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DETERMINATION OF DEEP TUBEWELL SPACING
USING AQUIFER CHARACTERISTICS AND
IRRIGATION REQUIREMENT



A. K. M. Jahir Uddin Chowdhury



Bangladesh University Of Engineering & Technology, Dacca
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THESIS

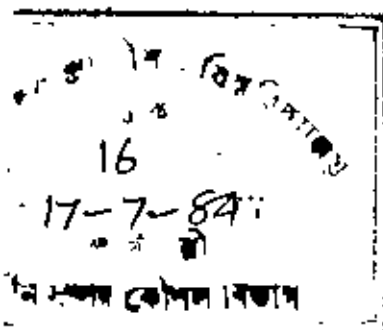
DETERMINATION OF DEEP ~~TUBEWELL~~ SPACING
USING AQUIFER CHARACTERISTICS AND
IRRIGATION REQUIREMENT

Submitted by

A.K.M. Jahir Uddin Chowdhury

In partial fulfillment of the requirements
for the Degree of Master of Science in
Engineering (Water Resources)

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED BY
A.K.M. JAHIR UDDIN CHOWDHURY
ENTITLED DETERMINATION OF DEEP TUBEWELL SPACING USING
AQUIFER CHARACTERISTICS AND IRRIGATION REQUIREMENT
BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE IN ENGINEERING (WATER
RESOURCES)

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H.R. Khan
(H.R. Khan)

Member

M.S. Islam
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H.R. Khan
(H.R. Khan)

A B S T R A C T

Relationship between deep tubewell spacing in square grid tubewell layout and aquifer characteristics has been studied using unsteady ground water flow equations. Both constant discharge and variable discharge conditions were considered and unsteady ground water flow equations were solved with the help of an IBM 360 digital computer. Comparison was made between spacing of wells subjected to mutual interference and spacing of wells without interference. Discharge, coefficient of transmissibility, storage coefficient, time of pumping, static lift and peak monthly irrigation water requirement have been used as variable parameters.

The storage coefficient should be the determining factor in selecting deep tubewell spacing when aquifer characteristics are considered. Some amount of mutual interference is allowable in selecting deep tubewell spacing and non-interference spacing is not always practicable. It is not important to consider the variability of well discharge due to increase in drawdown at the well with time.

A design chart has been developed for the selection of deep tubewell spacing considering aquifer characteristics and irrigation water requirement in square grid tubewell layout.

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LIST OF SYMBOLS

- a, α, β = discharge parameters;
 c = Euler's constant;
 D = peak monthly irrigation water requirement in inches per month;
 $D_{A-R/2}$ = maximum allowable drawdown at the middle point between two adjacent wells in ft.
 D_{A-w} = maximum allowable drawdown at the well in ft.
 $E_1()$ = exponential integral;
 $\bar{E}_1()$ = logarithmic integral;
 h = piezometric head in ft.
 h_0 = saturated thickness of water table aquifer before pumping starts;
 Δh = decrease in head;
 $h(r, t)$ = head at a radial distance r from the axis of a well at time t ;
 $J_0()$ = zero-order Bessel function of the first kind;
 L_0 = static lift in ft.
 $\ln$ = logarithm to the base e ;
 $\log$ = logarithm to the base 10;
 m = number of wells;
 N = number of steps of flow change in time t ;
 Q = discharge in cfs or in gpm;
 $\bar{Q}$ = average discharge during time 0 to t ;
 Q_0 = initial discharge;

- Q_i = discharge of the i th well;
 $Q(H)$ = discharge corresponding to a head, H , in head-capacity relationship;
 $Q(t)$ = discharge at time t ;
 ΔQ = decrease in discharge in one step;
 R = spacing between two adjacent wells in ft.
 R_0 = initial spacing between adjacent wells in ft.
 ΔR = incremental increase in spacing in ft.
 r = radial distance of any point from the axis of a well in ft.
 r_i = distance of any point from the i th well;
 r_w = effective radius of well;
 S = storage coefficient;
 $s_e = \frac{[\bar{Q} - Q(t)]}{2.25 \lambda T}$
 $D_{R/2}$ = drawdown at the middle point between two adjacent wells in ft.
 s_w = drawdown at the well;
 $s(r,t)$ = drawdown at a distance r from a well at time t ;
 T = coefficient of transmissibility in ft^2/sec or in gpd/ft .
 t = time length
 t_0 = time at start;
 t_j = time interval ($t_0, t_1, t_2, \dots, t_k$);
 t_k = time at any instant;
 $= t_0 + \Delta t_N$;
 t_p = time of pumping in a day;

Δt_k = time increment;

Δt_H = time change;

u = $u(r, t)$
 $= \frac{r^2 g}{4Tt}$ in gallon-day-foot system;

u_1 = value of u when $r = r_1$;

$W[u]$ = well function;

$$= \int_u^\infty \frac{e^{-u}}{u} du;$$

$Y_0()$ = zero-order Bessel function of the second kind;

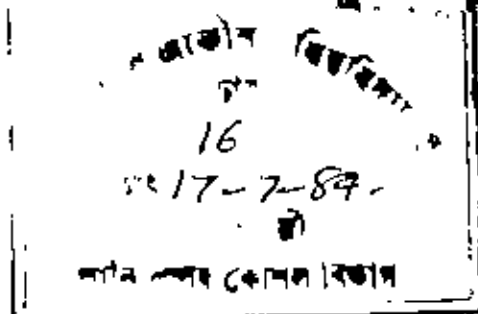
γ = $e^e = 1.781072$

λ = $\frac{Tt}{Sr_w^2}$

ϵ = $\frac{Q}{Q_0}$

= a factor less than one

μ = a factor greater than one;



CHAPTER I

INTRODUCTION

Bangladesh, one of the great population centres of the world, is now facing the challenging task of increasing her agricultural production. It is by no means possible to meet the increasing demand for food and fibre without proper development of irrigated agriculture. In achieving this task optimum utilization of her available water resources is a must. Major constraints to irrigation development include the scarcity of surface water and low irregular rainfall during the dry season in Bangladesh. The average rainfall amounts to only 2.5 to 4.5 inches during November through March which is insufficient to grow crops. Moreover, flows in rivers are significantly less during these winter months. Navigational problem restricts the withdrawal of water from many rivers during this period.

Ground water constitutes a major source of water to areas where irrigation from surface sources is difficult or impossible. Good quality aquifers, with static water levels not very far from ground surface, make it possible to extract ground water by tubewells economically. Recharge condition is also excellent due to heavy rainfall during monsoon. It is now well accepted that utilization of ground water resources is essential for the development of irrigated agriculture during dry period in

Bangladesh. Intensive tubewell irrigation projects undertaken by different government and autonomous bodies indicate expanded uses of ground water in agriculture. According to the national plan, about 19,000 deep tubewells will be sunk in the country to extract ground water for irrigation.

In order to ensure the maximum and the most beneficial use and conservation of available ground water, it is essential that there should be technically sound plans for sinking tubewells in the country. But uptill now there is no scientific basis for spacing tubewells giving proper considerations to the aquifer characteristics and water requirement by the crop. Improper spacing of tubewells may ^{cause} either closely spaced tubewells leading to excessive lowering of water table or widely spaced tubewells leading to problems of inadequate water supply for the area covered. Thus to optimise the distribution of tubewells and yield from aquifers, it is required to determine the proper spacing between deep tubewells. At present, the 2-cfs capacity deep tubewells in the country are spaced about 3,000 feet apart. No detailed investigation has been made to justify the use of such spacings for the existing aquifer conditions and irrigation water requirement.

The specific objective of this study is to determine spacing between two adjacent wells in square grid tubewell layout analytically considering aquifer response and to relate well spacing with aquifer characteristics and irrigation water requirement.

CHAPTER II

EQUATIONS OF GROUND WATER FLOW

General

General flow equations of ground water movement are derived from Darcy's Law and the equation of continuity. The approximate partial differential equation governing the unsteady radial flow in a homogenous, isotropic and compressible confined aquifer of uniform thickness as shown in Figure 1 in plane polar co-ordinate is

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = \frac{S}{T} \frac{\partial h}{\partial t} \quad (1)$$

in which h is the piezometric head; r the radial distance from the well axis; S the storage coefficient; T the coefficient of transmissibility and t is the time. The corresponding equation for an unconfined aquifer has a nonlinear form, which makes direct solution impossible. By approximation, however, Eq. 1 can be applied to unconfined aquifers as shown in Figure 2 where variations in the saturated thickness are small.

Unsteady Radial Flow to a Well with Constant Discharge

Theis (1935) obtained a solution for the unsteady radial flow to a well in a nonleaky confined aquifer from Eq. 1 based on the analogy between ground water flow and heat conduction. In the analysis the well is replaced by a mathematical sink of constant strength and assumed to have an infinitesimal diameter.

For the boundary conditions

$h \rightarrow h_0$ as $r \rightarrow \text{infinity}$ for $t \geq 0$

$$\lim_{r \rightarrow 0} \left(r \frac{\partial h}{\partial r} \right) = \frac{Q}{2\pi T}$$

and the initial conditions

$$h(r, 0) = h_0 \text{ for } t \leq 0,$$

the solution to the problem (Figure 1) given by Eq. 1 is as follows:

$$h_0 - h = \frac{Q}{4\pi T} \int_{\frac{r^2 s}{4Tt}}^{\infty} \frac{e^{-u}}{u} du \quad (2)$$

where h_0 is the piezometric head before pumping starts as shown

in Figure 1; Q the discharge of the well; and $u = \frac{r^2 s}{4Tt}$.

Theis (1935) first applied this equation to well hydraulics and this equation is known as the nonequilibrium equation.

With the exponential integral expressed symbolically as

$W[u]$, that is,

$$W[u] = \int_u^{\infty} \frac{e^{-u}}{u} du$$

$W[u]$ is read as the "Well Function" for nonleaky isotropic confined aquifers fully penetrated by wells and constant discharge conditions.

Expanding the exponential integral in a convergent series,

$$W[u] = -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \dots \quad (3)$$

Eq. 2 may be rewritten in the gallon-day-foot system of unit in abbreviated form as

$$h_0 - h = \frac{114.6 Q}{T} W[u] \quad (4)$$

where $u = \frac{1.87 r^2 S}{Tt}$.

Jacob (1946) modified the nonequilibrium equation for small values of $u (\leq 0.01)$ and can be expressed in gallon-day-foot system of unit as

$$h_0 - h = \frac{264Q}{T} \log \frac{0.37t}{r^2 S} \quad (5)$$

Unsteady Radial Flow to a Well with Variable Discharge

Jacob and Lohman (1952) gave a solution of Eq. 1 for unsteady flow to a well with variable discharge but with constant drawdown. In the analysis it was assumed that the water level in the well drops instantaneously to a lower stage, and a constant drawdown is maintained thereafter, resulting in a variable discharge governed by Eq. 1. With the boundary conditions

$$h \rightarrow h_0 \text{ as } r \rightarrow \text{infinity for } t > 0$$

and

$$h = h_0 - s_w \text{ for } r = r_w \text{ and } t > 0,$$

and the initial condition

$$h = h_0 \text{ for } t \leq 0$$

and for all values of r_w ,

the solution given by Jacob and Lohman (1952) is

$$Q = 2\pi r_w \frac{4\lambda}{\pi} \int_0^\infty x e^{-\lambda x^2} \left[\frac{\lambda}{2} + \tan^{-1} \frac{y_0(x)}{y_0(x)} \right] dx \quad (6)$$

where s_w is the drawdown at the well; r_w the radius of the well;
 $\lambda = \frac{Tt}{S r_w^2}$; $J_0(x)$ the zero-order Bessel function of the first
 kind and $Y_0(x)$ is the zero-order Bessel function of the second
 kind.

Actually seldom drawdown remains constant before steady
 state is reached. The drawdown at the well continuously increases
 with time as pumping continues. And a continuous lowering of the
 water level inside wells normally corresponds to a decreasing
 pumping rate. Abu-Zeid and Scott (1963) gave a solution for this
 situation considering a discharge-time exponential function given
 by

$$Q(t) = Q_0(\alpha + \beta e^{-at}) \quad (7)$$

in which $Q(t)$ is the discharge at time t ; Q_0 the initial discharge
 and a, α, β , are the discharge parameters. The drawdown at any
 radial distance r from a well, at any time t , was then expressed
 in fps system of unit as

$$\begin{aligned} s(r,t) = & -\frac{Q_0}{4\pi T} Ei(-u) [\alpha + \beta e^{-at} J_0(2\sqrt{\frac{ar^2 S}{4T}})] \\ & + \frac{\beta Q_0}{4\pi T} e^{(-at-u)} \left[\{Ei(at) - \ln(\gamma at)\} \right. \\ & + u \left\{ 1 - \frac{ar^2 S}{4T} - J_0(2\sqrt{\frac{ar^2 S}{4T}}) \right\} \\ & + \left. \left\{ \sum_{i=1}^{\infty} \sum_{j=1}^i \frac{(-1)^j (i-j+1)!}{((i+2)!)^2} \left(\frac{ar^2 S}{4T} \right)^{i+2} \right\} \right] \quad (8) \end{aligned}$$

where $E_1()$ is the exponential integral; $E_i()$ the logarithmic integral; $J_0()$ the first kind Bessel function of the zero-order; $\gamma = e^\gamma = 1.781072$ and γ is the Euler constant.

The above Eq. 8 further modified by Abu-Zeid, Scott and Aron (1964) to a form expressed as

$$\begin{aligned} s(r,t) = & -\frac{Q_0}{4\pi T} E_i(-u) \left[\alpha + \beta e^{-at} J_0\left(\sqrt{\frac{ar^2s}{4T}}\right) \right] \\ & + \frac{\beta Q_0}{4\pi T} e^{(-at-u)} \sum_{i=1}^{\infty} \sum_{j=0}^{i-1} \frac{(-1)^j (i-j-1)! \left(\frac{ar^2s}{4T}\right)^j}{(i!)^2 (u)^{i-j}} \end{aligned} \quad (9)$$

Aron and Scott (1965) gave a simplified solution, considering a well discharge with a starting value Q_0 , which decreased in equal steps $\Delta Q = \epsilon Q_0$, occurring at time $t_1, t_2, \dots, t_N$ as shown in Figure 3. And the solution is

$$s(r,t) \approx \frac{Q(t)}{4\pi T} \ln\left(\frac{2.25 T t}{r^2 S}\right) + s_e \quad (10)$$

where $s_e = \frac{[\bar{Q} - Q(t)]}{2.25 \pi T}$; $Q(t) = (1 - N\epsilon) Q_0$; $\bar{Q}$ is the average discharge during time 0 to t and N the number of steps of flow change in time t .

Relationship between discharge and time, as was suggested by Abu-Zeid, Scott and Aron, may not be unique for a well. Sternberg and Scott (1967) suggested that the pumping rate of a well will usually decline after a deep well turbine pump of constant speed adjusts itself to the lowering of the water table in accordance

with the head-capacity curve — a characteristic of the pump.

Accordingly they gave a solution which can be expressed as

$$s(r, t_k) = \frac{1}{4\pi T} \sum_{j=0}^{k-1} [Q(t_{j+1}) - Q(t_j)] W[u(r, t_k - t_j)] \dots \quad (11)$$

where $s(r, t_k)$ is the drawdown at distance r from the well after time t_k ; t_j the time interval ($t_0, t_1, t_2, \dots, t_k$); $Q(t_j)$ the average discharge during the time interval t_{j-1} to t_j ; $Q(t_{j+1})$ the average discharge during the time interval t_j to t_{j+1} ; $W[u(r, t_k - t_j)]$ is the well function and $u(r, t_k - t_j) = \frac{r^2 S}{4(t_k - t_j)T}$.

The variation of discharge with time in Eq. 11 can be obtained from head-capacity curve which can be expressed mathematically by a polynomial.

Mutual Interference of Wells

If the pumping time is long and or the well spacing is not large enough, the drawdown in an individual well might be influenced significantly by the adjacent wells in a multiple well system. In this situation, drawdown at any point can be evaluated by adding every drawdown produced at that point by individual wells. Sternberg and Scott (1967), Krizek, Karadi and Rao (1971) also used above procedure i.e., the principle of superposition to calculate drawdown produced at any point by a group of pumping wells.

Thus for a number of wells with constant discharge the total drawdown at any point after time t governed by Eq. 2 will be

$$s(r_i, t) = \frac{1}{4\pi T} \sum_{i=1}^m Q_i W[u_i] \quad (12)$$

where r_i is the distance from the i th well; Q_i the discharge of the i th well and $u_i = \frac{r_i^2 S}{4Tt}$.

The general equation, given by Sternberg and Scott (1967), for the drawdown at any point after time t_k when n wells are operating with variable discharge is

$$s(r_i, t_k) = \sum_{i=1}^m \frac{1}{4\pi T} \left\{ \sum_{k=0}^{N-1} Q_i(t_k) W[u(r_i, t_{N-k})] - \sum_{k=0}^{N-2} Q_i(t_k) W[u(r_i, t_{N-k-1})] \right\} \quad (13)$$

where $W[u(\quad)] = \int_u^{\infty} \frac{e^{-u}}{u} du$; $u(r_i, t_{N-k}) = \frac{r_i^2 S}{4T t_{N-k}}$.

The foregoing Eqs. 1 to 13 refer to confined aquifers. By approximation, however, these equations can be applied also to unconfined aquifers when the drawdown is small compared to total saturated thickness of the aquifer. Assumptions involved in the derivation of those equations are

- i. the aquifer is homogeneous and isotropic;
- ii. the aquifer is infinite in areal extent and is of the same thickness throughout;

- iii. the formation receives no recharge from any source;
- iv. the pumped well penetrates full thickness of the aquifer and the flow is radial throughout;
- v. the water removed from storage of the aquifer is discharged instantaneously with the lowering of head.

CHAPTER III

DETERMINATION OF WELL SPACING

General

Uptill now no suitable method is available for the selection of spacing between irrigation wells giving proper considerations to aquifer characteristics and water requirement. Spacing of wells should be such that water requirement is fulfilled and no adverse condition arises within the aquifer. Keeping this in mind, analytical methods were developed in this study for the determination of spacing between two adjacent deep tubewells in square grid tubewell layout as shown in Figure 4 using available ground water flow equations. An IBM 360 digital computer has been used to solve these equations and to perform iterations necessary in the method developed. Various situations were considered and these were constant discharge condition at the well; decreasing discharge situation at the well; wells subjected to mutual interference; noninterference situation all over the well field.

Computation of Drawdown

Drawdown at any point due to a pumping well of constant discharge was calculated using the equation given below:

$$h_0 - h = \frac{114.6 Q}{T} W [u] \quad (4)$$

The well function $W[u]$ was calculated by the following equation (flow chart shown in Figure 5)

$$W[u] = -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \dots \quad (3)$$

$$\text{in which } u = \frac{1.87 r^2 S}{T t}$$

Drawdown at any point due to a pumping well with decreasing discharge condition was calculated by converting Eq. 11 into gallon-day-foot system of unit as follows:

$$s(r, t_k) = \frac{114.6}{T} \sum_{j=0}^{k-1} \{Q(t_{j+1}) - Q(t_j)\} W[u(r, t_k - t_j)] \quad (14)$$

In this case the discharge of the well has been supposed to decline in accordance with the head-capacity curve of the pump. Three head-capacity curves for 2-cfs (898 gpm) capacity deep tubewell pumps as shown in Figure 6 supplied by KSB (Klein, Schanzlin & Becker Aktiengesellschaft), Dacca, were selected for this study. These head-capacity curves were expressed mathematically by the following polynomials:

$$U = 0.1H - 2.0 \quad (15)$$

$$Q = 1410 - 108U - 10U(U-1) + 2.833U(U-1)(U-2) - 1.9167U(U-1)(U-2)(U-3) + 0.2667U(U-1)(U-2)(U-3)(U-4) \quad (16)$$

for curve 1.

$$U = 0.2H - 4.0 \quad (17)$$

$$Q = 1550 - 97U - 4.5U(U-1) - 0.667U(U-1)(U-2) - 0.375U(U-1)(U-2)(U-3) + 0.0667U(U-1)(U-2)(U-3)(U-4) - 0.1764U(U-1)(U-2)(U-3)(U-4)(U-5)$$

$$\text{for curve 2} \quad (18)$$

$$U = 0.2H - 3.0 \quad (19)$$

$$Q = 1425 - 125U - 4.167U(U-1)(U-2) \quad (20)$$

for curve 3.

The total pumping time, t_p , was divided into small increments $\Delta t_1, \Delta t_2, \Delta t_3, \dots, \Delta t_k$ of increasing magnitude such that $\Delta t_k = \mu \Delta t_{k-1}$ where μ is a constant greater than unity. Value of μ was varied from 1.1 to 2.0. The initial time increment Δt_1 , was taken equal to 0.0001 day (8.64 seconds). It was assumed that discharge of the well during each time increment remained constant. The discharge, $Q(H_0)$, of the pump during the first time increment, Δt_1 , was obtained from the head-capacity relationship corresponding to a head equal to static lift, L_0 , i.e., $H_0 = L_0$. (21)

Using this discharge, $Q(H_0)$, the incremental drawdown, $\Delta s_{w,1}$, at the well after first time increment, Δt_1 , was calculated using Eq. 4. This incremental drawdown, $\Delta s_{w,1}$ was added to the static lift, L_0 , to get the new head, H_1 , after time $t_1 = \Delta t_1$. Therefore,

$$H_1 = L_0 + \Delta s_{w,1} \quad (22)$$

A new discharge, $Q(H_1)$, corresponding to the new head, H_1 , was computed using the head-capacity relationship. Again with this new discharge, $Q(H_1)$, the incremental drawdown, $\Delta s_{w,2}$, at the end of the second time increment, Δt_2 , was calculated and has been added to the previous head, H_1 , to get the new head, H_2 , after time $t_2 = t_1 + \Delta t_2$. Hence total head (i.e. lift) after time,

t_2 , is

$$H_2 = H_1 + \Delta s_{w,2} \quad (23)$$

This process repeated upto the last time increment, Δt_N , to get the total head, H_N , after time $t_N = t_{N-1} + \Delta t_N$ when pumping ends. Therefore the final lift is

$$H_N = H_{N-1} + \Delta s_{w,N}. \quad (24)$$

The static lift, L_0 was subtracted from H_N to get the drawdown at the well i.e.

$$s_w = H_N - L_0. \quad (25)$$

The drawdown, $s_{R/2}$, at the middle point between two adjacent wells was obtained by adding all the incremental drawdowns,

$\Delta s_{r,1}, \Delta s_{r,2}, \dots, \Delta s_{r,k}$; produced at that point after each of time increments, $\Delta t_1, \Delta t_2, \dots, \Delta t_k$,

$$\text{i.e. } s_{R/2} = \sum_{k=1}^N \Delta s_{r,k} \quad (26)$$

The total drawdown at any point due to pumping of m number of same capacity wells subjected to mutual interference was calculated by converting Eqs. 12 and 13 into gallon-day-foot system of unit as follows assuming every pump has same head-capacity relationship:

$$s(r_i^o, t) = \frac{114.6}{T} \sum_{i=1}^m Q_i W[u_i] \quad (27)$$

and

$$\Delta(r_i^o, t_k) = \sum_{i=1}^m \frac{114.6}{T} \left\{ \sum_{k=0}^{N-1} Q_i(t_k) W[u(r_i^o, t_{N-k})] - \sum_{k=0}^{N-2} Q_i(t_k) W[u(r_i^o, t_{N-k-1})] \right\} \quad (28)$$

In this case the lift at the well after each time increment increased not only by the incremental drawdown due to pumping of the well itself but also due to incremental drawdown contributions from surrounding wells i.e.

$$\Delta H_k = \Delta s_{w,k} + \sum_{i=1}^m \Delta s_{i,k} \quad (29)$$

in which ΔH_k is the increase in head after incremental time Δt_k ; $\Delta s_{w,k}$ the incremental drawdown at the well due to pumping of well itself after incremental time, Δt_k ; and $\Delta s_{i,k}$ the incremental drawdown contribution from the i th well after incremental time Δt_k .

For the computation of drawdown at a well, the drawdown contributions from surrounding eight wells were considered as explained in Figure 4 i.e.

$$DD_w = \frac{114.6Q}{T} \left\{ W[u(r_w, t)] + W[u(\sqrt{2}R, t)] \times 4 + W[u(R, t)] \times 4 \right\} \quad (30)$$

For the computation of drawdown at the middle point between two adjacent wells, the drawdown contribution from eight surrounding wells as shown in Figure 4 were considered i.e.

$$DD_{R/2} = \frac{114.6Q}{T} \left\{ W[u(R/2, t)] \times 2 + W[u(1.5R, t)] \times 2 + W[u(\sqrt{5}R, t)] \times 4 \right\} \quad (31)$$

Successive steps in computing drawdown as described earlier is explained with the flow chart shown in Figures 7 and 8.

Determination of Well Spacing allowing Interference

The spacing between two adjacent wells in square grid tubewell layout allowing some amount of interference was determined satisfying conditions outlined below:

- 1) The drawdown, s_w , at the production well is equal to or less than a value, D_{A-w} , so that the lift at the well remains equal to or less than the maximum allowable lift as explained in Figure 9.
- 2) The drawdown $s_{R/2}$ at the middle point between two adjacent wells is equal to or less than a selected value, $D_{A-R/2}$, as explained in Figure 10.

The first condition will ensure that the discharge will not decrease below the design value. The second condition will prevent excessive lowering of water table so that adverse condition is not created within the aquifer.

The maximum allowable lifts which correspond to design discharge (898 gpm) of the well were obtained from head-capacity curves of pump as shown in Figure 6. They are 59.0 ft, 45.0 ft, and 33.5 ft.

for curves (1), (2) and (3) respectively. The allowable drawdowns D_{A-w} at the well were obtained by subtracting static lift, L_0 , from maximum allowable lifts as shown in Figure 9.

An iterative procedure was developed to determine spacing between two adjacent wells analytically. An initial value of spacing $R_0 = 100$ feet was selected. Then total drawdowns s_w and $s_{R/2}$ at the well and at the middle point of the spacing respectively were computed according to the procedure outlined previously. Then it was checked whether the computed drawdowns, s_w and $s_{R/2}$ were greater or less than the respective allowable values, D_{A-w} and $D_{A-R/2}$. If any one was found greater, then spacing R has been increased by an increment $\Delta R = 25$ feet. And again the process was repeated. This repetition continued until computed drawdowns s_w and $s_{R/2}$ were equal to or less than respective allowable values, D_{A-w} and $D_{A-R/2}$. In this way spacing corresponding to various values of discharge; coefficient of transmissibility; storage coefficient; static lift; time of pumping; allowable drawdowns; were determined analytically. Both variable discharge condition and constant discharge condition were considered in mutual interference situation. Successive steps in determining spacing between two adjacent wells in square grid tubewell layout as described before is explained with the flow chart shown in Figure 11.

Determination of Spacing allowing no Interference

In this case also similar iterative procedure was followed. The noninterference spacing between two wells is considered to be equal to two times the radius of influence of the well. The ~~outer~~-most point of the radius of influence was assumed to be at a distance where drawdown was equal to a selected tolerance value and it was 0.3 inch. This iterative procedure is similar to previous one. But only the drawdown at the middle point between two wells was compared with the tolerance value as shown in Figure 10. Constant discharge condition was considered in this case.

Computer Programming

Iterative procedure outlined previously for computation of drawdown and for determining well spacing were solved with the help of an IBM 360N-FO-479 3-6 digital computer located at Bureau of Statistics, Bangladesh Planning Commission, Secretariate Building, Dacca. Computer programmes were formulated using FORTRAN-IV language as presented in Appendix C.

A sub-routine was made for the calculation of 'well function' $W[u]$, using Eq. 3 and presented in Appendix C.

While using the equations in the analytical method developed to determine well spacing, simplifying assumptions were made to make this solution possible. However, these assumptions are found

valid as will be discussed later on. The assumptions are as follows:

- 1) Every well in the layout is of same capacity.
- 2) Effective radius of every well is equal to one foot as suggested by Karim (1976).
- 3) Depth of every well is same.
- 4) Static water table is horizontal before pumping.
- 5) Static lift at every well is same before pumping.
- 6) Every pump starts at the same instant and continues for same time length. Although every pump may not start at the same instant and may not continue for same duration, this assumption takes care of worst possible combination.
- 7) Well loss component of total drawdown at the well is negligible during pumping.
- 8) The aquifer does not receive any recharge. Actually some portion of rainfall, if any, and irrigation water will reach the groundwater table due to deep percolation. This will reduce the water table lowering as compared to calculated values. However this will make the calculated well spacing conservative.

Spacing to Satisfy Water Requirement

Spacing required in a square grid tubewell layout to satisfy irrigation water requirement has been calculated on the following basis:

$$\begin{aligned} \text{Spacing} &= \sqrt{\frac{Q \times 60 \times 60 \times t_p \times 30 \times 12}{D}} \\ &= 360 \sqrt{\frac{10 Q t_p}{D}} \end{aligned} \quad (32)$$

where Q is the well discharge in cfs; t_p the daily pumping hours; and D is the peak monthly irrigation water requirement in inches/month.

Variables

Variables considered in this study are discharge; coefficient of transmissibility; storage coefficient; pumping time; static lift; maximum allowable lift at the well; maximum allowable drawdown at the middle point between two adjacent wells and peak monthly irrigation water requirement. They are presented in the following table.

Table 1. List of Variables

Variable	Range
Well discharge, Q	1 cfs, to 4 cfs
Coefficient of Transmissibility, T	0.5×10^5 to 5.5×10^5 gpd/ft,
Storage coefficient, S	0.01 to 0.20
Pumping time, t_p	8, 16 hrs/day, 1, 14, 28, & 42 days
Static lift, L_0	10, 20, 30 feet.
Allowable lift at the well in variable discharge condition, D_{A-w}^*	33.5, 45.0, 59.0 feet
Allowable lift at the well in constant discharge condition, D_{A-w}	33.5, 40, 45, 50, 59, 60, 70 feet.
Allowable drawdown at the mid.pt. between to adjacent wells, $D_{A-R/2}$	0.25, 0.5, 1.0, 2.0, 5.0 ft.

* Obtained from head-capacity curves shown in Figure 6.

CHAPTER IV

RESULTS AND DISCUSSION

This study shows that much greater spacings between adjacent tubewells are required to keep water table lowering equal to or less than allowable value at the middle point between two nearest wells in square grid tubewell layout than those required to keep the drawdown at the well equal to or less than the maximum allowable value. Some of results have been presented in Table 2 to show this. This suggests that the allowable drawdown at the middle point between two adjacent wells controls the deep tubewell spacing when some amount of interference is allowed.

Equal values of well spacing has been obtained from both variable discharge condition and constant discharge condition when spacing is equal to or greater than 1200 feet as seen from Table 2. For spacings less than 1200 feet, variations are mostly 25 to 50 feet i.e. 2.22% to 7.14% with a maximum of 100 feet i.e. 18.18% which can be neglected for practical purposes. This is because the high initial discharge corresponding to static lift in accordance with the head-capacity relationship of the pump decreases to the vicinity of design discharge within short interval of time as seen from Figure 12 before it could produce significant effect at distances for away from the well. Hence it is not so important for practical purposes to consider the variability of discharge

due to increase in drawdown at the well with time.

Effect of formation constants upon depth, shape and extent of cone of depression is shown in Figure 13. It shows that drawdown at the well decreases significantly with the increase in transmissibility. But change of storage coefficient has negligible effect on it. This figure also shows that radius of influence of a well increases or decreases as transmissibility increases or decreases respectively. From Darcy's law it is evident that, for same discharge, aquifers with lower transmissibility value will have higher hydraulic gradient than those with higher transmissibility values. Hydraulic gradient is dependent on difference of head and length of flow path. Hence higher hydraulic gradient is associated with large drawdown and smaller radius of influence. This is why, with the increase in transmissibility of an aquifer, depth and extent of cone of depression decrease and increase respectively.

Curves presented in Figures 14 to 17 show logarithmic plotting of spacing against coefficient of transmissibility for various values of storage coefficient. Only four combinations of discharge, pumping time and allowable drawdown at the middle point of well spacing are shown in these figures out of 48 combinations studied as they are similar in nature. These figures show that spacing at first increases slowly with the increase in transmissibility

value and reaches the maximum for intermediate values of transmissibility. Then it again decreases slowly with the increase in transmissibility. Lower transmissibility value is associated with smaller radius of influence as explained earlier. Hence, to keep the interference at the middle point between two adjacent wells below the allowable limit, wells need not to be spaced much further apart and spacing is smaller. Now as transmissibility increases, influence area enlarges. This causes considerable amount of interference at the middle point even with larger distance between adjacent wells. Hence greater spacings are required. If transmissibility increases further, still radius of influence increases exponentially. But in this case drawdown is very small as seen from Figure 13. Hence to produce given amount of interference at the middle point, lesser spacing between wells is required.

Curves presented in Figures 14 to 17 also show that variation in spacing due to variation of storage coefficient is more pronounced than those due to variation in transmissibility. This is because, amount of water table lowering depends on the storage coefficient of the aquifer and not on transmissibility value.

Relationship between well spacing and storage coefficient are presented in Figures 18 to 20. These curves have been drawn by selecting maximum value of spacing from spacing versus transmissibility plottings for each value of storage coefficient.

As the maximum values of spacing are selected from spacing versus transmissibility curves, this will eliminate the effect of transmissibility on spacing. Figures 18 to 20 show that spacing increases with the decrease in storage coefficient. This is because, greater area is to be dewatered in case of smaller storage coefficient for same amount of pumping.

Storage coefficient is mainly dependent on the type of aquifer material. It can be estimated reasonably by collecting samples of aquifer material. Representative values of storage coefficient in water table aquifers are listed in Table 4 for various types of aquifer material. But it is not so easy to determine coefficient of transmissibility in the field as it requires test data from well. Hence, selection of storage coefficient as the deciding factor in determining well spacing when aquifer characteristics are considered will make the process easier from practical considerations.

Noninterference spacing, which is two times the radius of influence, is plotted against transmissibility for various values of storage coefficient and pumping time. Two sets of them are shown in Figures 21 and 22 out of 24 sets. In this case it is seen that both transmissibility and storage coefficient have significant effect on radius of influence and it increases with the increase in transmissibility but decreases with the increase in storage coefficient. This can be seen also from Figure 13.

From the comparison of spacings presented in Table 3, it is seen that for the selected range of transmissibility and storage coefficient, spacing varies between 875 to 5050 feet for 2-cfs discharge when interference from surrounding wells is allowed. But with no interference, spacing varies between 1475 to 12,600 feet for 2-cfs discharge which is very high. Hence spacing between adjacent wells without allowing some amount of interference is impracticable.

This study also shows that the amount of interference from surrounding eight wells in percent of total drawdown at the well is between 0.1% to 10% for the selected range of aquifer characteristics as can be seen from Figure 23. It is noted that interference is higher for greater values of transmissibility. This is because of larger radius of influence for high values of transmissibility.

Total drawdown at the well also is not very high as seen from Figure 24 and the range is 2.85 to 30 ft. when interference from surrounding wells is allowed. Whereas drawdown at the well without interference varies from 2.6 to 29.3 ft, as can be seen from Figure 21. This justifies that acceptance of some amount of interference in selecting deep tubewell spacing will not be very harmful to aquifer condition.

Figure 18 shows the effect of pumping time on spacing vs. storage coefficient relationships for 2-cfs discharge. The spacing increases slowly with the increase in pumping time. For example, spacing increases from 870 feet to 1600 feet only when pumping time increases from 8 hours to 24 hours for storage coefficient equal to 0.1.

Figure 20 shows relationship between spacing and storage coefficient for various values of discharge. In this case also the spacing increases slowly with the increase in discharge. For example, if discharge is increased from 1 cfs to 4 cfs, corresponding increase in spacing is from 1140 ft. to 2240 ft. only for storage coefficient equal to 0.1.

Instead of total irrigation water requirement, peak monthly irrigation water requirement has been selected as parameter in this study. Because length of growing season is not same for all types of crop and water requirement varies with time during growing period. Well spacings required in square grid tubewell layout to satisfy irrigation water requirement is shown in Figures 25 and 26.

A chart as presented in Figure 27 has been prepared for the selection of deep tubewell spacing considering aquifer characteristics and irrigation water requirement. Spacing corresponding to storage coefficient might result a maximum drawdown of 0.5 ft.

only at the middle point of two nearest wells, if every well in square grid tubewell layout runs continuously for 24 hours. On the other hand spacing corresponding to peak monthly irrigation water requirement has been calculated on the basis of 18 hours of continuous pumping per day. Of the two spacings, based on storage coefficient and irrigation water requirement, greater one is to be selected. Because, if spacing corresponding to water requirement is larger, it is unnecessary to select smaller spacing. But when spacing corresponding to storage coefficient is larger, it might cause adverse effect within the aquifer by excessive lowering of water table, if smaller spacing is selected. In this case some portion of the land might remain unserved.

Aquifers in Bangladesh are mostly water table type. Lithological analysis shows that thickness of aquifers are several thousand feet and these aquifers have no defined impermeable bottom. Hence full thickness of aquifers can not be penetrated as required by the assumption in ground water flow Eqs. 1 to 13 and moreover full penetration is not possible. Hence in this case the coefficient of transmissibility is equal to the product of saturated thickness of aquifer penetrated by the well and average permeability of aquifer. As a result same value of transmissibility can not be used for tubewells of different depth, even if aquifer permeability does not vary with depth of aquifer. At a given locality coefficient of transmissibility will vary almost directly with the tubewell depth if permeability assumed to remain constant.

For this reason, it has been assumed in this study that the depth of every well in the layout is same. This assumption will not restrict the application of the design chart presented in Figure 27, while selecting spacing between deep tubewells of different depth. Because, effect of transmissibility on spacing has been eliminated as discussed earlier in developing relationships between storage coefficient and well spacing presented in Figures 18 to 20. It is important to mention here that same value of transmissibility can not be used while designing tubewells of different depth for a given locality.

Effect of recharge during pumping period is not considered in this study. Actually some portion of rainfall, if any, and irrigation water will reach the ground water table due to deep percolation. This will reduce the water table lowering as compared to calculated values. However this will make the calculated well spacing conservative.

Well loss component of the total drawdown at the well has been neglected in this study. Well loss is a function of capacity, size, construction and condition of the well. Aquifer performance has no relation with it. Calculated values of water table lowering in the aquifer which depend on formation constants have not been affected by this assumption. But calculated values of total lift at the well has been smaller than the actual as the well loss component of the total drawdown at the well has been neglected.

This no doubt gave greater values of discharge obtained from head-capacity relationship in the variable discharge condition. However, as the variable discharge condition does not control the spacing between deep tubewells, this assumption will not affect the result of this study.

It is assumed in this study that water table is horizontal before pumping starts. This might not be the actual situation in the field. Because it is most likely that there will be natural ground water movement. But this will not limit the application of results of this study as natural ground water velocity is very small with very little water table slope.

It is further assumed that static lift at every well is same. This may not be true as elevation of ground surface level might differ at different well. Difference in static lift will cause different initial discharge in different wells. But as the variable discharge condition does not control spacing, this will not affect the result of this study.

Amount of withdrawal per year from a ground water basin should not exceed the amount of recharge would occur during a year according to safe yield concept. Hence maximum number of tubewells possible in a basin is dependent on annual recharge. It requires extensive study to determine the ground water recharge due to withdrawal of water by tubewells. Safe yield

is also dependent on the extent of water table lowering, water quality, cost of pumping, water rights, possibility of saline water intrusion in coastal areas, etc. So, determination of safe yield itself is a highly complex problem. It might so happen that spacing between tubewells as limited by the maximum possible number of tubewells in a basin is greater than the spacing obtained from design chart. Hence this factor is also to be considered in the final selection of deep tubewell spacing.

CHAPTER V

CONCLUSIONS

The conclusions that can be drawn from this study are as follows:

1. Storage coefficient is the determining factor in selecting deep tubewell spacing when aquifer characteristics are considered.
2. Some amount of mutual interference is allowable in selecting deep tubewell spacing and noninterference spacing is not always practicable.
3. Of the two spacings, one considering aquifer characteristics and the other considering irrigation water requirement, the greater value to be selected from the design chart prepared.
4. It is not of practical importance to consider the variability of well discharge due to increase in drawdown at the well with time.
5. Variation of storage coefficient has negligible effect on the amount of drawdown at the well.
6. Radius of influence of a well enlarges with the decrease of and increase of storage coefficient and transmissibility coefficient respectively.

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APPENDIX - A

FIGURES

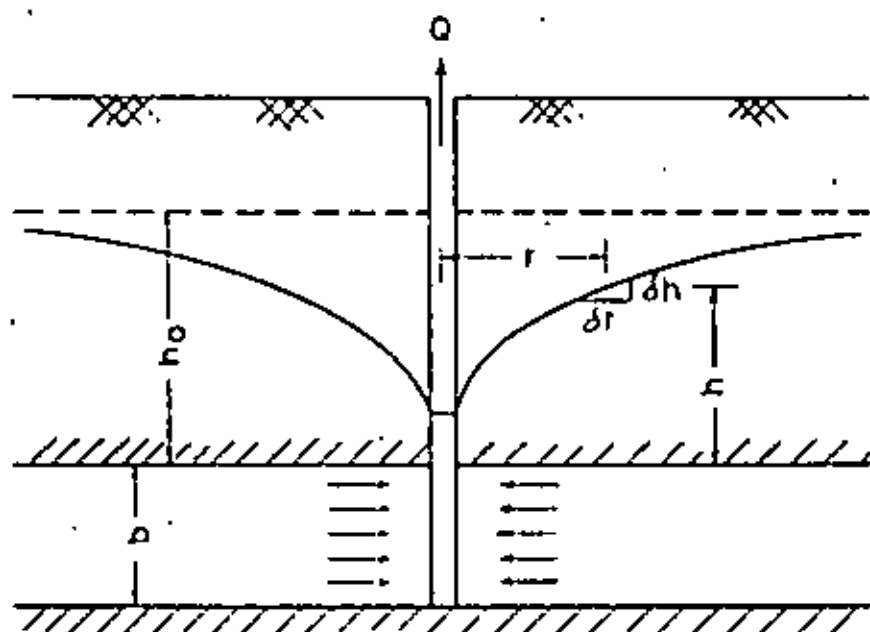


FIG. 1. RADIAL FLOW TO A WELL PENETRATING CONFINED AQUIFER.

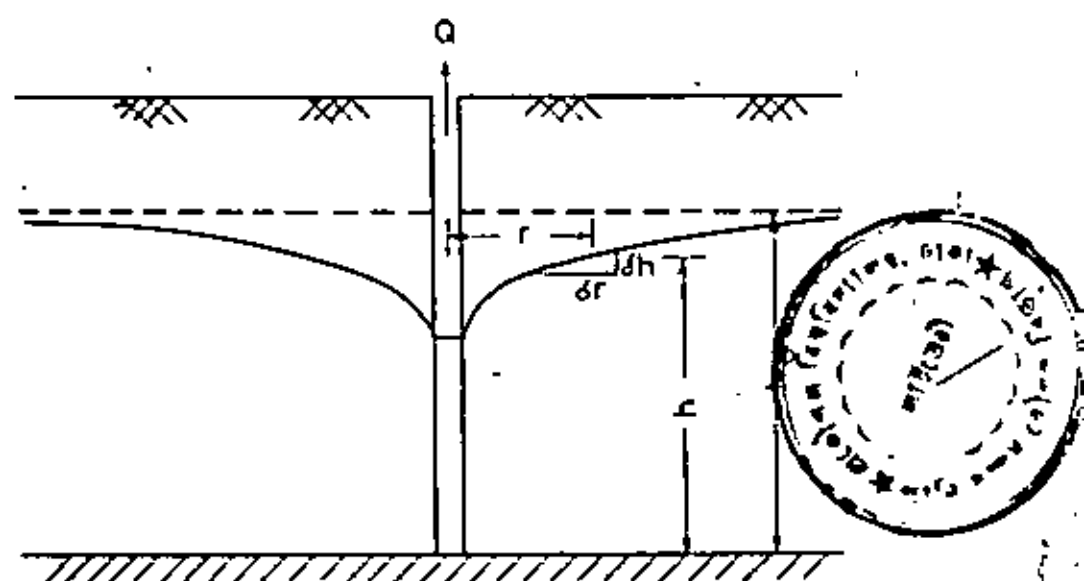


FIG. 2. RADIAL FLOW TO A WELL PENETRATING UNCONFINED AQUIFER.

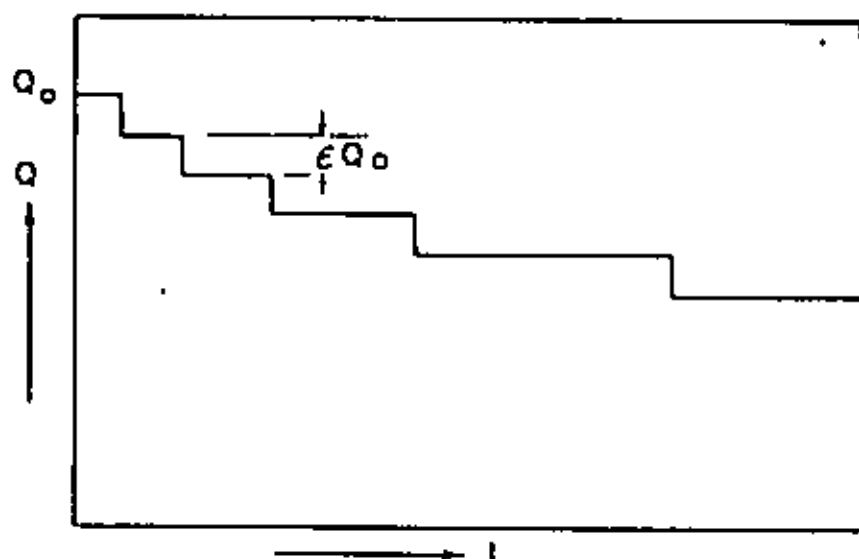


FIG. 3 CHANGE OF WELL DISCHARGE WITH TIME.

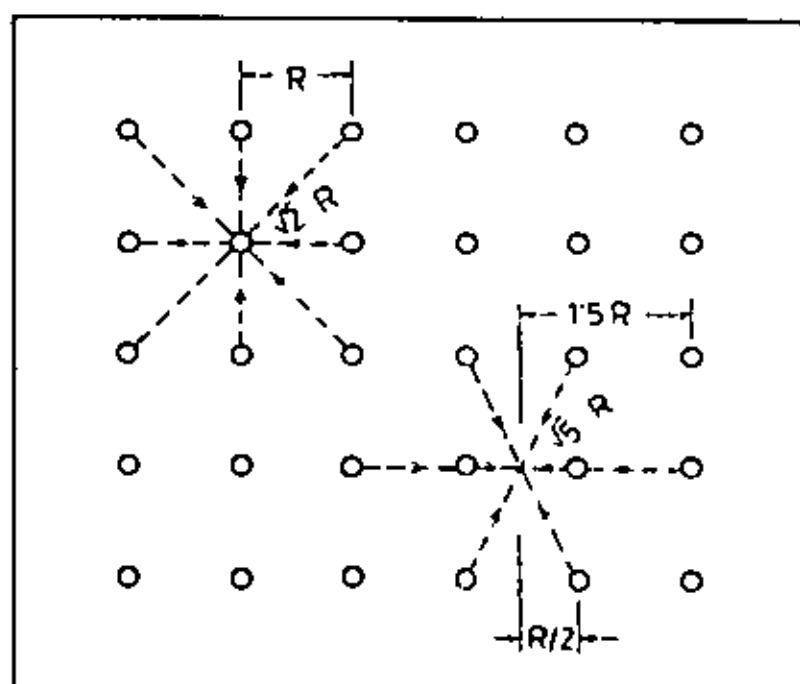


FIG. 4. TUBEWELL LAYOUT.

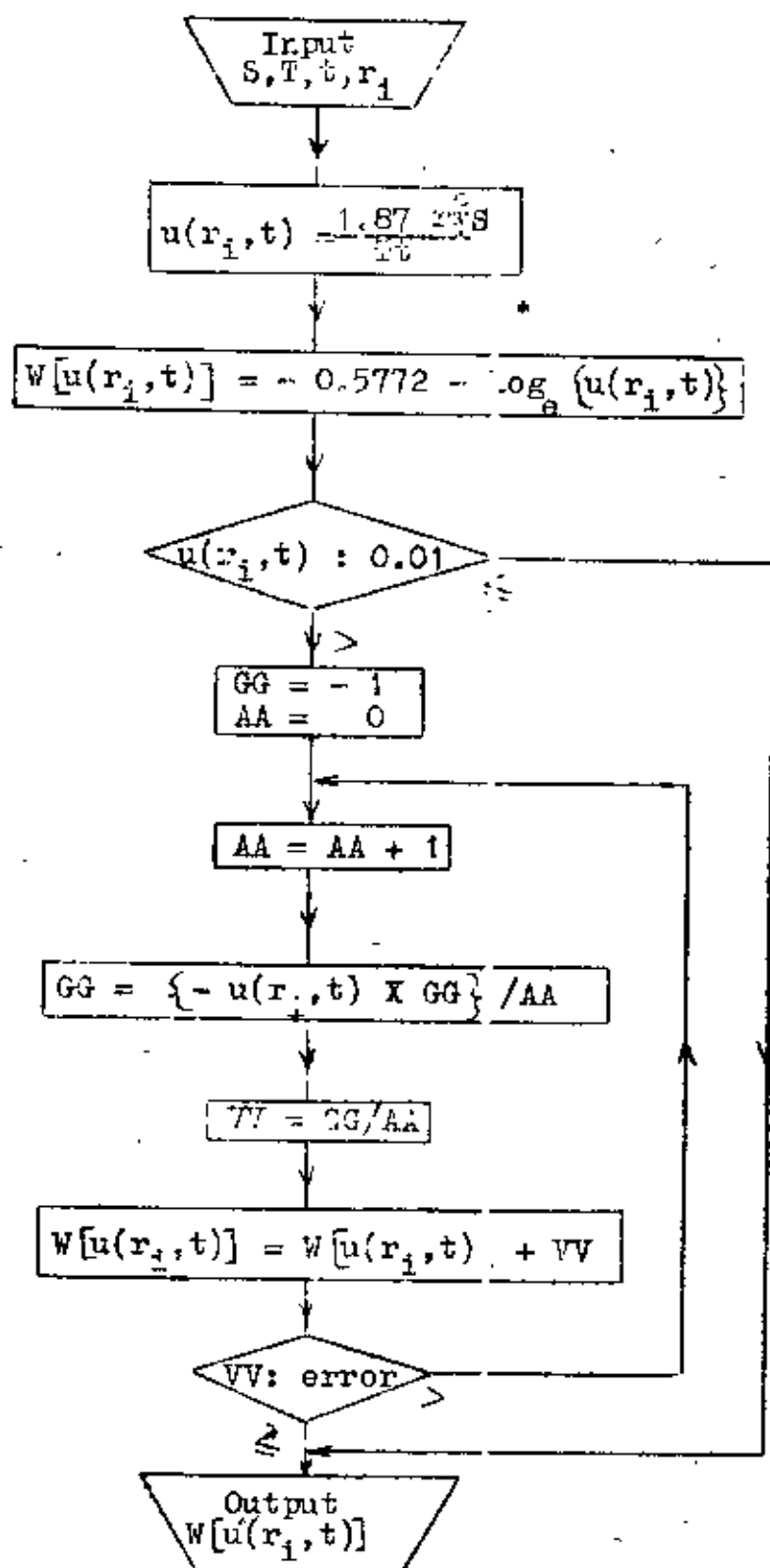
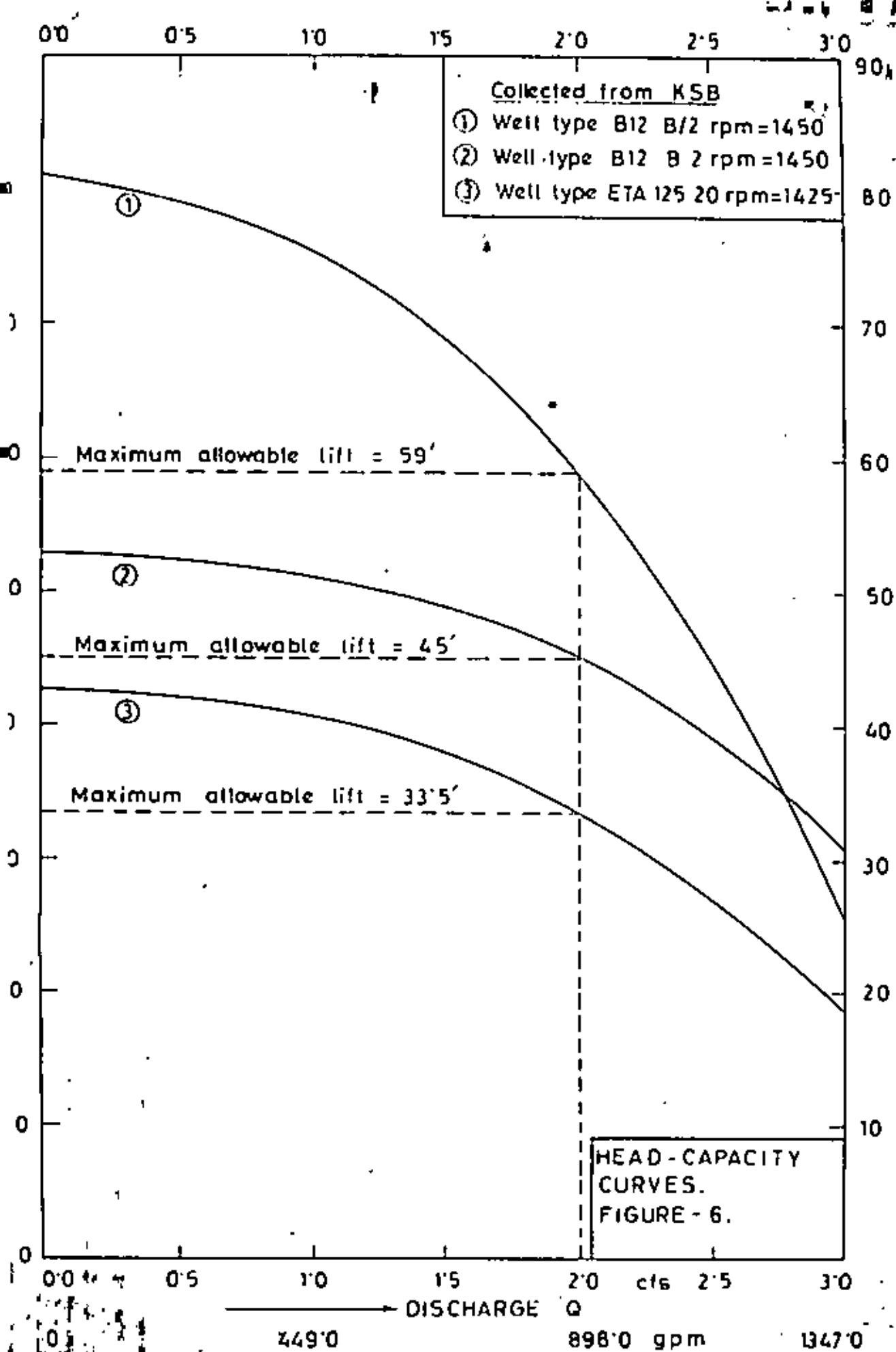
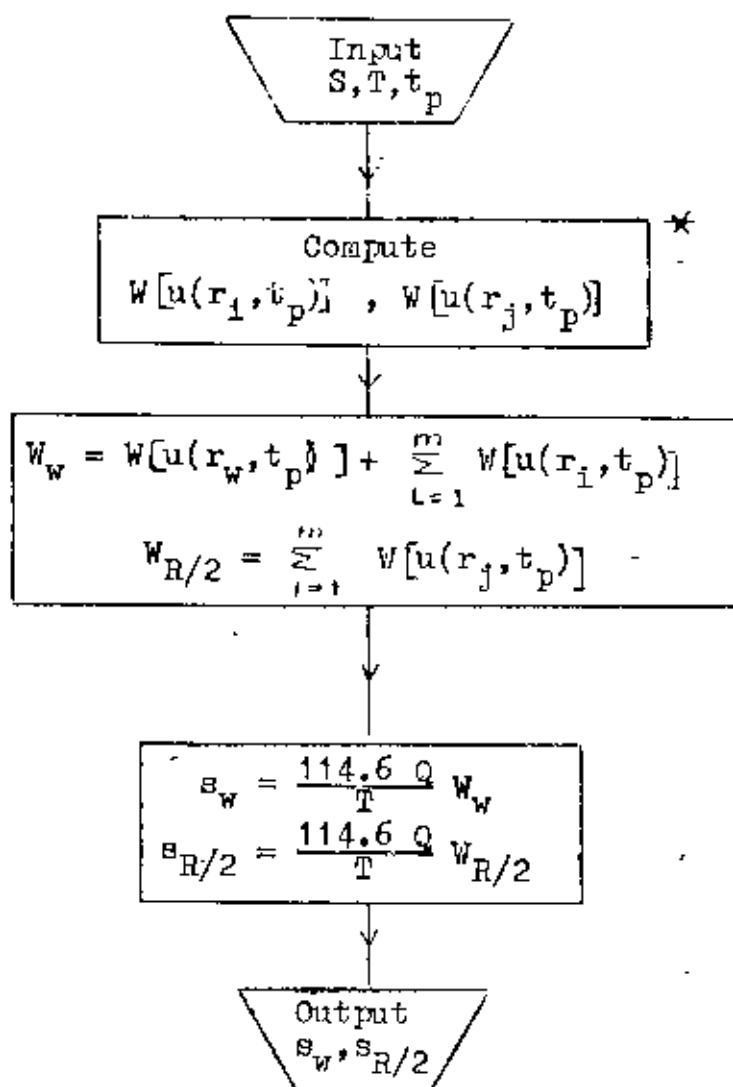


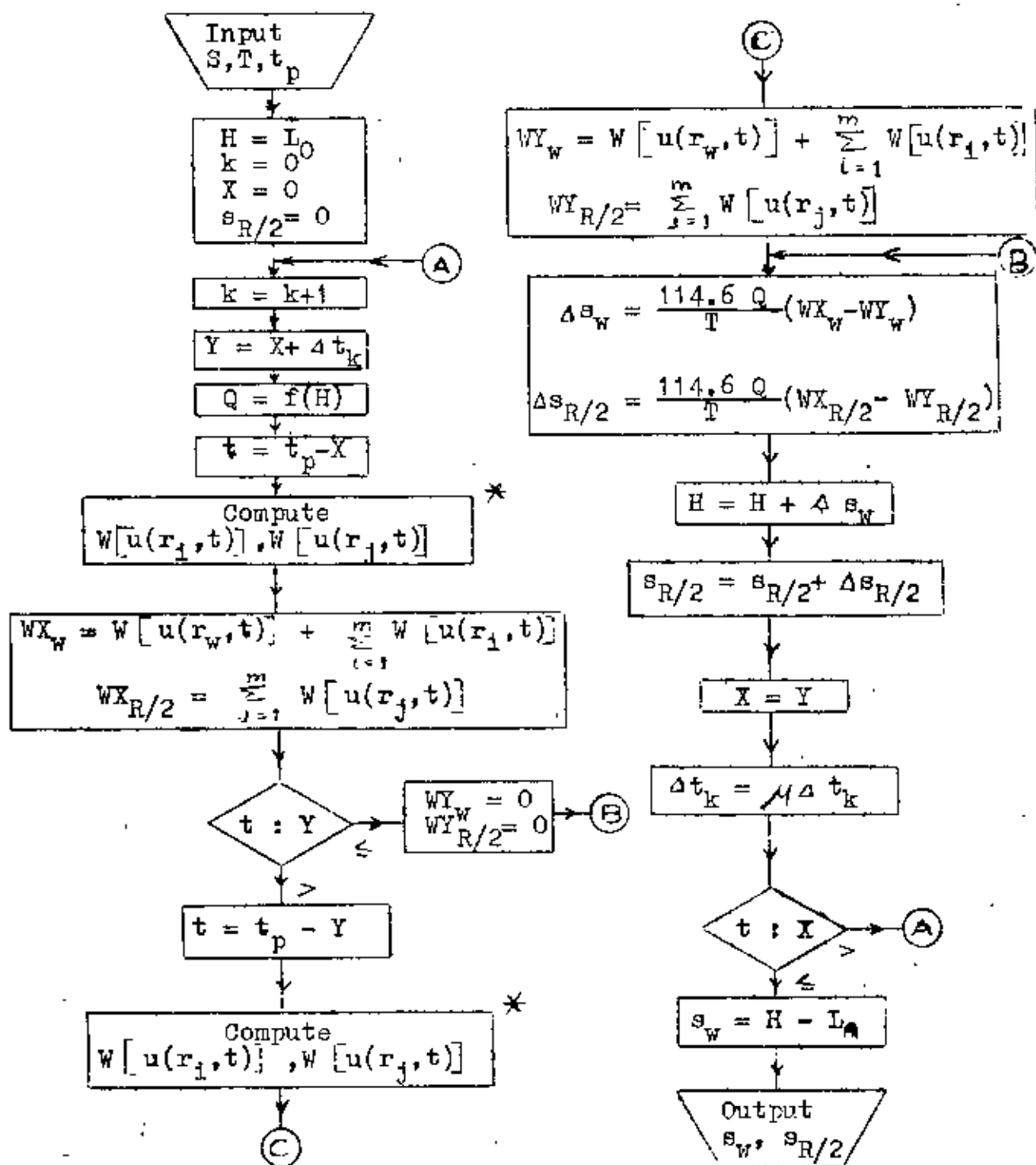
Figure 5. Flow chart showing computation of well function.





* Computation of $W[u(r, t_p)]$ is shown in Figure 5.

Figure 7. Flow chart showing computation of drawdown in constant discharge condition.



*Computation of $W[u(r, t)]$ is shown in Figure 5.

Figure 8. Flow chart showing computation of drawdown in variable discharge condition.

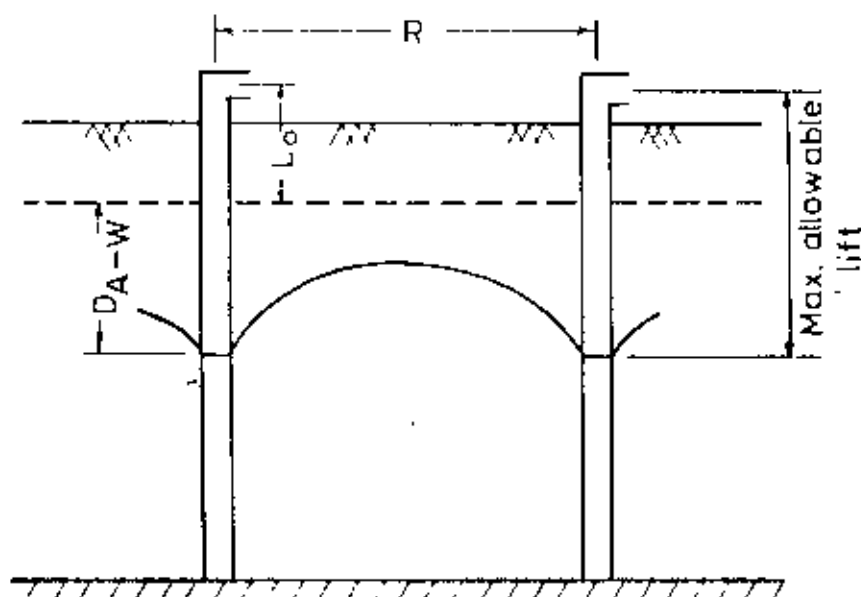


FIG. 9. ALLOWABLE DRAWDOWN AT THE WELL, $D_A - W$.

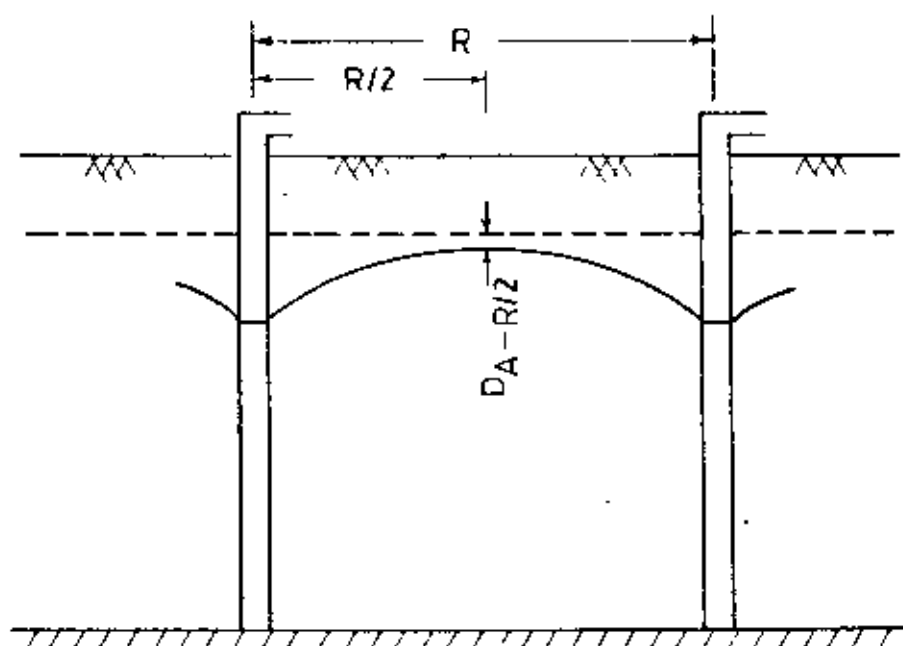
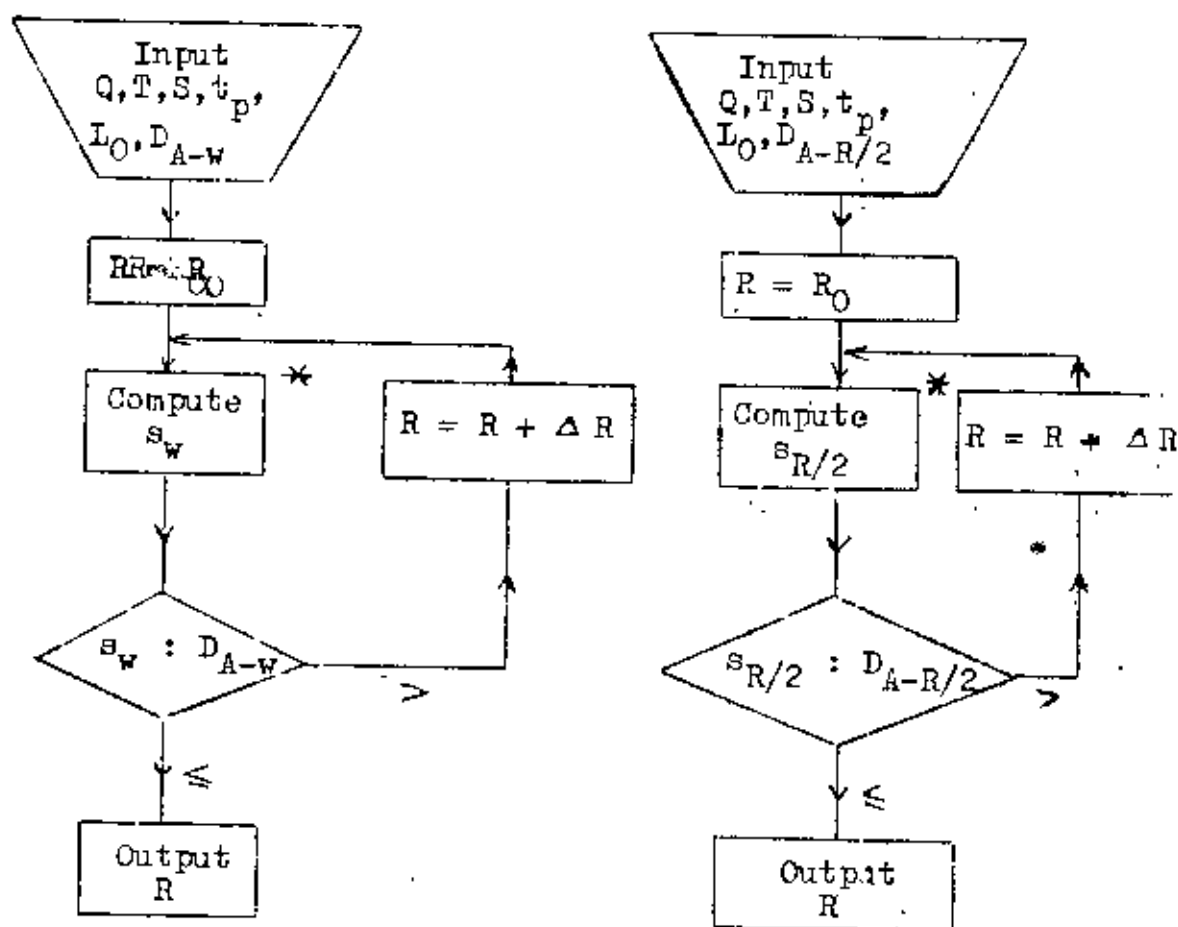


FIG. 10. ALLOWABLE DRAWDOWN AT THE MID. PT.
BETWEEN TWO ADJACENT WELLS, $D_A - R/2$

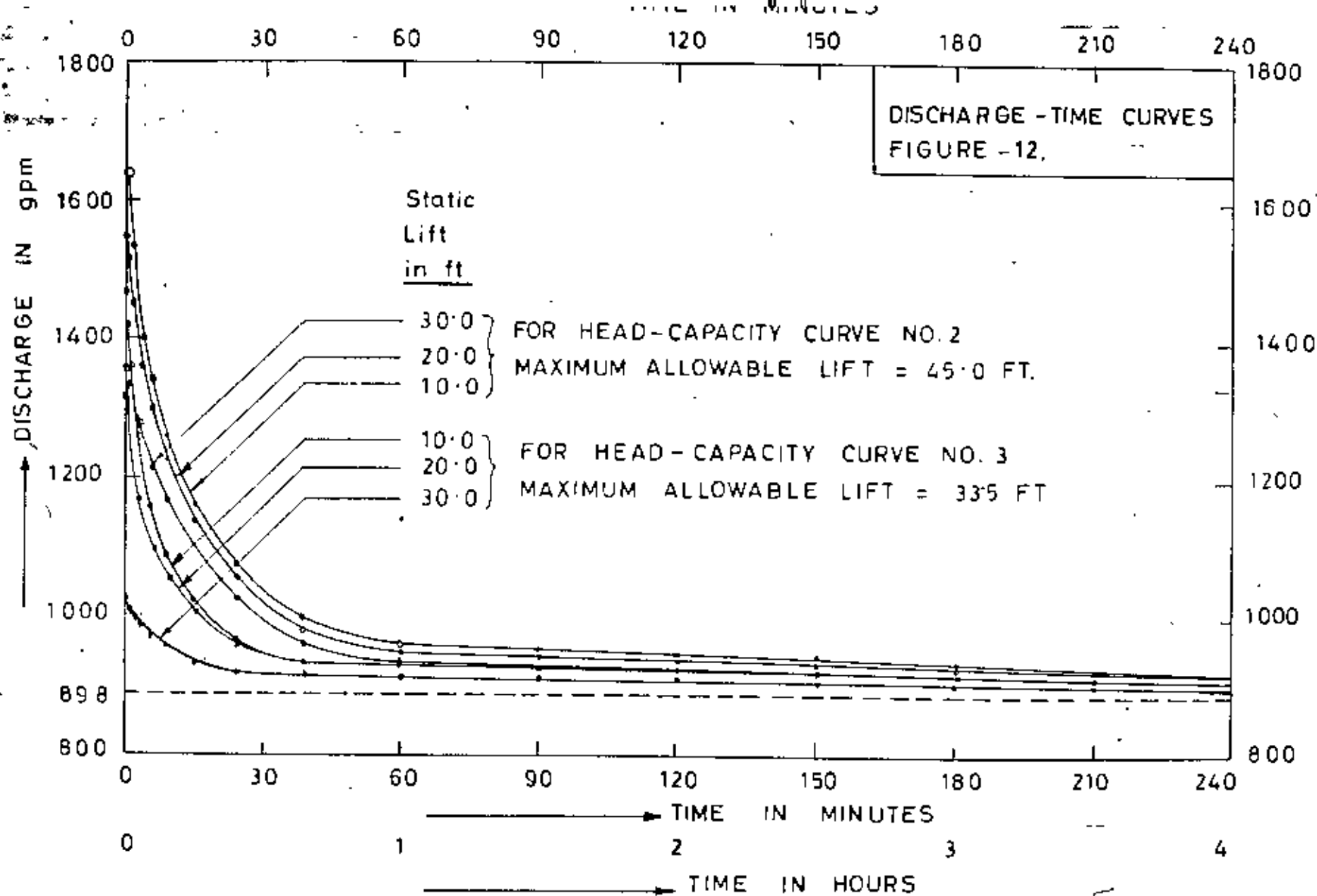


(a) Water level control
at the well

(b) Water level control
at the mid.point

* Computation of s_w and $s_{R/2}$ is shown
in Figures 7 and 8.

Figure 11. Flow charts showing determination
of well spacing.



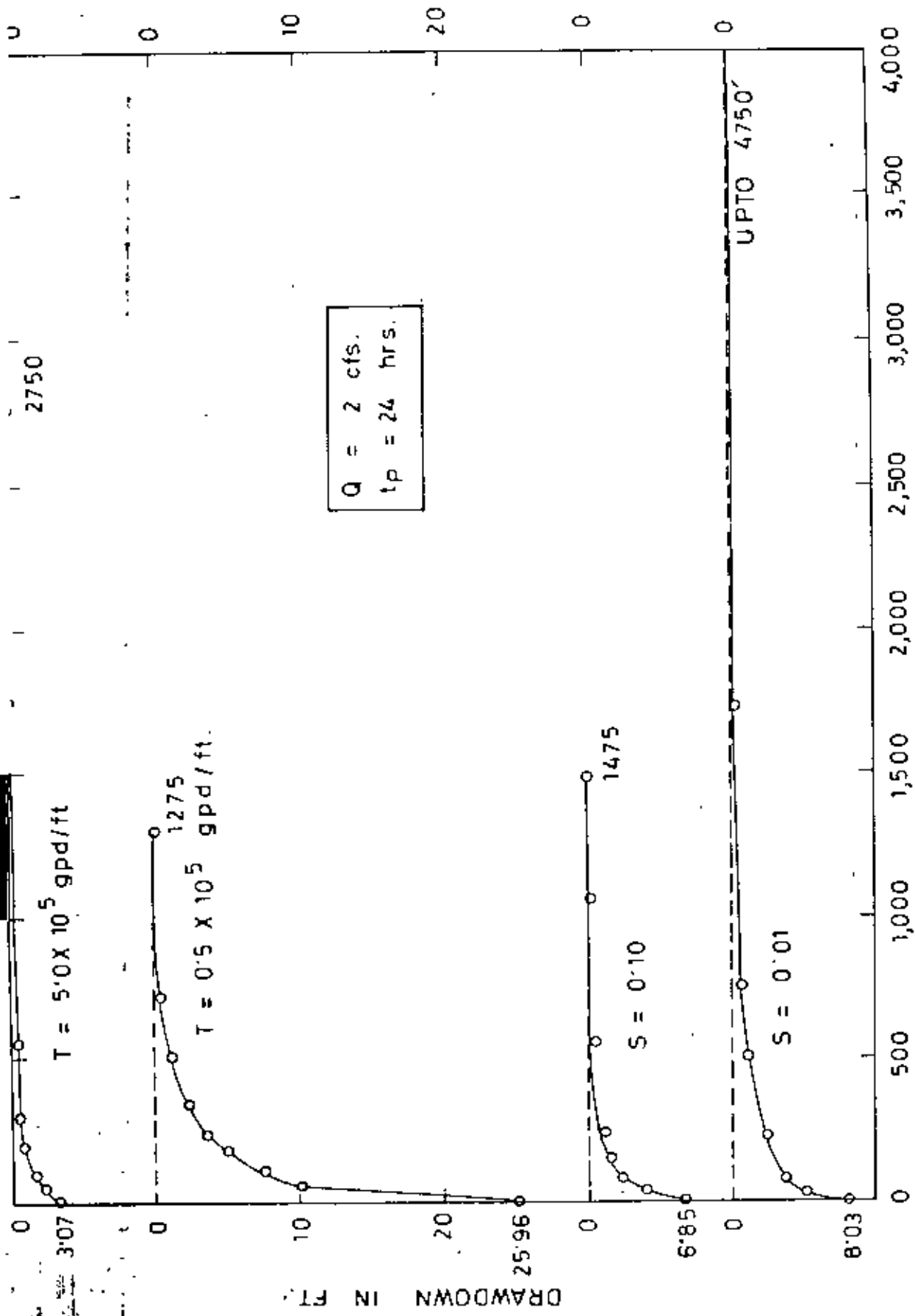
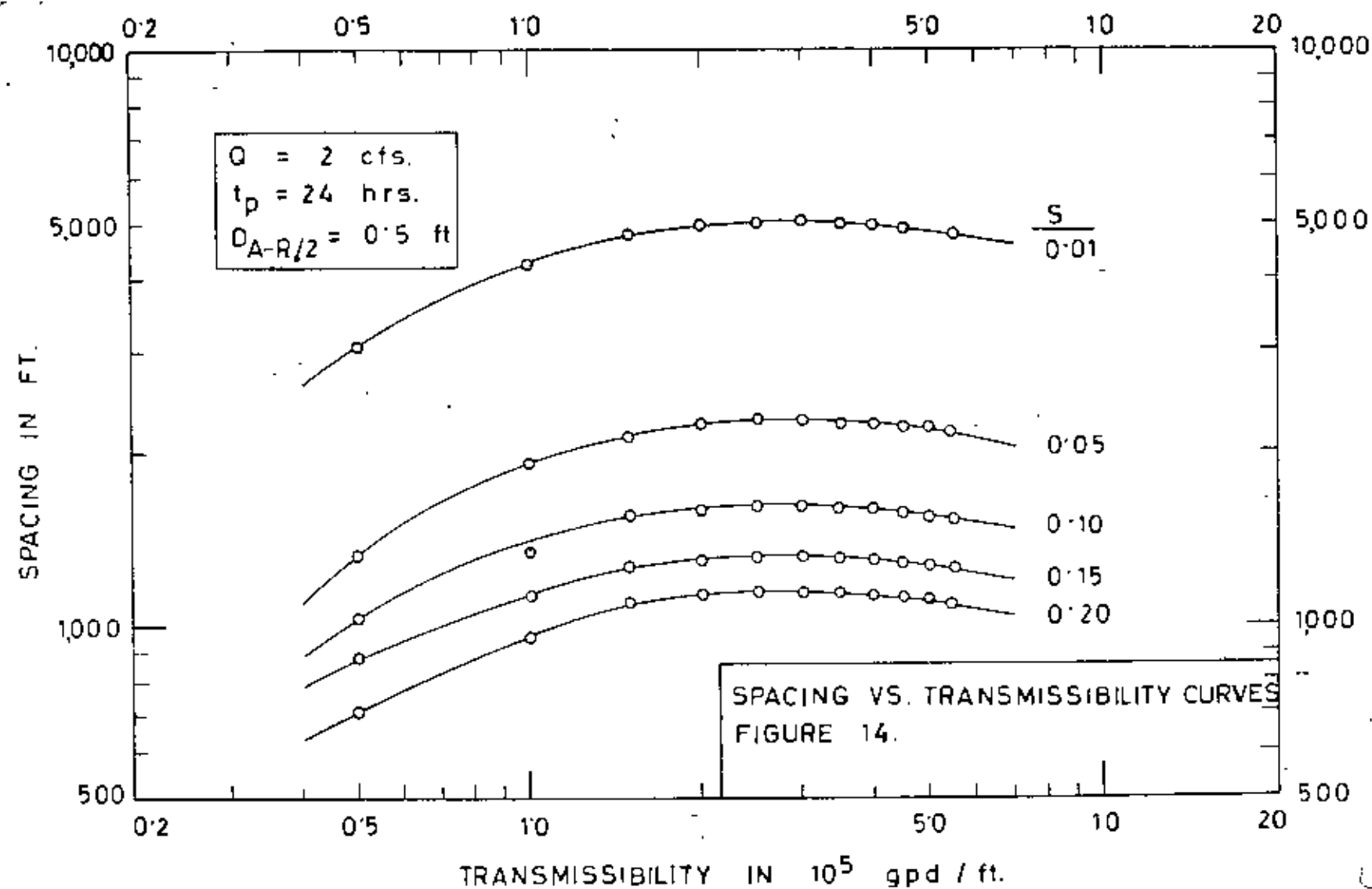
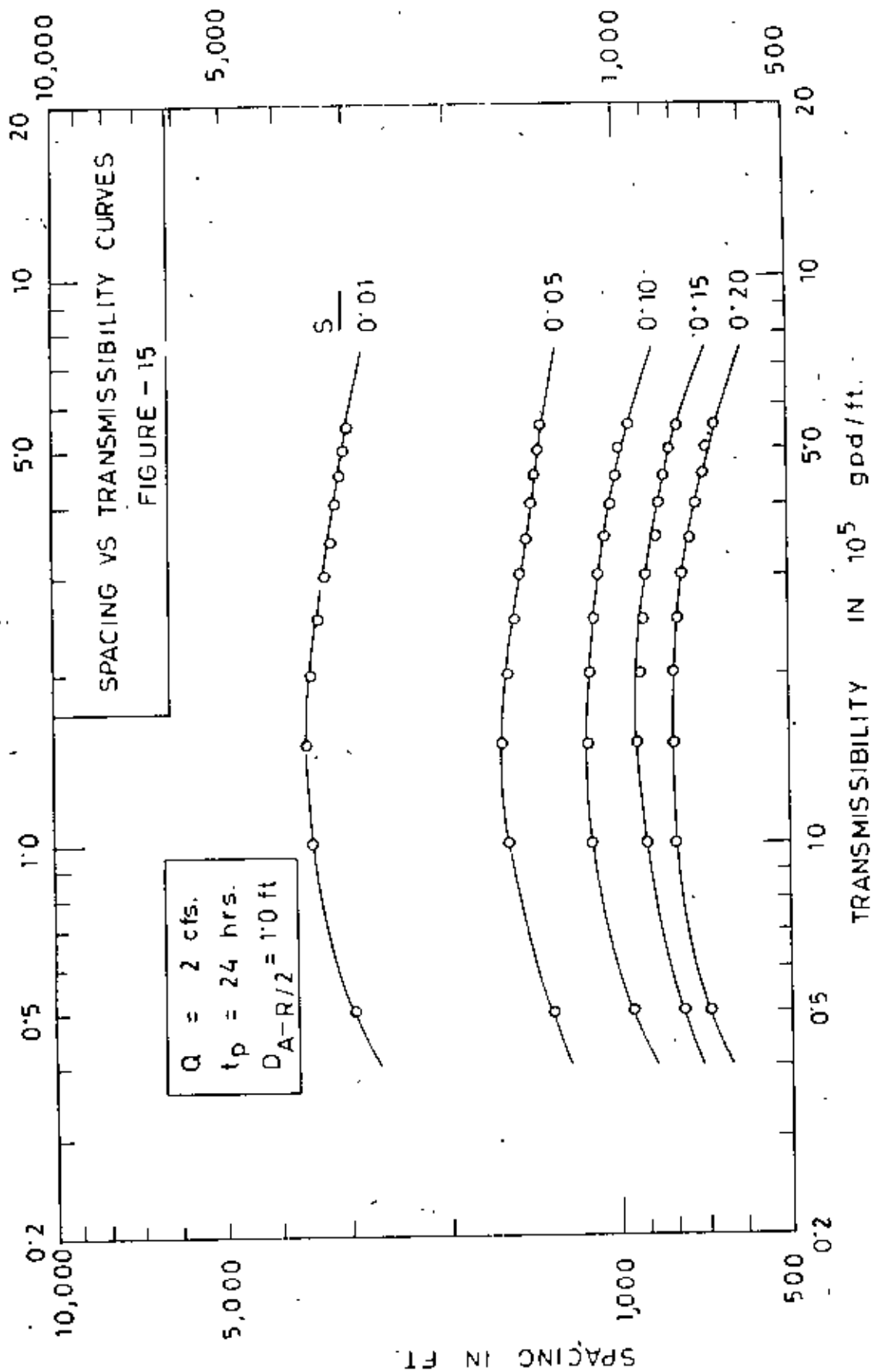
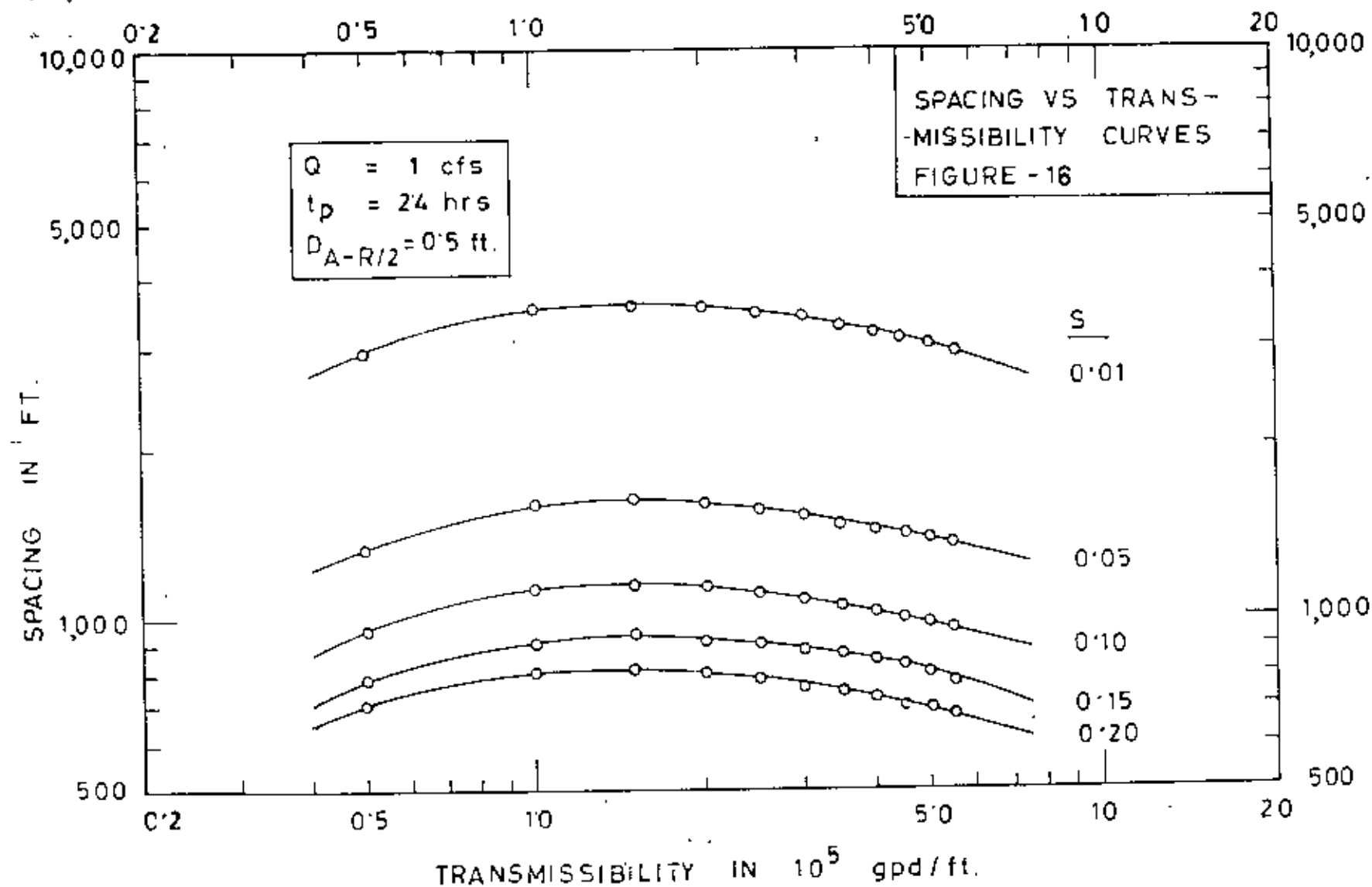
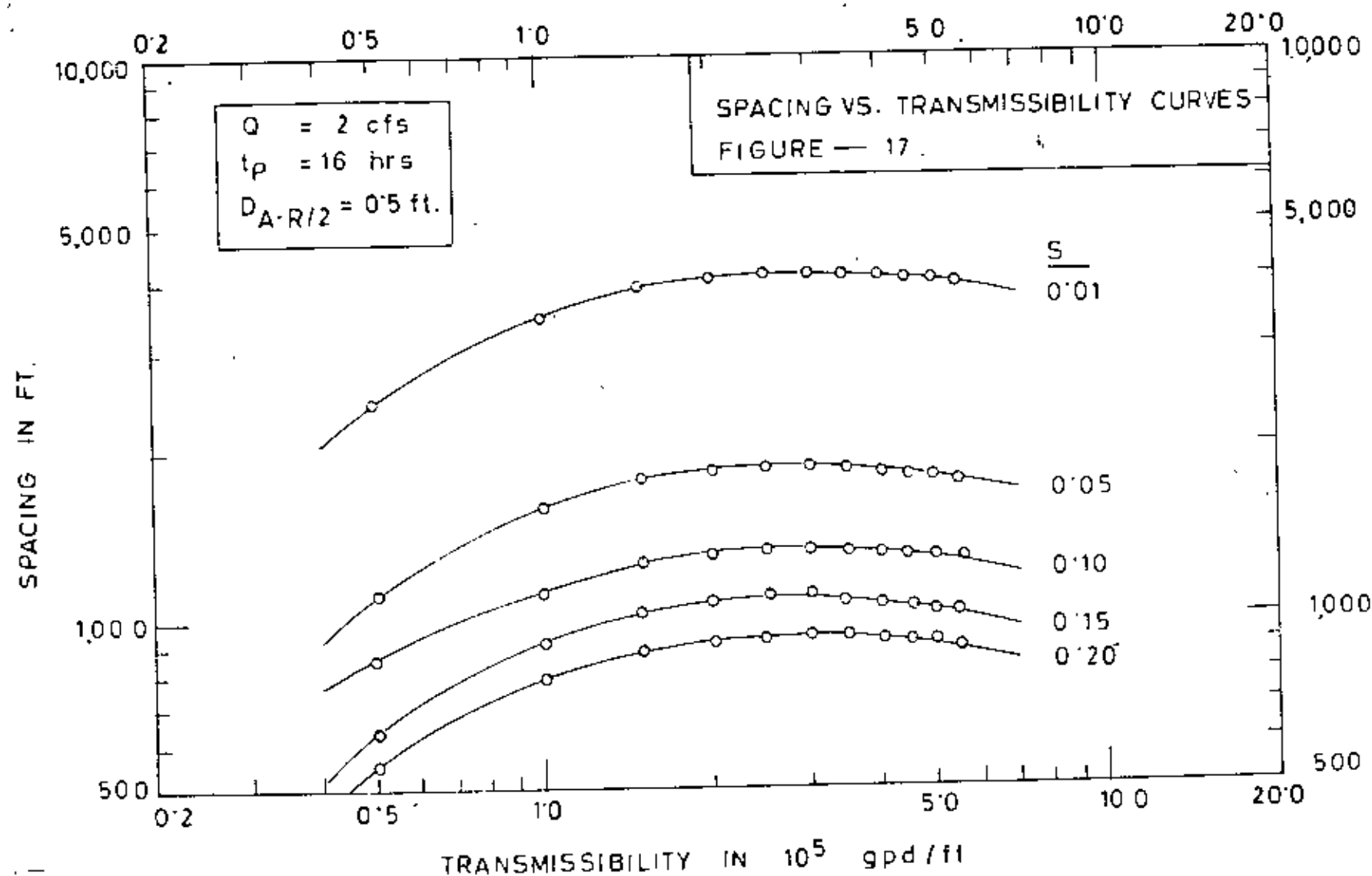


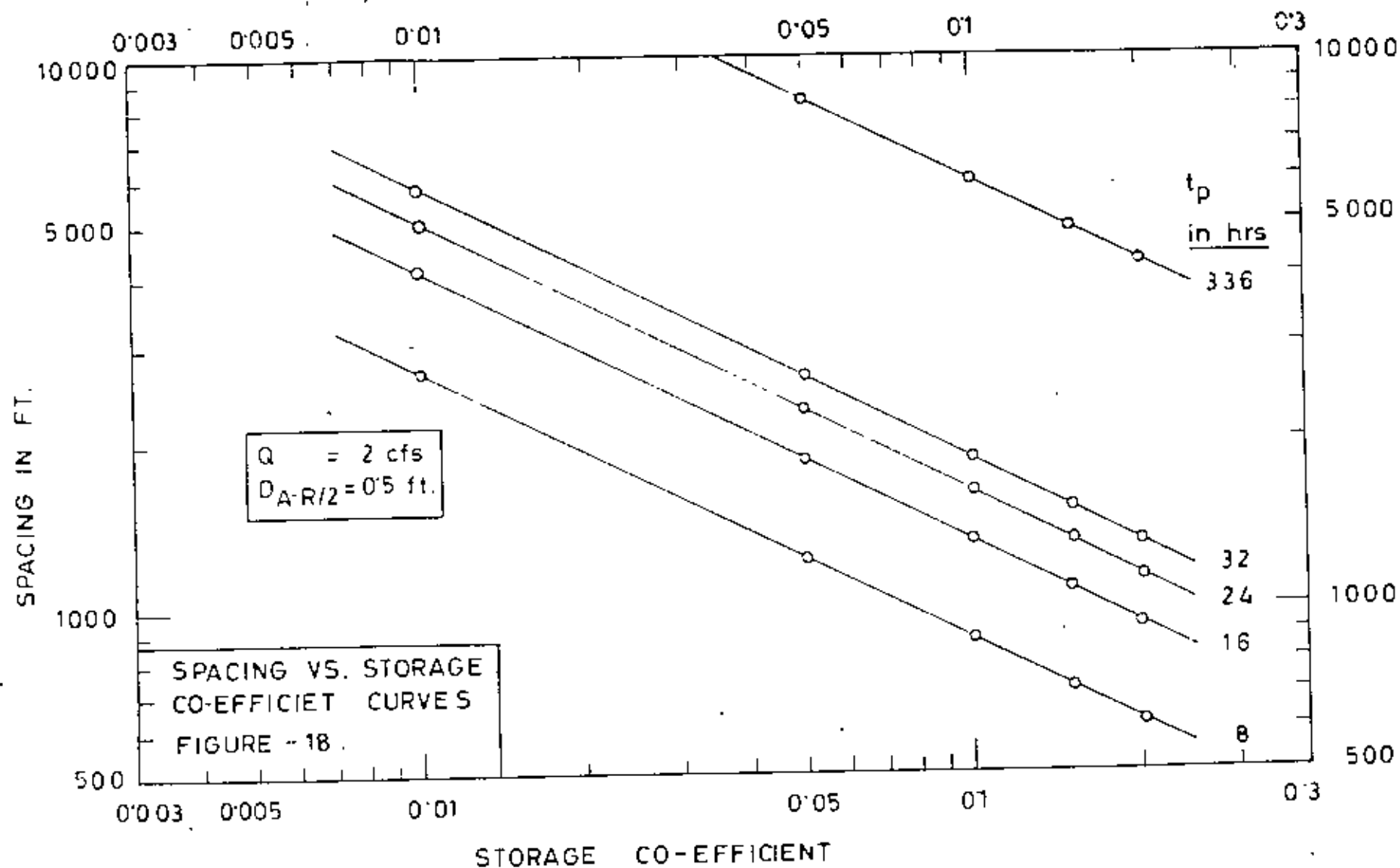
Fig. 13. Effect of formation constants upon shape, depth and extent of cone of depression.

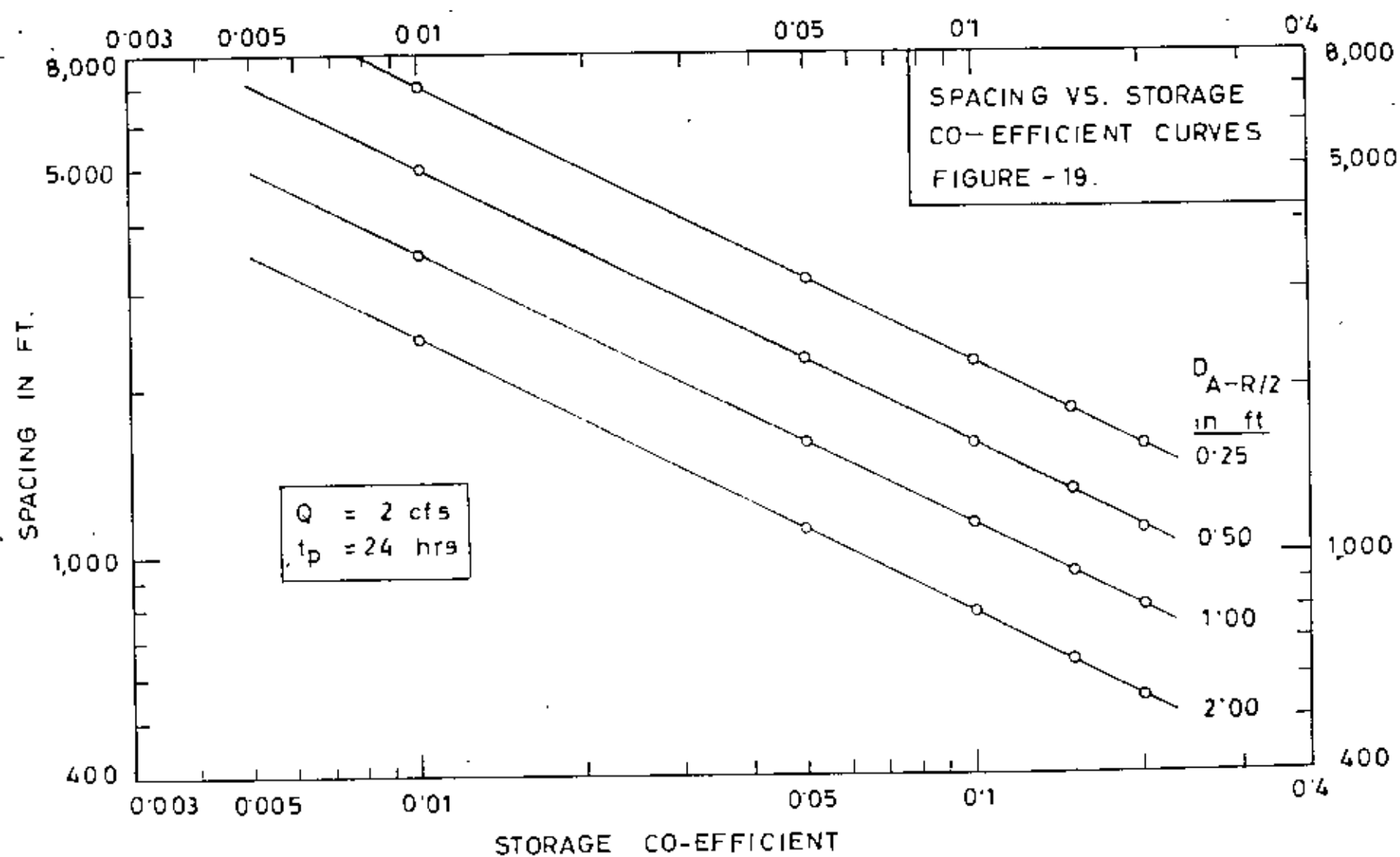


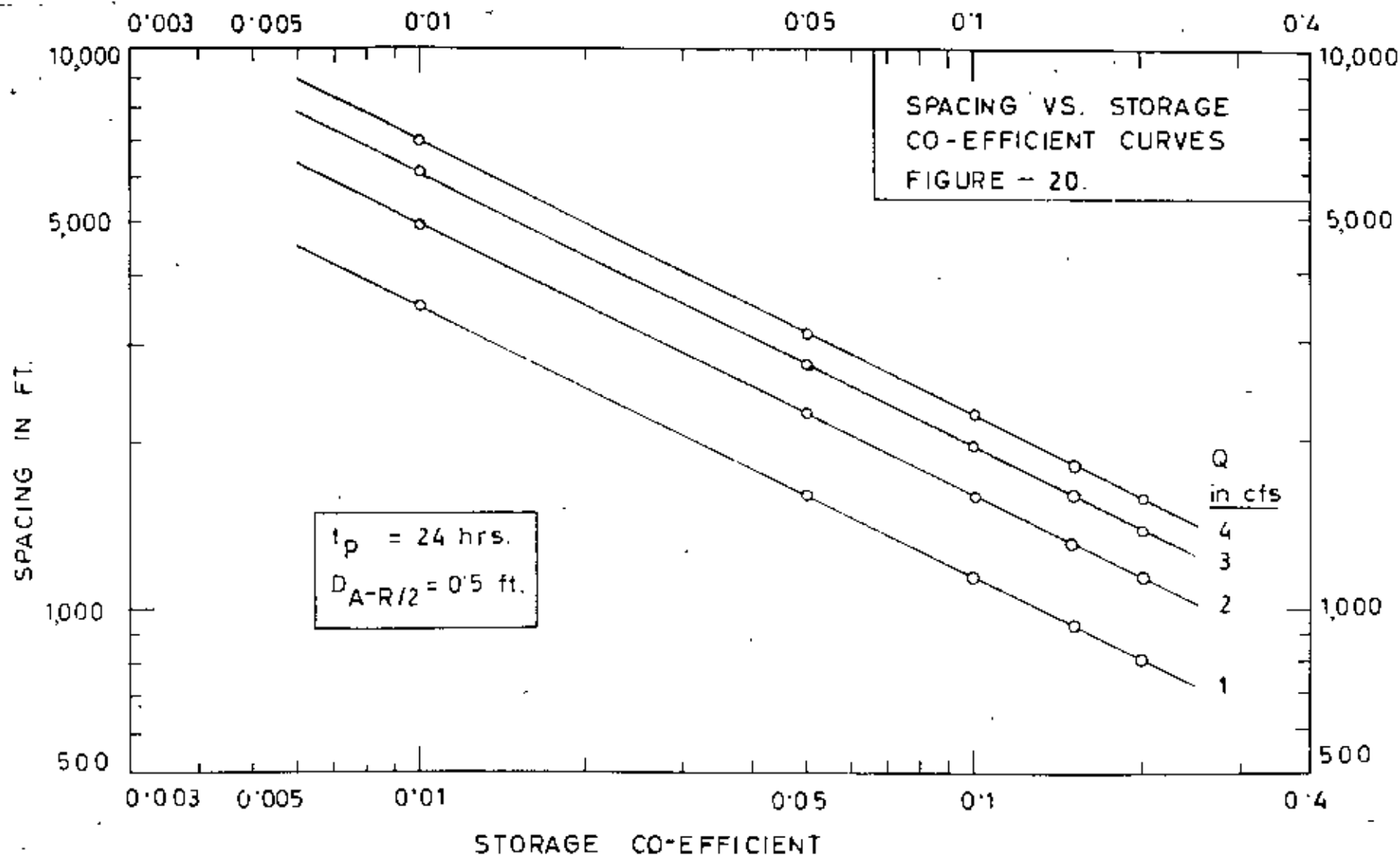




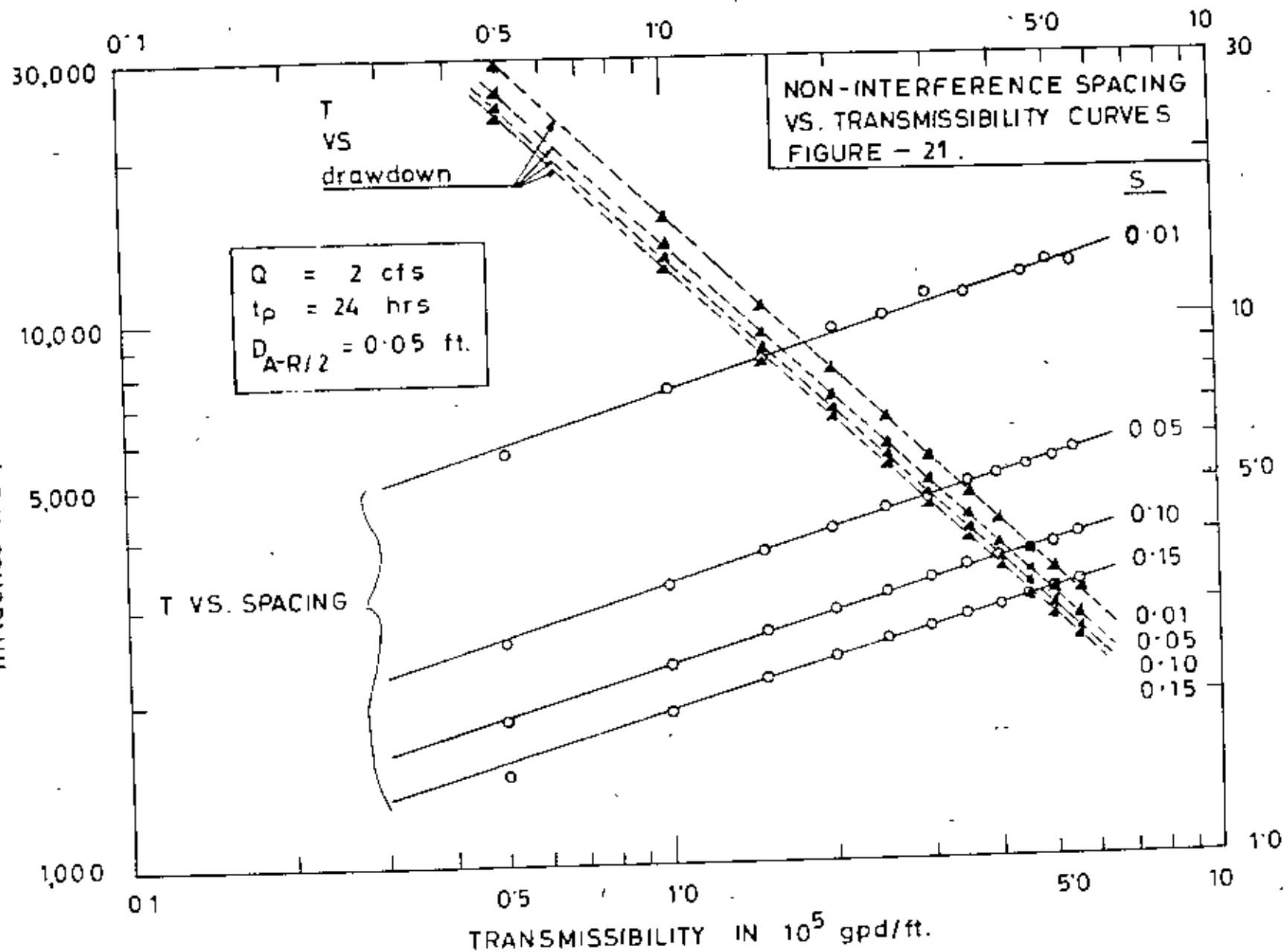


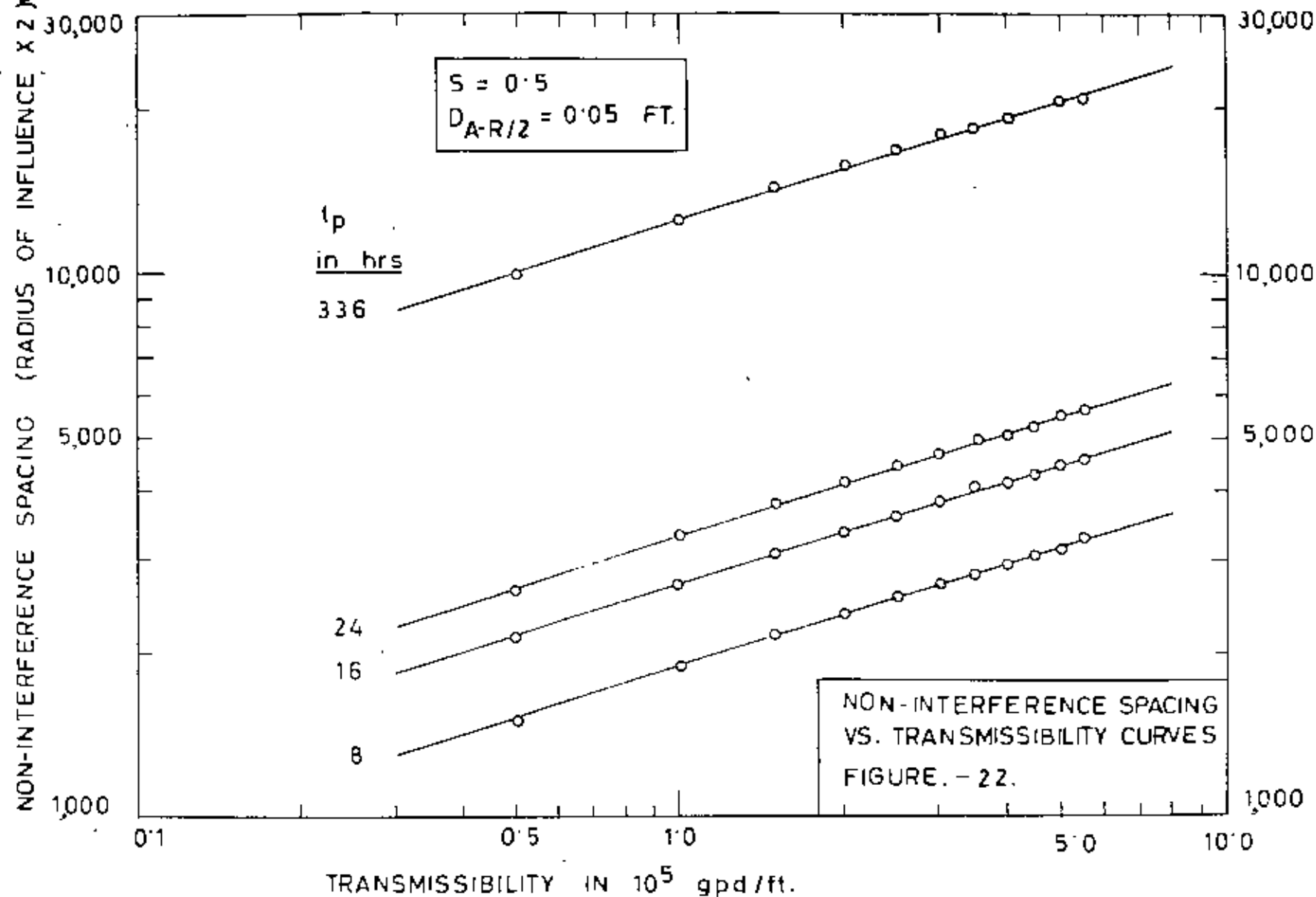




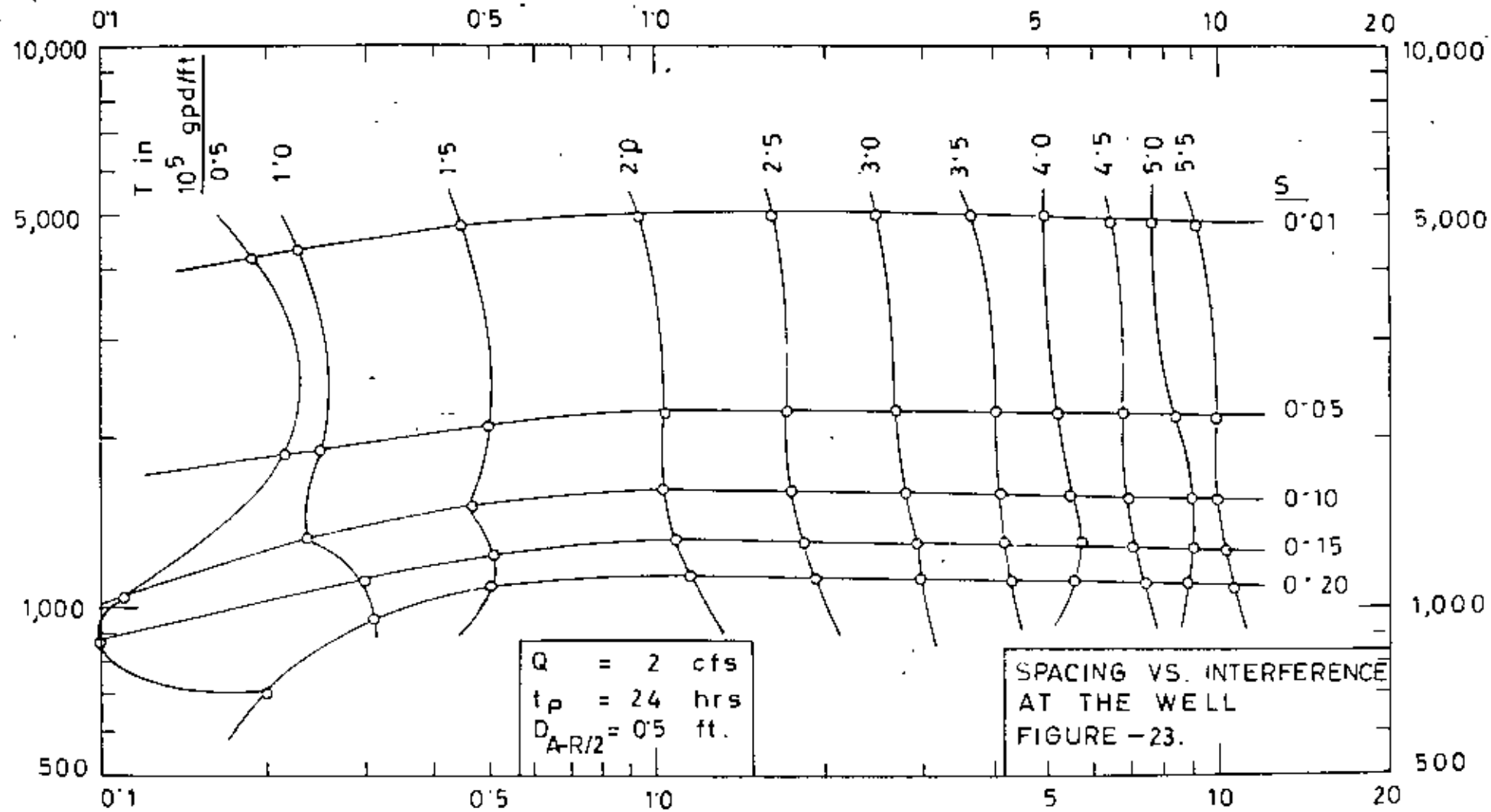


NON INTERFERENCE SPACING (radius of influence $\times 2$) in ft.

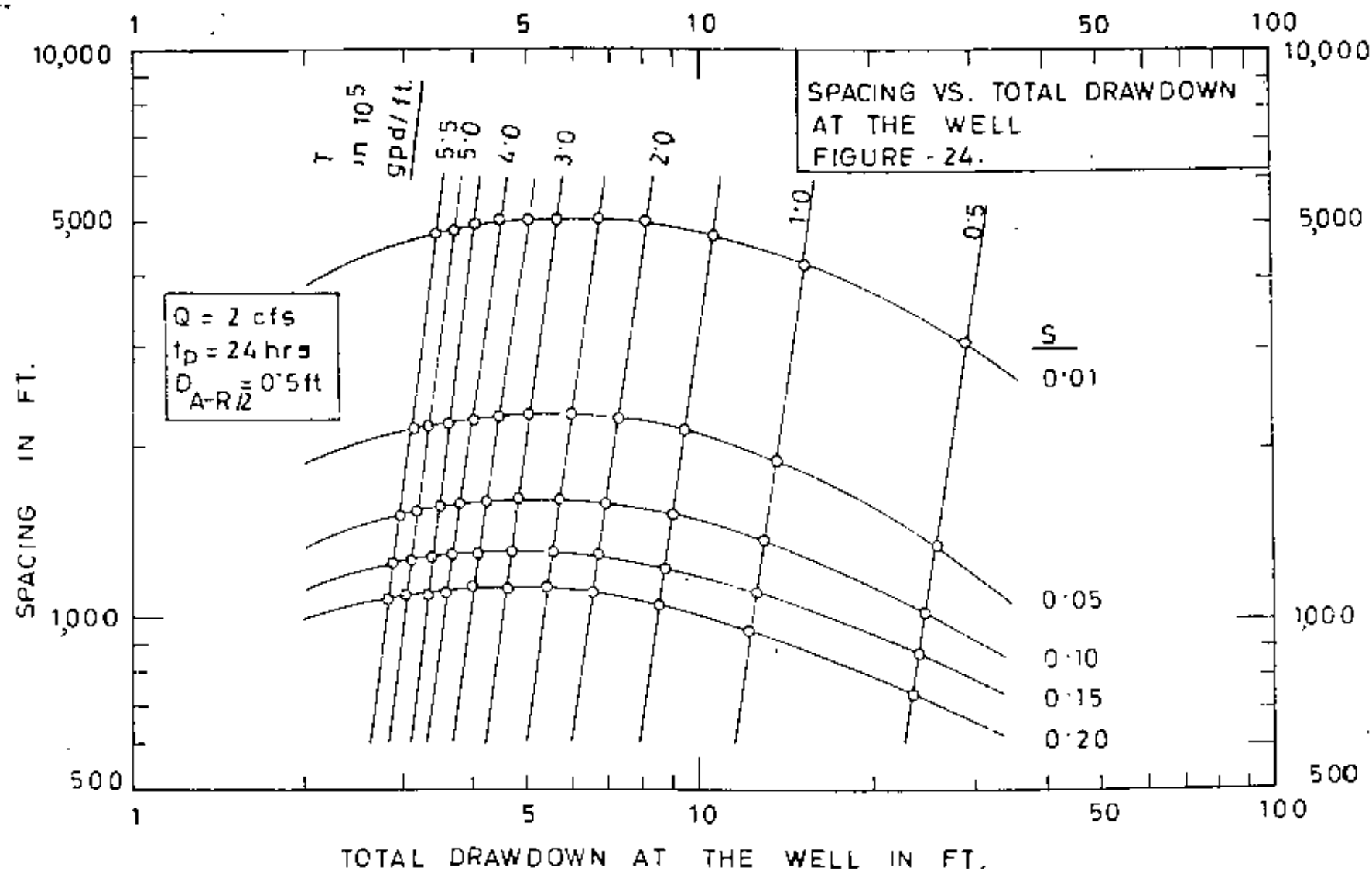


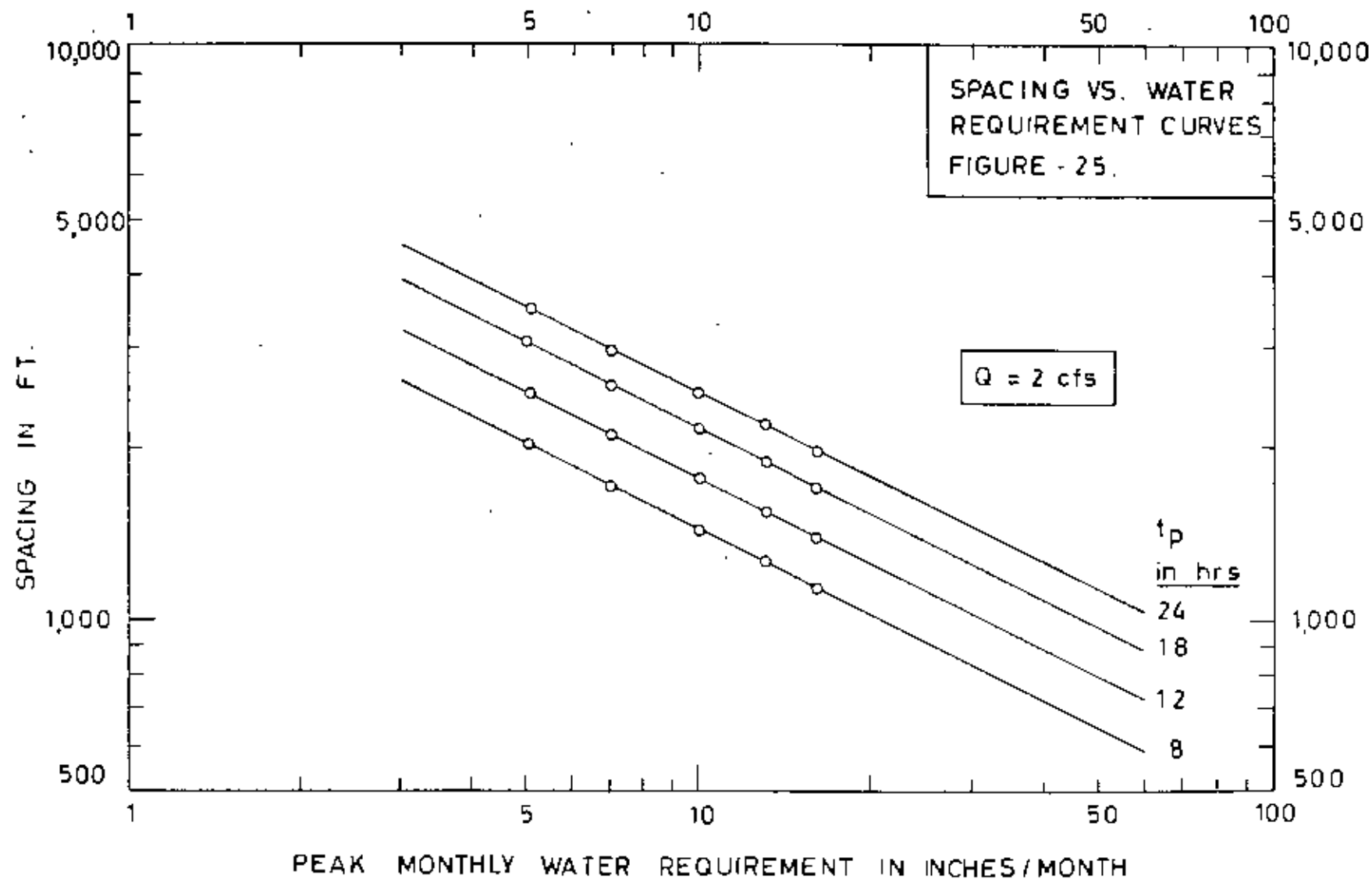


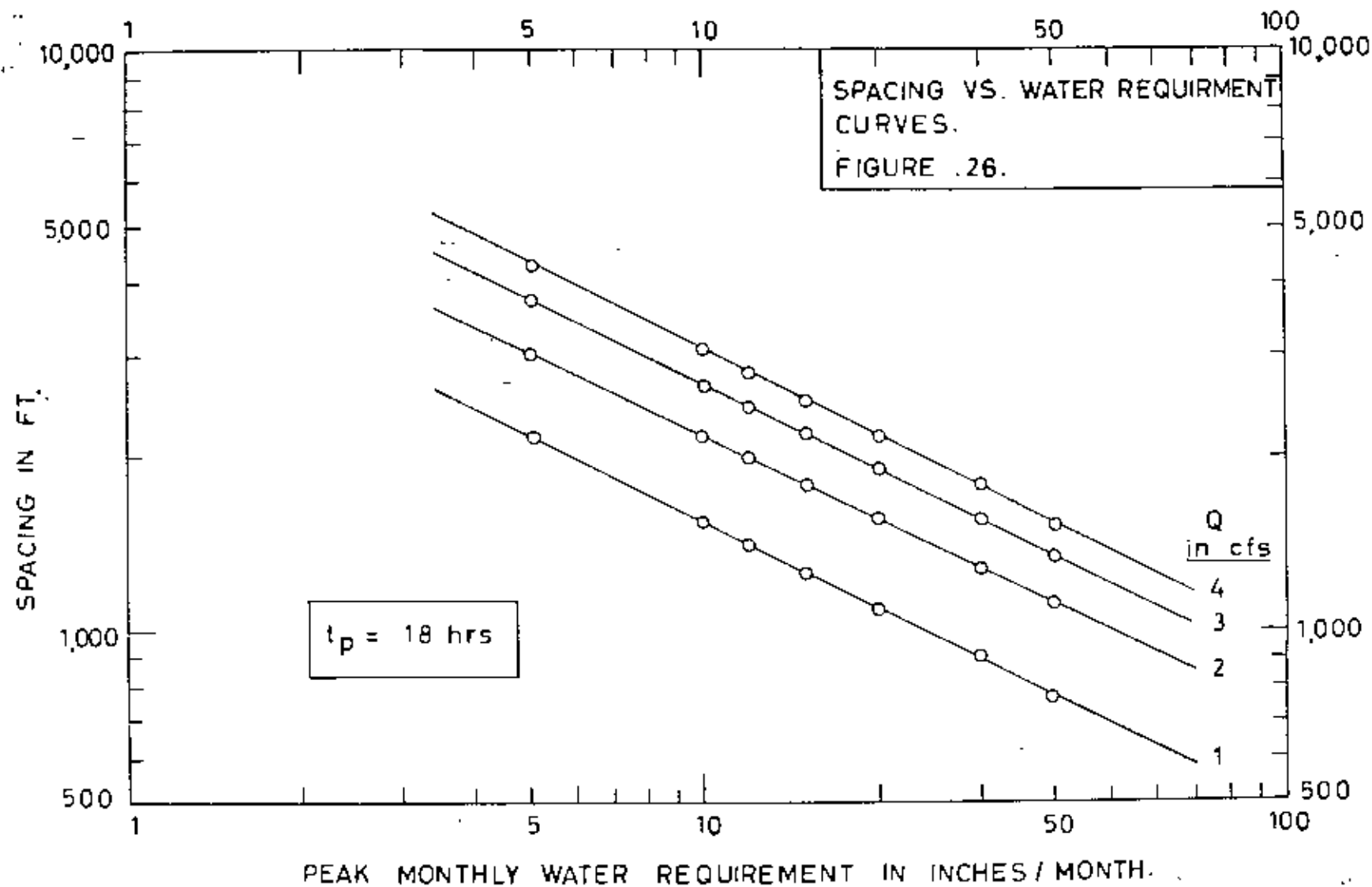
SPACING IN FT.



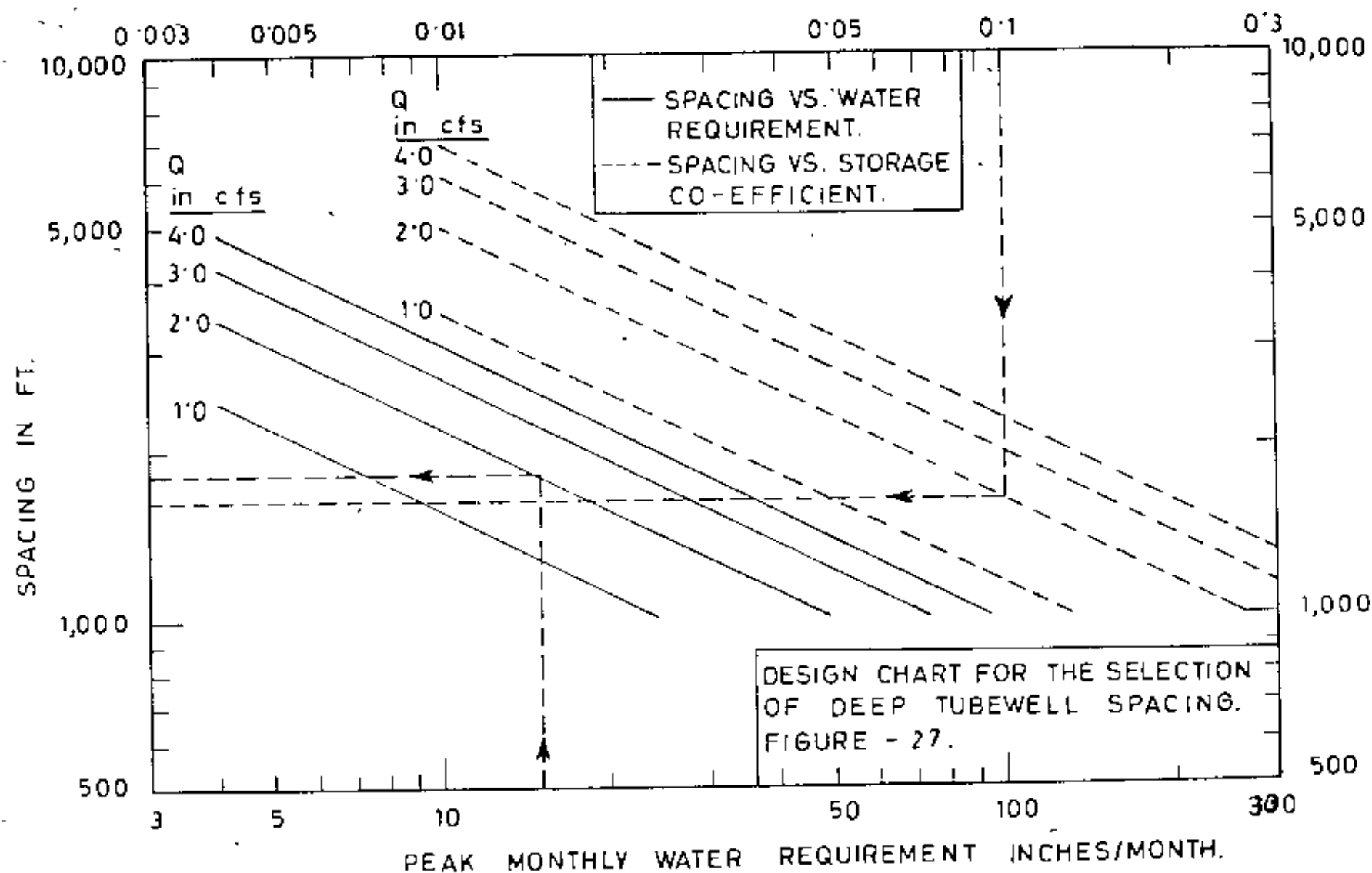
INTERFERENCE IN % OF TOTAL DRAWDOWN AT THE WELL.







STORAGE CO-EFFICIENT



A P P E N D I X - B
T A B L E S

Table 2 Well Spacing in Various ConditionsDischarge of well, $Q = 2$ cfsAllowable drawdown at the mid. pt. of spacing, $D_{A-R/2} = 0.5$ ft.

Maximum allowable lift = 45 ft.

Static lift, $L_0 = 30$ ft.

T in 10^5 gpd/ft	S	W in hrs.	Spacing due to control of water level position			
			At the well		at the mid.pt.	
			Variable case(ft)	Constant Q case(ft)	Variable Q case(ft)	Constant Q case(ft)
0.50	0.01	16	-	950	2450	2450
		24	-	1225	3025	3025
		32	-	-	3625	3625
	0.10	16	700	650	950	875
		24	725	700	1075	1025
		32	900	875	1200	1175
	0.20	16	525	475	650	550
		24	575	525	750	700
		32	650	600	850	825
	0.01	16	400	350	4100	4100
		24	575	400	5000	5000
		32	650	475	6100	6100
2.50	0.10	16	250	175	1300	1300
		24	275	200	1600	1600
		32	325	250	1925	1925
	0.20	16	200	150	1000	925
		24	225	200	1150	1125
		32	300	250	1375	1375
	0.01	16	225	150	3950	3950
		24	300	150	4825	4825
		32	350	175	5875	5875
	0.10	16	150	100	1275	1250
		24	175	125	1525	1525
		32	200	125	1875	1875
5.00	0.20	16	125	100	950	900
		24	150	100	1125	1100
		32	200	125	1325	1325
	0.01	16	125	100	950	900

* - indicate allowable drawdown at the well exceeded by drawdown due to pumping well itself only.

Table 3 Comparison of Well Spacing Subjected to Interference and no-interference for 24 hours pumping of 2 cfs Well.

T in 10 ⁵ gpd/ft	S	Spacing in feet	
		allowing interference	without interference
0.50	0.01	3025	5700
	0.05	1325	2550
	0.10	1025	1825
	0.15	875	1475
1.00	0.01	4175	7500
	0.05	1875	3300
	0.10	1325	2350
	0.15	1100	1900
2.00	0.01	4925	9500
	0.05	2200	4200
	0.10	1575	2950
	0.15	1275	2400
3.00	0.01	5050	10900
	0.05	2275	4550
	0.10	1625	3350
	0.15	1300	2775
4.00	0.01	4900	11500
	0.05	2225	5100
	0.10	1575	3500
	0.15	1275	2950
5.50	0.01	4750	12600
	0.05	2150	5600
	0.10	1525	3950
	0.15	1250	3175

Table 4. Representative Specific Yield (Storage coefficient in water table Aquifer) Ranges for Selected Rocks.

After Walton (1970)

Rocks	Specific yield
Clay	0.01 - 0.10
Sand	0.10 - 0.30
Gravel	0.15 - 0.30
Sand and gravel	0.15 - 0.25
Sandstone	0.05 - 0.15
Shale	0.005- 0.05
Limestone	0.005-0.05

A P P E N D I X - C

COMPUTER PROGRAMMES

DETERMINATION OF SPACING BETWEEN WELLS

T.....TRANSMISSIBILITY IN GPD/FT. AND EQUAL TO TT MULTIPLIED BY 100000
 S.....STORAGE COEFFICIENT
 DELTT.....INCREMENT OF STORAGE COEFFICIENT
 SPC.....SPACING IN FT.
 DELSPC.....INCREMENT OF SPACING IN FT.
 ANSPC.....INITIAL SPACING IN FT. (CALCULATION STARTED WITH THIS SPACING THEN INCREASED BY DELSPC SUCCESSIVELY)
 RW.....EFFECTIVE RADIIUS OF THE WELL IN FT.
 TP.....PUMPING TIME IN DAYS
 DD.....DRAWDOWN IN FT.
 STLIFT.....STATIC LIFT IN FT.
 AREA.....AREA PER WELL IN ACRES
 TOTDD.....TOTAL DD AT THE WELL IN FT.
 D.....INTERFERENCE AT THE WELL IN % OF TOTDD
 DINTF.....DD CONTRIBUTION TO TOTDD DUE TO INTERFERENCE OF SURROUNDING WELLS ONLY IN FT.
 H1.....HEAD IN FT. DUE TO PUMPING WELL ITSELF ONLY
 H.....TOTAL LIFT IN FT. WHEN STATIC LIFT, AQUIFER LOSS DUE TO PUMPING WELL ITSELF AND AQUIFER LOSSES DUE TO INTERFERING WELLS ARE ADDED.
 TIMEIN.....STARTING TIME INCREMENT IN DAYS (CALCULATION STARTED WITH THIS TIME INCREMENT)
 DGDISC.....DESIGN DISCHARGE IN GPM.
 DGHEAD.....LIFT IN FT. CORRESPONDING TO DESIGN DISCHARGE
 Q.....DISCHARGE IN GPM
 WU.....WELL FUNCTION IN THEIS SOLUTION

WRITE(3,1111)

1111 FORMAT(1H1,'WELL SPACING FOR VARIABLE DISCHARGE CONDITION',1H1)
 WRITE(3,1112)

1112 FORMAT(3X,'RESULTS FOR SQUARE GRID'//)
 WRITE(3,276)

276 FORMAT(5X,2HTT,9X,1HS,8X,6HSTLIFT,5X,2HTP,9X,3HSPC,7X,24HAR3A,7X,5HTOTDD,8X,1HD,8X,6HDDSPCH,2X,6HDGHEAD)
 DGDISC=898.
 ANSPC=100.
 RW=1.
 DGHEAD=45.
 P=1.5
 NT=11

```

NS=3
STARTT=6.0
DELSS=0.05
TIMEIN=0.0001
TT=STARTT
NNN=NT+1
DO 84 I=1,NNN
IF(NT-I)911,912,912
911 CALL EXIT
912 DELTT=0.5
TT=TT-DELTT
IF(TT)911,911,8888
8888 T=TT*1.0E05
KKK=NS+1
DO 84 J=1,KKK
IF(J-1)555,555,556
555 SS=0.01
GO TO 557
556 SSJ=J-1
SS=DELSS*SSJ
557 S=SS
DO 84 I=10,30,10
STLIFT=L
DO 84 KPTT=8,32,8
PTT=KPTT
IF(PTT-24.)851,851,852
851 TP=PTT/24.
IF(PTT-8.)853,853,22
853 SPC=ANSPC
GO TO 22
852 TP=14.0
22 Z=TIMEIN
X=0.
H1=STLIFT
H=STLIFT
9 Y=X+Z
999 U=H*0.2-4.0
U1=U-1.
U2=U-2.
U3=U-3.
U4=U-4.
Q=1550.-97.*U-4.5*U*U1-0.667*U*U1*U2-0.375*U*U1*U2*U3
2+0.0667*U*U1*U2*U3*U4
TIME=TP-X
RR=RW
CALL WELFCN(S,T,TIME,RR,WU)
W1=WU

```

```

RR=SPC
CALL WELFCN(S,T,TIME,RR,WU)
W2=WU
RR=1.41421*SPC
CALL WELFCN(S,T,TIME,RR,WU)
W21=WU
31 W3=W1+W2*4.+W21*4.
51 IF(TP-Y)3,3,5
5 TIME=TP-Y
RR=RW
CALL WELFCN(S,T,TIME,RR,WU)
W5=WU
RR=SPC
CALL WELFCN(S,T,TIME,RR,WU)
W6=WU
RR=1.41421*SPC
CALL WELFCN(S,T,TIME,RR,WU)
W61=WU
61 W7=W5+W6*4.+W61*4.
GO TO 14
3 W7=0.
14 IF(H)17,17,7
7 EIMDD=(114.6*Q*(W3-W7))/T
DINC=ABS(EIMDD)
H=H+DINC
17 EIMDD1=(114.6*Q*(W1-W5))/T
DINC1=ABS(EIMDD1)
H1=H1+DINC1
X=Y
951 Z=Z*P
952 IF(TP-X)52,52,9
52 IF(H1-DGHEAD)122,53,53
122 IF(H-DGHEAD)16,16,308
16 DINTF=H-H1
TOTDD=H-STLIFT
D=(DINTF*100.)/TOTDD
AREA=(SPC**2)/43560.
TIME=TP
2222 RR=SPC*1.5
CALL WELFCN(S,T,TIME,RR,WU)
W101=WU
RR=SPC*0.5
CALL WELFCN(S,T,TIME,RR,WU)
W102=WU
RR=SPC*2.23016
CALL WELFCN(S,T,TIME,RR,WU)
W103=WU
W105=W101*2.+W102*2.+W103*4.

```

```
DDEPCM=(114.6*Q*W105)/T
WRITE(3,23)TT,S,STLIFT,TP,SPC,AREA,TOTDD,D,DDSPCM,DGHEAT
23  FORMAT:(F9.3,3(4X,F7.3),2(2X,F9.3),3(4X,F7.3),3X,F5.1)
GO TO 84
308 DELSPC=25.
44  SPC=SPC+DELSPC
GO TO 22
53  WRITE(3,54)TT,S,STLIFT,PT,H1
54  FORMAT(20X,4(2X,F7.3),2X,'NO SPACING HEAD='F7.3)
84  CONTINUE
END
```

DETERMINATION OF WELL SPACING (CONSTANT DISCHARGE)

T.....TRANSMISSIBILITY IN GPD/FT.
 DELTD.....INCREMENT OF TRANSMISSIBILITY
 S.....STORAGE COEFFICIENT
 DELSS.....INCREMENT OF STORAGE COEFFICIENT
 SPC.....SPACING IN FT.
 DELSPC.....INCREMENT OF SPACING IN FT.
 ANSPC.....INITIAL SPACING IN FT. (CALCULATION STARTED WITH
 THIS SPACING THAN INCREASE BY DELSPC SUCCESSIVELY)
 Q.....DISCHARGE OF THE WELL IN GPM
 RW.....EFFECTIVE RADIOUS OF THE WELL IN FT.
 TP.....PUMPING TIME IN DAYS
 STLIFT.....STATIC LIFT IN FT.
 DD.....DRAWDOWN IN FT.
 DDSPCM.....DD IN FT. AT THE MID. PT. OF TWO ADJACENT WELLS
 D.....INTERFERENCE AT THE WELL IN % OF TOTDD
 AREA.....AREA PER WELL IN ACRES
 DINTF.....DD CONTRIBUTION TO TOTDD DUE TO INTERFERENCE OF
 SURROUNDING WELLS ONLY IN FT.
 DDW.....DD IN FT. DUE TO PUMPING WELL ITSELF ONLY
 SPCAP.....SPECIFIC CAPACITY IN GPM/FT.
 TOLER.....ALLOWABLE DD AT THE MID. PT. OF SPACING
 WU.....WELL FUNCTION IN THEIRS SOLUTION

ANSPC=100.

STLIFT=10.

RW=1.

NQ=7

NT=11

NS=4

STARQ=0.

STARTT=6.0

DELSS=0.05

WRITE(3,1111)

1111 FORMAT(1H1,'WELL SPACINGS FOR CONSTANT DISCHARGE CONDITION'//

WRITE(3,1112)

1112 FORMAT(3X,'RESULTS FOR SQUARE GRID'//)

WRITE(3,1113)

1113 FORMAT(3X,'MID SPACING DRAWDOWN CONTROL'//)

WRITE(3,276)

276 FORMAT(7X,'Q', 8X,'TT', 9X,'S', 10X,'TP', 7X,'TOLER', 9X,'SPC',
 210X,'AREA', 6X,'TOTDD', 8X,'D', 8X,'~~SPCAP~~', 10X,'DIV'//)

NNQ=NQ+1

DO 84 KQ=1, NNQ

IF(NQ-KQ) 911, 910, 910

911 CALL EXIT

```

910 QK=KQ
    Q=5TARQ+224.5*(QK+1.)
909 DELTT=0.5
    DO 84 J=1,NT
912 TTI=I
    TT=STARTT-DELTT*TTI
    IF(TT)911,911,8888
8686 T=TT*1.0505
    KKK=NS+1
    DO 84 J=1,KKK
    IF(J-1)555,555,556
555 SS=0.01
    GO TO 557
556 SSJ=J-1
    SS=DELSS*SSJ
557 S=SS
    DO 84 KPTT=8,32,8
    PPT=KPTT
851 TP=KPTT*24.
22 TIME=TP
    SPC=ANSPC
    DO 84 KTOLER=1,4
    TOLERK=KTOLER
    IF(TOLERK-2.)601,601,602
601 TOLER=2.0/TOLERK
    GO TO 604
602 TOLER=0.5/(TOLERK-2.0)
604 RR=SPC/2.
    CALL WELFCN(S,T,TIME,RR,WU)
    W102=WU
2222 RR=SPC*1.5
    CALL WELFCN(S,T,TIME,RR,WU)
    W101=WU
    RR=SPC*2.23016
    CALL WELFCN(S,T,TIME,RR,WU)
    W103=WU
    W105=W101*2.+W102*2.+W103*4.
    DDSPCM=(114.6*Q*W105)/T
    IF(DDSPCM-TOLER)88,88,301
83 AREA=(SPC**2)/43560.
    RR=RW
    CALL WELFCN(S,T,TIME,RR,WU)
    W1=WU
    ALW=(114.6*Q*W1)/T
    RR=SPC
    CALL WELFCN(S,T,TIME,RR,WU)
    W2=WU
    RR=SPC*1.41421
    CALL WELFCN(S,T,TIME,RR,WU)
    W3=WU

```

```
W4=W2*4.0+W3*4.0
DINTF=(114.6*Q*W4)/T
TOTDD=W4DINTF
D=(DINTF*100.)/TOTDD
SPCAP=Q/TOTDD
WRITE(3,23)Q,TT,S,TP,TOLBR,SPC,AREA,TOTDD,D,SPCAP
23  FORMAT(F11.2,3X,F6.3,3(4X,F7.3),2(3X,F10.3),3(4X,F7.3))
GO TO 84
301 DELSPC=25.
301 SPC=SPC+DELSPC
GO TO 604
84  CONTINUE
END
```

DETERMINATION OF NON-INTERFERENCE SPACING BETWEEN WELLS

T.....TRANSMISSIBILITY IN GPD/FT.
 DELTT.....INCREMENT OF TRANSMISSIBILITY
 S.....STORAGE COEFFICIENT
 DELSS.....INCREMENT OF STORAGE COEFFICIENT
 Q.....DISCHARGE OF THE WELL IN GPM
 DD.....DRAWDOWN IN FT.
 TP.....PUMPING TIME IN DAYS
 AREA.....AREA PER WELL IN ACRES
 SPC.....SPACING IN FT.
 DELSPC.....INCREMENT OF SPACING IN FT.
 ANSPC.....INITIAL SPACING IN FT.(CALCULATION STARTED WITH
 THIS SPACING THAN INCREASED BY DELSPC SUCCESSIVELY)
 DEL.....LIFT IN FT. CORRESPONDING TO DESIGN DISCHARGE
 DELDL.....INCREMENT OF LIFT IN FT.
 SPCAP.....SPECIFIC CAPACITY IN GPM/FT.
 TOLER.....ALLOWABLE DD AT THE MID.PT.OF SPACING
 WU.....WELL FUNCTION IN THIS SOLUTION

WRITE(3,1111)
 1111 FORMAT(1H1,4X,'NONINTERFERENCE WELL SPACINGS'//)
 WRITE(3,275)
 276 FORMAT(5X,'TT',9X,'S',10X,'TP',7X,'TOLER',9X,'SPC',11X,
 2'AREA',10X,'ALW',7X,'SPCAP')
 Q=898.
 ANSPC=100.
 RW=1.
 NT=11
 NS=3
 STARTT=0.
 DELTT=0.5
 DELSS=0.05
 NNN=NT+1
 DO 84 I=1,NNN
 IF(NT-I)911,912,912
 911 CALL EXIT
 912 TTI=I
 TT=STARTT+DELTT*TTI
 T=TT*1.0E05
 KKK=NS+1
 DO 84 J=1,KEK
 IF(J-1)555,555,556
 555 SS=0.01
 GO TO 557
 556 SSJ=J-1
 SS=DELSS*SSJ
 557 S=SS

```

DO 84 KPTT=8,32,8
PTT=KPTT
IF(PTT-32.)851,852,652
851 PT=PTT
TE=PT/24.
GO TO 77
852 TP=14.0
77 SPC=ANSPC
TIME=TP
DO 84 KTOLER=1,3
TOLERK=KTOLER
IF(2.0-TOLERK)601,602,603
601 TOLER=0.01
GO TO 604
602 TOLER=0.05
GO TO 604
603 TOLER=0.1
604 RR=SPC/2.
CALL WELFCN(S,T,TIME,RR,WU)
W1=WU
DD=(114.6*Q*W1)/T
DSPCM=DD*2.0
IF(DSPCM-TOLER)88,88,308
88 AREA=(SPC**2)/43560.
RR=RW
CALL WELFCN(S,T,TIME,RR,WU)
W102=WU
ALW=(114.6*Q*W102)/T
SPCAP=Q/ALW
WRITE(3,23)TT,S,TP,TOLER,SPC,AREA,ALW,SPCAP
23 FORMAT(F9.3,3(4X,F7.3),2(4X,F11.3),2(4X,F7.3))
GO TO 84
308 DELSPC=25.
310 SPC=SPC+DELSPC
GO TO 604
84 CONTINUE
END

```

