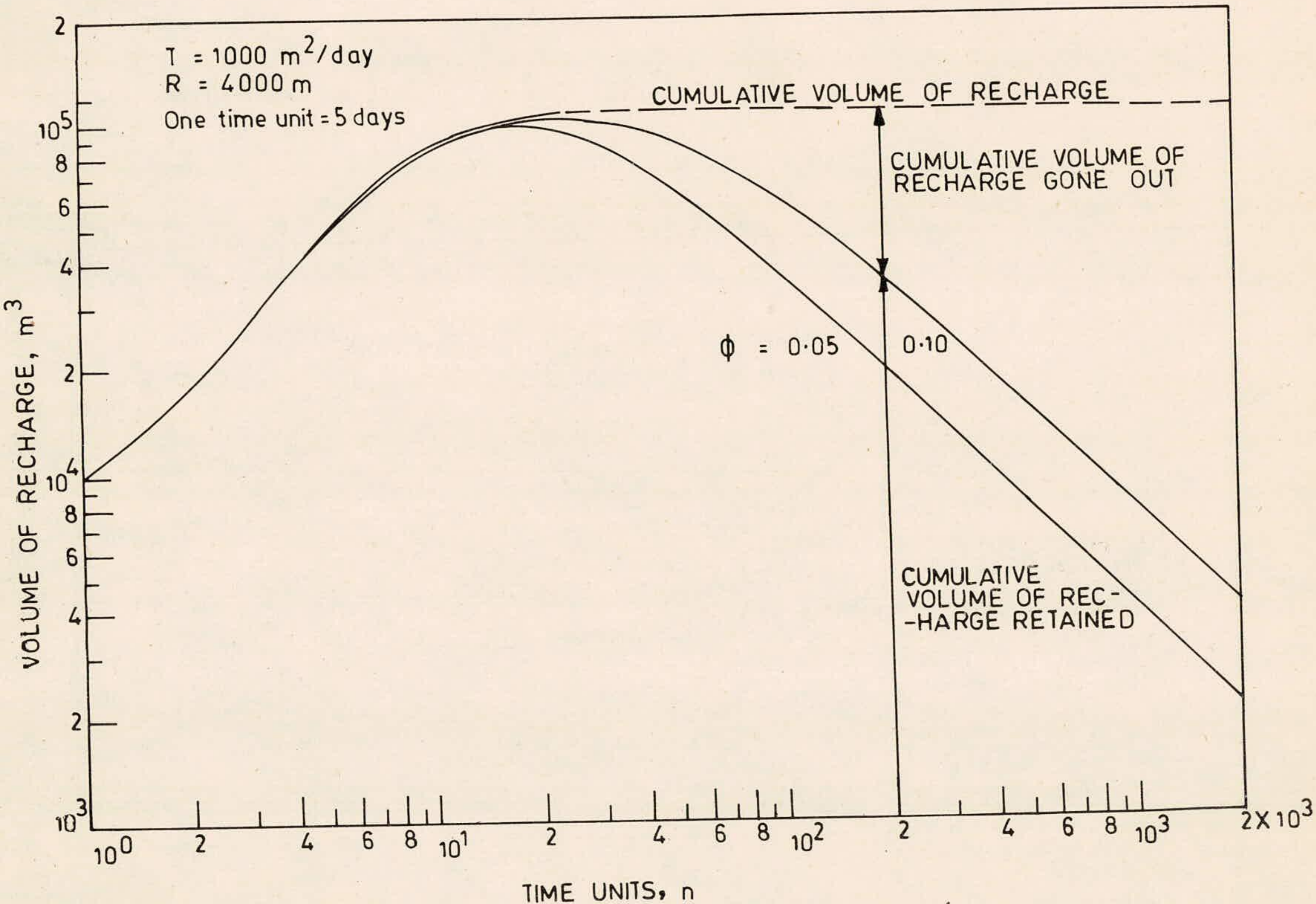

FIG.12(b) VARIATION OF VOLUME OF RECHARGE WITH TIME n FOR T = 1000 m^2/day and R = 4000 m

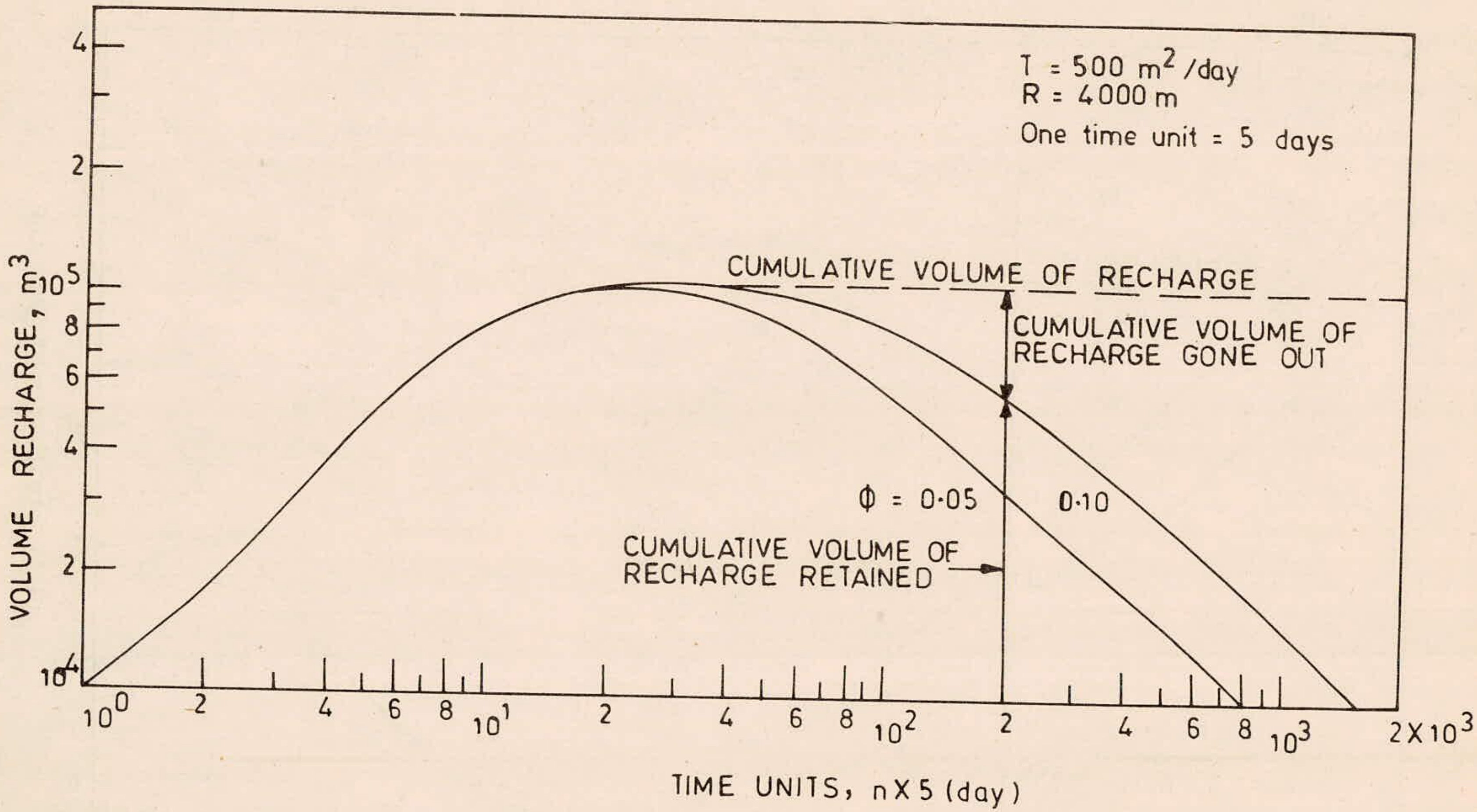

FIG.12(c) VARIATION OF VOLUME OF RECHARGE WITH TIME n FOR T = 500 m^2/day and R = 4000 m

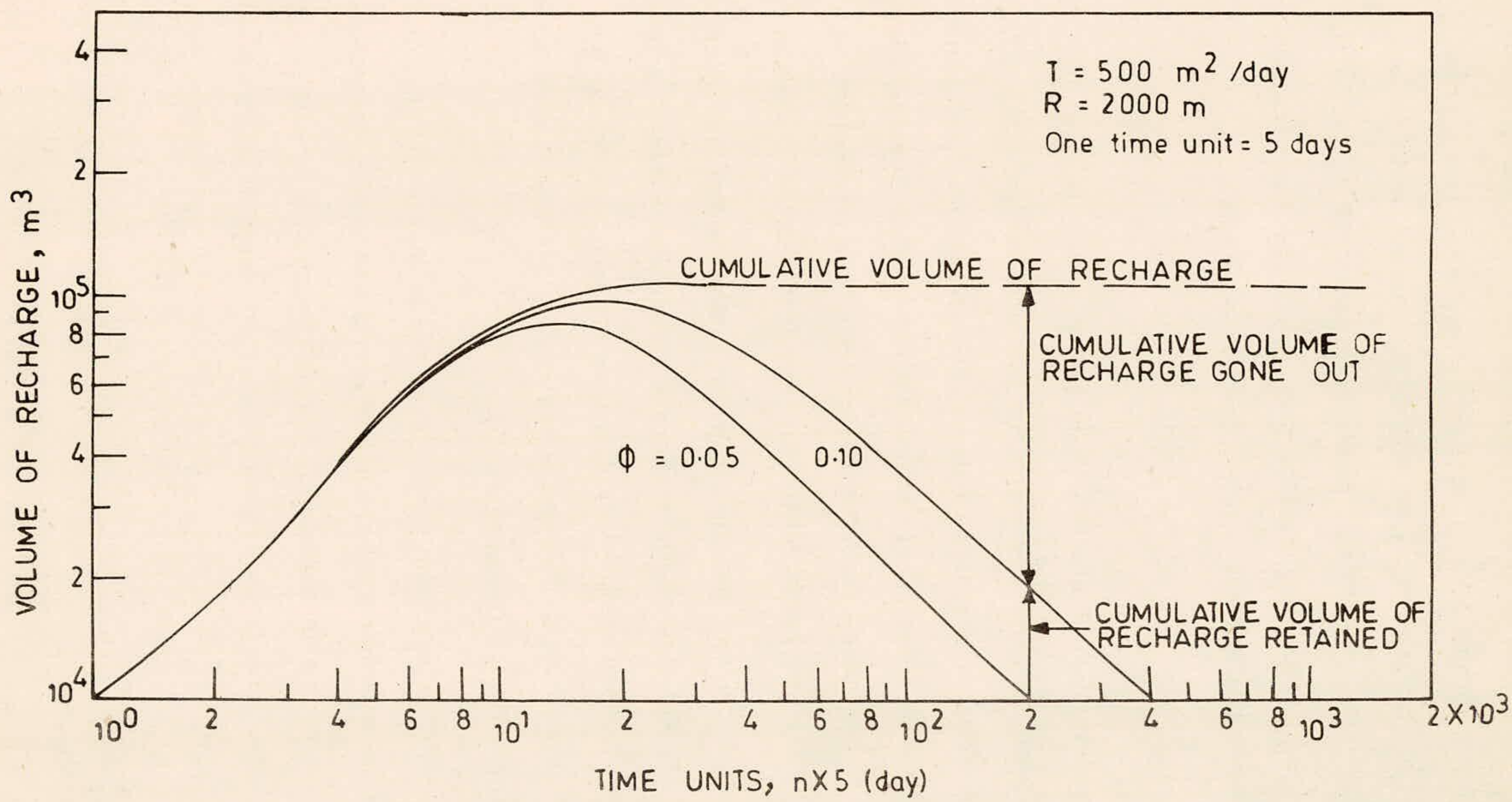

FIG.12(d) VARIATION OF VOLUME OF RECHARGE WITH TIME n FOR T = 500 m^2/day and R = 2000 m are presented in Figures 13(a) through 13(d). The results have been presented for different sets of aquifer parameters. Using these graphs the fraction of recharge going to individual aquifer could be ascertained. Recharge through injection well is discontinued at $4T_1t/\phi_1 r_w^2 = 10^8$. The variation of $Q_{R1}(t)/Q_R$ beyond this time represents the quantities of water coming from the lower aquifer to the upper one.

CONCLUSIONS

A methodology which is based on discretization of time parameter, has been developed to ascertain groundwater recharge affected through a rectangular recharge basin. The storativity, and transmissivity of the aquifer, dimension of the recharge basin, duration of recharge and a continuous record of water level in a observation well in the vicinity of the recharge basin, are required for the assessment.

A methodology has also been presented to find the temporal variation of the fraction of the recharged quantities available in a circular zone around the recharge basin. A typical example has been given for knowing the fraction of recharged water available within a circular zone of known radius R at different time.

A solution has been given to assess recharge to individual aquifer from an injection well which is open to two confined aquifers that are separated by an aquiclude. The methodology can assess, the exchange of flow between the aquifers after stoppage of recharge through the injection well.

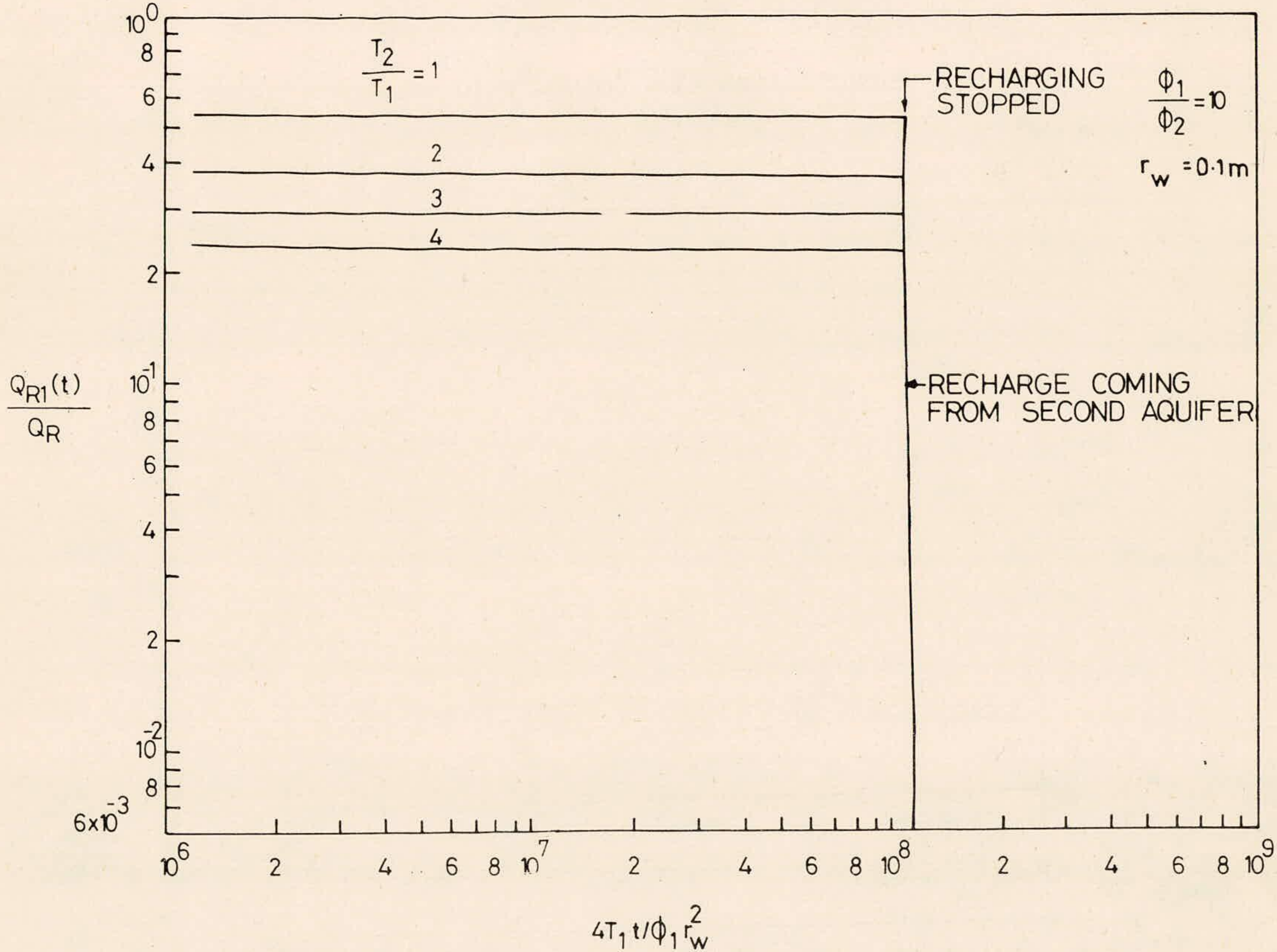

FIG.13(a) VARIATION OF $Q_{R1}(n)/Q_R$ WITH NON-DIMENSIONAL TIME FOR $\phi_1/\phi_2 = 10$

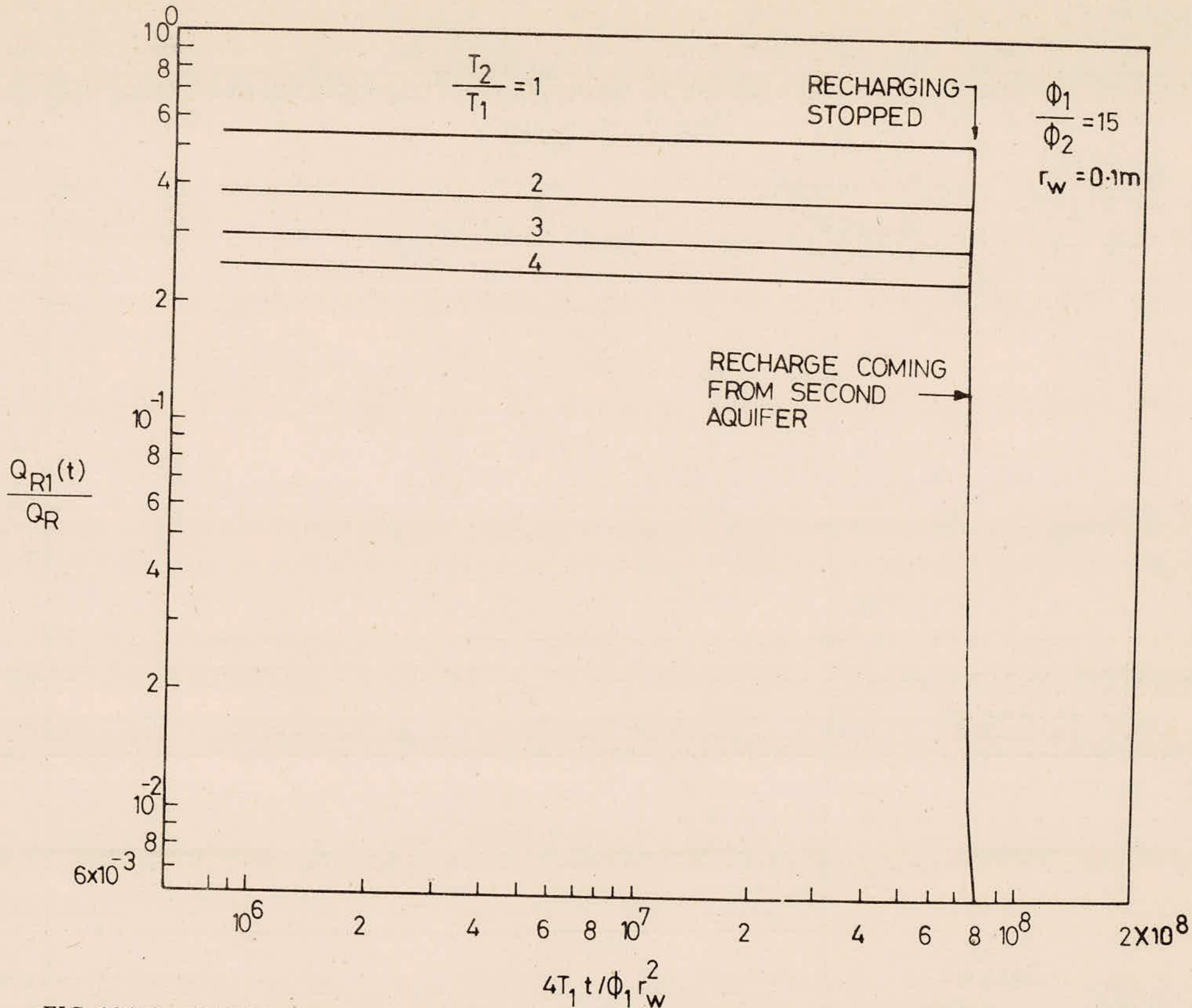

FIG.13(b) VARIATION OF $Q_{R1}(n)/Q_R$ WITH NON-DIMENSIONAL TIME FOR $\phi_1/\phi_2 = 15$

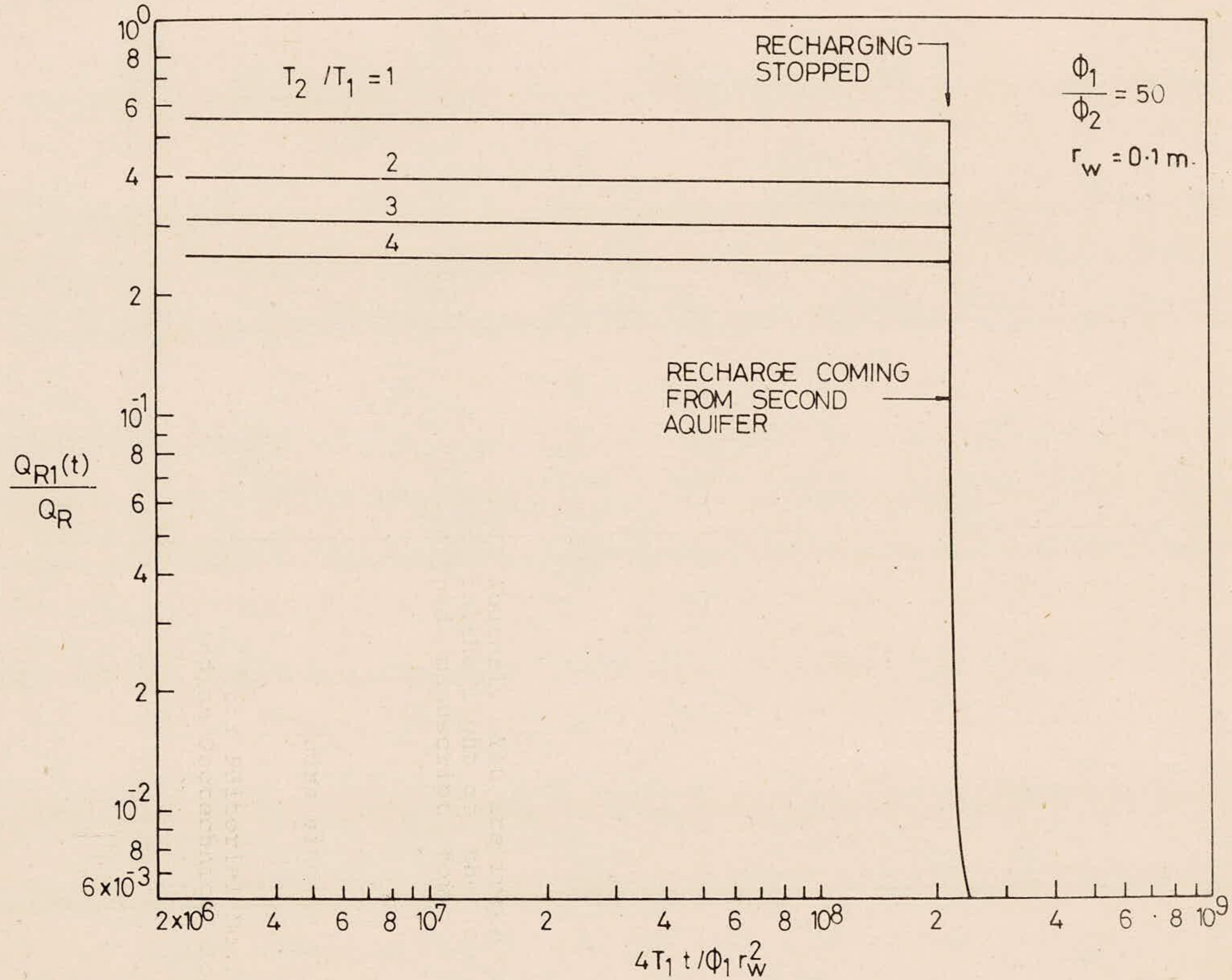

FIG.13(c) VARIATION OF $Q_{R1}(n)/Q_R$ WITH NON-DIMENSIONAL TIME FOR $\phi_1/\phi_2 = 50$

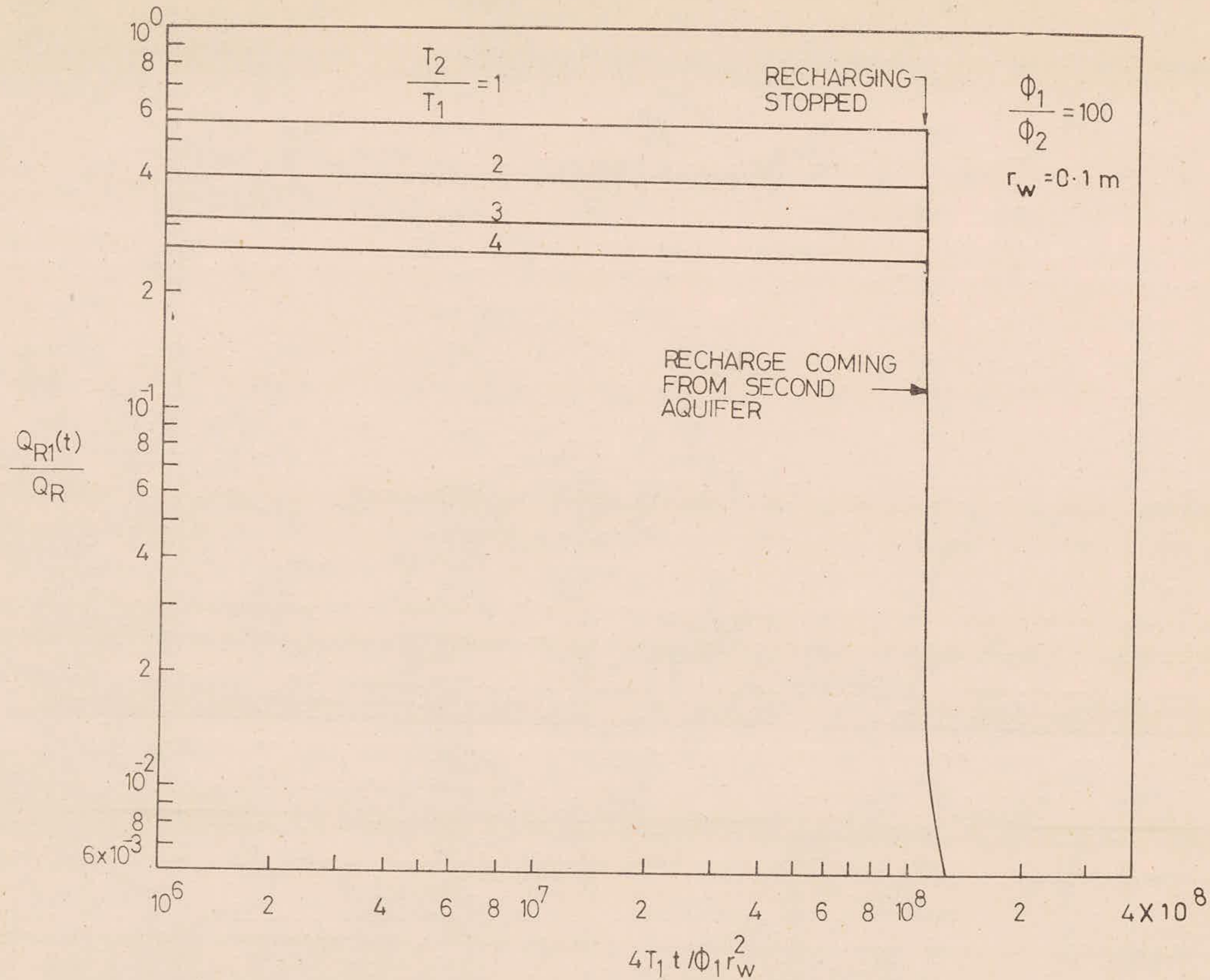

FIG.13(d) VARIATION OF $Q_{R1}(n)/Q_R$ WITH NON-DIMENSIONAL TIME FOR $\phi_1/\phi_2 = 100$

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