Mutual Interference of Wells in Confined Aquifers

A Dissertation for Master of Engineering
in
Water Resources Development

by

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WATER RESOURCES DEVELOPMENT TRAINING CENTRE
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CERTIFICATE

Certified that the Dissertation entitled " MUTUAL INTERFERENCE OF WELLS IN CONFINED AQUIFERS" which is being submitted by Shri S.N. Goel in partial fulfillment of the requirements for Degree of Master of Engineering in Water Resources Development of University of Roorkee, is a record of student's work carried out by him under my supervision and guidance. The matter embodied in this has not been submitted for any other Degree or Diploma.

This is further to certify that he has worked for a period of 11 months from 1.10.1968 to 28.8.1969 in connection with the preparation of this Dissertation.

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A C K N O W L E D G E M E N T

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C O N T E N T S

COMMON NOTATIONS

The following notations have been commonly used. Other notations have been explained in the text.

H	Piezometric height on recharge boundary.
h_w	Piezometric height on outer face of the well.
h	Piezometric height at any point in the zone of influnece.
R	Radius of influence
R'	Equivalent radius of influence i.e., the radius of influence of a single isolated well that will give the same discharge, as a well & the given group of wells, under identical conditions.
r	Radial distance of any point from the centre of the well.
$r_1, r_2, r_3, \ldots$	Radial distances of Centres of wells from any point.
r_w	Radius of well.
a	Spacing between wells.
d, d_1	distance of a well from first array of wells or from a line drive.
d_2	distance of second well or second array of wells from the line drive.
K	Coefficient of permeability.
B	Thickness of the aquifer.
Q	Discharge of a sigle well or the average discharge of group of wells.
$Q_1, Q_2, Q_3, \ldots$	Discharges of individual wells i in a group.
Q_a	Discharge of a single isolated well used as base.

SYNOPSIS

An attempt has been made in the present study to provide a systematic presentation of the effects of mutual interference of wells in confined aquifers in a steady state. The scope of the subject has been indicated in Chapter I.

Terms commonly used in well hydraulics and having significant bearing on the behaviour of wells have been explained and basic equations for flow towards wells in confined and unconfined aquifers have been derived in Chapter II. Although the treatment in the present study is limited to steady flow towards wells in confined aquifers, the similarity of basic equations, enables the treatment to be extended to unconfined aquifers with a change in the value of constants.

The behaviour of a single well has been discussed in Chapter III with the specific purpose of studying the influence of different variables, physical factors and natural boundaries on the performance of the well. The following cases have been analysed.

(a) single well located at the centre of a circular recharge boundary,

(b) single well located eccentrically in a circular recharge boundary.

(c) single well located close to a straight recharge boundary, impervious boundary or intersections of recharge and impervious boundaries.

The effects of mutual interference between wells placed in groups have been analysed in Chapter IV. The following cases have been treated.

(a) Groups of wells located in closed recharge boundaries.

(i) Two wells- equal dradown

(ii) Three wells in a straight line-
Equal drawdown.
Equal discharge.

Three wells in the form of a triangle -
Equal drawdown.

(iii) Four wells-forming a square-equal drawdown,

(iv) Five wells- four wells forming a square and them fifth in the centre,
Equal drawdown
Equal discharge.

(v) Battery of 'n' wells placed along the circumference of a circle-

Constant spacing between wells, Constant radius of battery circle.

(b) Groups of wells located on one side of a straight line recharge boundary or a line drive.

(i) Two wells parallel to line drive,

Two wells at right angles to line drive.

(ii) Three wells parallel to line drive,

(iii) Infinite number of wells arranged in single array parallel to line drive.

(iv) Infinite number of wells arranged in double array parallel to line drive -

square setting,

staggered setting.

Computations for a working range of variables, graphs and discussion of results have been given after analytic derivations of equations for each case.

Chapter V details briefly the significant conclusions arrived at on the basis of the present study. This is followed by a review of the nature of practical problems and the application of the results of present study to such problems.

CHAPTER-I

INTRODUCTION

INTRODUCTION:

Wells have been dug in all parts of the world since times immemorial, for meeting the needs of domestic water supply and irrigation of small plots of land. So long as the number of wells was few and far between, and the withdrawals were low and intermittant, no problems were involved, except those of digging a well and striking a reasonably good water bearing statum. With the turn of this century, much greater effort and planning have gone into the development of available water resources. Major surface flows of the world have either been tapped or are in the process of development. Naturally, of late, the development of ground water is getting an increasing attention and forms an essential part of the water resource planning of most of the countries. Some of the countries of the world, particularly the western states of USA have depleted the ground water supplies to such an extent that recharge of ground water through wells and other methods has become a pressing problem. Apart from utilisation as sources of water supply and recharge, the wells have an extensive application in many other practical problems e.g., drainage of water logged areas pressure relief wells, dewatering operations for foundations, offsetting operations prevention of sea water inrusion into coastal waters, tapping oil and flooding and flushing of oil beds. It is therefore useful to have a proper understanding of the physical principles of ground water movement, behaviour of individual wells and groups of wells and ~~their action and interaction under differ.~~

their action and interaction under different field conditions.

INTERFERENCE OF WELLS:

When water is pumped from a surface well, there is a general lowering of the watertable in the area surrounding the well. The area from which water is drawn to-wards the well is known as area of influence or region of influence. The drop in the watertable is known as drawdown. If water is pumped from a confined aquifer, the watertable may remain undisturbed, but there is a general depression in the piezometric levels of the aquifer in the area surrounding the well. The area in which the depression in piezometric surface occurs forms the region of influence of the confined aquifer. The drop in piezometric levels is draw-down. The shape and extent of the region of influence and drawdown depend on the geometry of the well, characteristics of the formation and discharge with-drawn from the well. Other variables remaining constant, the drawdown increases and the region of influence extend as the discharge withdrawn from the well increases.

If another well is placed close to the first well, nothing happens so long as the regions of influence of the two wells are independent and do not overlap each other. However, if the wells are close enough or the regions of influence extend sufficiently to overlap each other the performance or efficiency of both the wells suffers. The implications are that,

(a) For a given drawdown, the discharge obtained from each well is less than what it would have been, if one well had been pumping alone. However, the combined discharge of the two wells is more than the discharge of a single well.

(b) For a given discharge from each well, the drawdown caused by two wells pumping simiultaneously is much more than the drawdown of a single well.

If more wells are added to the group, the discharge of each well is reduced although the total available discharge is more. Similarly, for a given discharge from each well, the drawdown of every well in the group increases with the installation of every additional well.

The reduction in the efficiency and general performance of wells, when placed in a group is known as mutual interference of wells. If there are three wells in a straight line, the central well suffers more as compared to the end wells, because the central well is interfered with from both sides whereas, the end wells are interfered with from are side only. Similarly, in a large group of wells, the wells that are placed in the inner rings or are surrounded from all sides, suffer maximum interference, whereas, the effect of interference on wells lying in the outer rings is comparatively lesser. The extent of interference and reduction in the efficiency of the individual wells, depends on the spacing and geometry of the well system and disposition of recharge and other natural boundaries.

METHODS OF APPROACH TO A PROBLEM.

Normally, all engineering programmes or field problems need some sort of assessment, evaluation and prediction at the stage of planning, detailed design and execution. The commonly

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The commonly available methods are:

(a) Reliance on practical or field experience:

In the earlier days, this was by far the most accepted method. Working on the basis of precedents or actual field experience has obvious advantages. It works on the principle of 'seeing is believing' and brings a man closert to the problem in most practical aspects. The method however lacks a physical basis or reasoning. It works more by intuition, thumb rules and empirical formulae and involves the use of cut and dry methods and trials which are uneconomical and wasteful. It also involves, at every stage, the ~~sciences~~ services of a man who had the requisite experience under similar field conditions and has the capacity to interpret and apply available experience to the problems in hand.

(b) Model studies and laboratory experiments:

Are usually restricted to a solution of specific field problems. They also rely on trials and cut and dry methods, b but the results are obtained at a comparatively much lesser cost and in a very much shorter period. Utility of model studies and laboratory work depends, on the extent to which the field conditions are simulated and limitations and variations if any, are properly interpreted. Apart from application to specific problems, the results of the model studies can be generalised to some extent is such studies are based on proper application of physical principles and scientific reasoning.

In spile of their limited role, the model studies have become extremely propular and are undertaken extensively, almost at all stage of planning, design and execution of major engineering programmes.

(c) Analytical Approach:

Analytical work is usually based on idealised conditions and assumptions which are far removed from conditions in the field, and therefore such work and its results are looked upon with scepticism by men of experience or men in the field. The analytical work is however based on sound physical laws and the results are obtained by a gradual but rigourous process of scientific reasoning and mathematical analysis. It aims at establishing basic premises and then deducing and generalising physical relationships, which could find universal application in the field.

(d) Composite Approach:

Under the present day conditions, when knowledge is developing fast, the best approach is to combine and utilise all the best of all the three methods.

An active co-ordination at all stages, between the planner, designer, the theorist, men in the laboratories and men in the field should yield sound and economical results.

SCOPE OF THE WORK:

The main objective of the present study is, to provide a systematic presentation, of the effects of mutual interference of wells, in confined aquifers in a steady state. It also aims at providing a proper understanding and appreciation of the physical laws governing the problem. Broadly, the scope of the work includes the following:

(a) Explanation of the common terms and physical factors involved in ground water movement in general and flow towards wells in particular, with an emphasis on physical properties and characteristics that influence ground water movement, significantly.

(b) Statement of idealised assumptions for analysis of flow towards wells, practical limitations and implications of such assumptions and derivation of basic equations for steady and unsteady flow towards wells in confined and unconfined aquifers. This should give an understanding of the basic physical principles involved in flow towards wells and to spotlight the points of similarily in basic equations for flow under different conditions.

(c) Detailed analysis of the behaviour of a single well in a confined aquifer under the influence of different types of natural recharge boundaries, impervious boundaries, and geological discontinuties. This should provide a base for study of the behaviour of groups of wells and the effects of mutual interference between them. It should also help in identifying ~~the~~ and isolating the effects of mutual interference and the effects of other physical factors.

(d) Detailed analysis of the behaviour of groups of wells and the effects of mutual interference between them under the following conditions.

(i) Groups of wells in a closed recharge boundary,

(ii) Groups of wells on one side of an infinite line drive.

(e) Significant conclusions on the basis of present study and scope for the application of the treatment to practical problems.

CHAPTER II

DEFINITIONS, PHYSICAL PRINCIPLES AND BASIC EQUATIONS

2.1 Definitions :

The definitions and explanations given here, include some of the terms commonly used in the study of ground water movement. Particular emphasis has been placed on the properties and limitations of physical factors, which influence the behaviour of wells significantly.

'Ground water' - Water appears in nature in numerous phases and forms. That portion of water, which flows freely through the soil, under the action of gravity and is held in porous formations, under hydrostatic pressure, is known as ground water. Under normal conditions met with in practice, ground water is a single phase, homogeneous fluid. The flow of ground water towards wells and other areas of discharge is in a saturated state.

'Water bearing formations or aquifers' - These are geological formations, that hold and transmit sufficient water. Aquifers generally consist of consolidated or unconsolidated sands or gravels and can have any size, shape or thickness. Aquifers may be 'confined' or 'unconfined'.

'Unconfined aquifer' - is a formation of porous material, supported by an impermeable bed of rock or clay. The upper surface of the formation is exposed to atmosphere. The saturated surface of the unconfined aquifer, forms the water- table.

'Confined aquifer' is a formation or water bearing stratum, confined at the top as also at the bottom by thick and impervious layers of rock, clay or any other material. The thickness and expanse of the overlying material is such that there is no possibility of direct recharge of the aquifer from the surface. Water flows through a confined aquifer, as a result of differential pressure between the region of intake, which is generally far off and the point of discharge. Confined aquifers may be small or local, or may be extensive.

'Semi Confined aquifer' is that aquifer, in which the confining layers are leaky.

'Porosity' is defined as the percentage of pore space, per unit volume of soil. It provides a measure of the voids and interstices in the aquifer material. In the case of permeable formations, it provides an index to the capacity of the aquifer to hold water. Porosity depends on the size, shape, grading and packing of aquifer material. Different values of porosity can be obtained from the same material with changes in packing and distribution.

'Permeability' or co-efficient of permeability is defined as the constant of proportionality in Darcy's law or velocity through the soil for a unit gradient. It is an index of the ease, with which, water can move through the porous medium. Like porosity, permeability also depends on size, shape, grading and packing of aquifer material. However, the link between porosity and permeability is not direct. Clays have high porosity, but very low permeability and form poor aquifers. Some of the sands and gravels may have low porosity, but high permeability. Permeability can undergo substantial change, with a change in particle size distribution and packing. Permeability can have the same value or different values in different directions. Permeability can also have different values at different points and different levels in an aquifer.

Porosity and permeability of an aquifer material may change substantially after continuous operation of the well. This may happen, either due to mechanical clogging of pores by the sediment transported by the fluid or by gradual choking due to chemical action.

'Transmissibility' or Co-efficient of transmissibility is the product of aquifer thickness and co-efficient of permeability. Transmissibility is a property of the aquifer and is determined by field tests.

'Specific yield' is the volume of water, which can be released by a unit weight of a saturated soil, under the action of gravity. Specific yield provides a measure of the availability of ground water from an aquifer under free flow conditions. Specific yield depends directly on porosity and permeability, Specific yield from sands and gravels, which form the common aquifer material, varies from 10% to 20%.

'Storage Co-efficient' - when a confined aquifer is charged, the pressure of water in the pores of the aquifer material rises. Assuming that there is no yielding of the confining layers, the available storage volume within the aquifer, can be treated as constant. The increase in hydrostatic pressure results in compression of the aquifer material and water. The implications are, that the compression of the aquifer material makes more space available for the storage of water, whereas, compression of water makes it possible for more water to be stored within the same space.

When water is pumped out from the aquifer, the piezometric levels go down in the vicinity of the well. This results in a partial release of hydrostatic pressure, resulting in the expansion of aquifer material and water. Expansion of aquifer material leads to squeezing out of water from the pore spaces, as there is a reduction in space available for accomodating water, whereas, the expansion of water further results in release of water, as lesser water can be accomodated in available space.

Storage co-efficient is defined as the volume of water released per unit area of the aquifer for a unit change in drawdown. Storage co-efficient depends on the porosity and permeability of the aquifer and elastic properties of the fluid and aquifer material. Since, water and aquifer material are compressible to a very limited extent, the value of storage co-efficient is generally of a very low order. In most aquifers the value ranges between 0.005 to 0.00005. Storage co-efficient is a property of the aquifer and is determined in practice, by field tests.

'Isotropy' - Isotropy indicates identity of physical properties, e.g., elasticity or permeability in different directions. It is rare to find a truly uniform, homogeneous and isotropic aquifer material, in a natural state. In practice the material is treated as uniform, homogeneous and isotropic, if the significant engineering properties are reasonably uniform in all directions.

'Unsteady flow through aquifers' - If water is pumped continuously from an isolated aquifer, which does not have any source of recharge, the drawdown and region of influence go on extending for an indefinite period. Such a flow towards a well is unsteady. If the aquifer has a source of recharge, but the rate of recharge is low, the flow continues to be unsteady and the drawdown and region of influence still extend indefinitely, but at a substantially reduced rate. In an extensive aquifer, the source of recharge is at a far off place. The gradient available between external recharge boundary and region of influence is generally very flat and therefore, the time taken inflow is very long and the rate of recharge available to the region of influence is very low. In such a case, even if the available recharge is plentiful at the external boundary, the flow is unsteady for a substantially long period.

Unsteady flow towards wells can take place in confined as also in unconfined aquifers.

'Steady flow through aquifers' - Steady flow through aquifers, indicates balance between discharge of a well and rate of recharge in the region of influence. Theoritically, steady state flow towards wells does not exist in nature. However, in most of the cases met with in practice, a sort of quasi-equilibrium or stability is established after some time and subsequent rates of change in drawdown or region of influence are imperceptible. Such conditions can be treated as steady state conditions for purposes of analysis. In small aquifers with plentiful recharge, steady state or equilibrium conditions are established very soon. Similarly, in large aquifers, which have intermediate connections with sources of recharge and bodies of water, the steady state conditions develop quickly. Extensive aquifers, with far removed sources of recharge takes long time to establish equilibrium conditions.

2.2 A few Basic Concepts :

Radius of Influence :

When water is pumped from a well, there is a certain drawdown and general lowering of the water table in the case of unconfined aquifers and piezometric levels in the case of confined aquifers. If the pumping is continued at a steady rate, the region of influence extends gradually, but stablises after sustained pumping. Average radius of the region of influence is known as radius of influence. Radius of influence is a theoritical concept, which is rather vague, but it is extremely helpful in the solution of problems of flow towards wells.

The variables involved in the equation of radial flow towards wells in a steady state are co-efficient of permeability K, thickness of the aquifer B, radius of the well r_w, radius of influence R, maximum draw down at the face of the well $H-h_w$ and discharge Q. Variables K, B and r_w are normally predetermined, and can be taken as independent variables. Out of the remaining variables, one more variable can be treated as independent, say $H-h_w$. This leaves two variables Q and R, which are dependent on K, B, r_w and $H-h_w$ and are interdependent on each other. Since, there is only one flow equation, the problem is indeterminate and it is not possible to find unique solutions for Q and R. If the rate of recharge to the region of influence is known, another relation can be obtained and theoritically, the problem becomes determinate. However, there are practical difficulties involved in ascertaining and assigning suitable values of rate of recharge and then applying it to the problem. As such, to simplify the analysis, an arbitrary value is assigned to R.

The limitations involved in assigning an arbitrary value to R are :

(a) it does not take into consideration, the rate at which the region of influence is replenished,

(b) Different persons may assign widely different values of R for the same set of conditions.

However, the limitations are not very serious. In the flow equation, $H-h_w$ and Q are related to log R and therefore, even wide variations in the value of R have minor influence on the results. As such, with the data available from field tests and with a little experience, it should be possible to assign a fairly satisfactory value to R.

Nature of flow through the aquifers :

It is usual to assume that ground water flow is continuous, irrotational and laminar. The assumption is not truly correct. Unlike a pipe or a capillary, the aquifer material is in the form of a large number of irregular voids and interstices of different shapes and sizes, connected to each other in all directions. As such, the movement of ground water takes place through numerous channels following circuitous paths. Ground water velocities are generally of a very low order, and in most cases the flow through the individual channels is continuous and laminar. However, in some of the channels there may be continuous transverse movement of fluid particles from one flow channel to another, leading to turbulence and rotation and in some cases, even lack of continuity. The transverse velocities are however small and in most cases balance each other. As such, taking a macroscopic and statistical view of the aquifer as a whole, the flow through the aquifer can be treated as reasonably continuous, irrotational and laminar.

Applicability of Darcy's Law to ground water movement :

Darcy enunciated in 1858 a linear relationship between velocity and hydraulic gradient for flow of water through sands and thereby laid the foundation for rational analysis of problems of flow through porous media.

Hagen Poiseuille's equation gives a linear relation between velocity and hydraulic gradient for laminar, viscous flow through pipes. Since, ground water movement occurs through minute porous channels, the flow is viscous and therefore, Darcy's law is applicable, so long as the flow is laminar. Many investigators* have shown that for flow through porous material, the critical value of the Reynold's number (formed with mean grain diameter as length parameter) at which transition occurs from

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* Todd – Ground water hydrology.

laminar flow to turbulent flow, ranges between 1 to 10. Since, the ground water velocities are generally of a very low order, this limit is normally not exceeded. On the lower side, there is almost no practical limitation to the applicability of Darcy's law through common aquifer materials.

Combinations of flow patterns :

Laplace's equation gives a flow pattern for a given set of conditions. Laplace's equation is linear in form. If there are a number of flow patterns, each of which satisfies Laplace's equation, linear combinations of one or more of such flow patterns, will also satisfy the Laplace's equation. This property of the Laplace's equation, is very useful in combining or superimposing simple flow patterns to form a large number of complex flow patterns. Or conversely, complex flow patterns met with in practice, can be split and reduced to a number of simple flow patterns for which solutions are available.

Method of Images :

Very extensive aquifers are rare in nature. Generally, bodies of water, e.g. surface streams, lakes, reservoirs or seas bound the aquifers. In many cases the aquifers may be bounded by impervious boundaries or geological discontinuities on one or more sides. Evidently, all natural boundaries influence the pattern of flow towards wells.

Method of images is a mathematical device employed for the solution of such problems. Under this method, a natural boundary or flow field is replaced by an imaginary well (source or sink) or a combination of imaginary wells, located in such a manner, that the combined hydraulic effect of the group of imaginary wells, is the same as that of the given boundary. Since, the solutions for flow patterns for a single well or a group of wells are available, the solutions for flow fields of wells located in the neighbourhood of natural boundaries, can be obtained.

Method of images has a very wide application. It can be applied to confined and unconfined flow, steady flow and unsteady flow and normally to all types of natural boundaries, commonly met with in practice. The number of image wells, their location and type (discharging or recharging) depends on the type of the boundary. Actually, the number of image wells may vary from one to infinity.

2.3 Basic Equations :

Basic equations involved in the flow of ground water are, continuity equation, Darcy's equation and general flow equations of Laplacians form. These equations have been stated without giving derivations. Basic equations dealing with steady radial flow towards a well in confined and unconfined aquifers, have been deduced and dealt with in detail.

2.31 Equation of Continuity :

The general equation of continuity for flow of water through compressible medium can be written as,

$$-\frac{\partial}{\partial x}(\rho\, v_x) - \frac{\partial}{\partial y}(\rho\, v_y) - \frac{\partial}{\partial z}(\rho\, v_z) = n.\,\rho\,(\beta + \frac{\alpha}{n})\ \frac{\partial p}{\partial t}$$

.....(2.11)

where

ρ = mass density of the fluid,

n = porosity of the aquifer material,

α = vertical compressibility of sand,

β = compressibility of water.

For an incompressible flow in a steady state, the equation of continuity reduces to,

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \text{ (Cartesian co-ordinates)} \qquad \ldots\ldots\ldots(2.12)$$

and $$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{1}{r} + \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z} = 0$$

or $$\frac{1}{r}\frac{\partial}{\partial r}(\lambda v_r) + \frac{1}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z} = 0 \qquad \text{(Cylindrical co-ordinates)} \qquad \ldots\ldots\ldots\ldots(2.13)$$

2.32 Darcy's Equations :

According to Darcy's law, the velocity of flow through porous medium is directly proportional to hydraulic gradient. Symbolically, Dardy's law can be stated as follows :
Using cartesian co-ordinates,

$$v_x = -K\frac{\partial h}{\partial x}, \quad v_y = -K\frac{\partial h}{\partial y}, \quad v_z = -K\frac{\partial h}{\partial z} \qquad \ldots\ldots\ldots(2.21)$$

Using cylindrical co-ordinates,

$$v_r = -K\frac{\partial h}{\partial r}, \quad v_\theta = -\frac{K}{r}\frac{\partial h}{\partial \theta}, \quad v_z = -K\frac{\partial h}{\partial z} \qquad \ldots\ldots(2.22)$$

For unidirectional flow or symmetrical radial flow

$$v = -K \frac{\partial h}{\partial x} \quad \text{or} \quad v_r = -K \frac{\partial h}{\partial r} \qquad \text{........(2.23)}$$

2.33 <u>General flow equations</u> :

On integrating Darcy's equations with the equations of continuity, the following flow equations can be obtained.

For unsteady flow through compressible sands,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{\gamma n}{K} \left(\beta + \frac{\alpha}{n}\right) \frac{\partial h}{\partial t} \text{ ..... (2.31)}$$

where γ = specific weight of the fluid and other notations are the same as in para 2.31.

For flow through a confined aquifer of uniform thickness in a compressible medium, the equation reduces to

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{KB} \cdot \frac{\partial h}{\partial t} \qquad \text{........(2.32a)}$$

where S is the storage co-efficient.

$$\text{or} \quad \frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = \frac{S}{KB} \cdot \frac{\partial h}{\partial t} \qquad \text{.........(2.32b)}$$

(cylindrical co-ordinates)

For steady flow the equation reduces to the Laplacian form,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \text{ (Cartesian co-ordinates)}$$

......(2.33)

$$\text{or} \quad \frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} + \frac{1}{r^2} \frac{\partial^2 h}{\partial \theta^2} + \frac{\partial^2 h}{\partial z^2} = 0$$

$$\text{or} \quad \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial h}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 h}{\partial \theta^2} + \frac{\partial^2 h}{\partial z^2} = 0$$

(Cylindrical Co-ordinates)

2.34 **Basic Equations for Steady Radial Flow towards a well Confined aquifer:**

(a) **Assumptions :**

(i) The medium is uniform, homogeneous and isotopic. The well penetrates the entire depth of the porous medium,

(ii) The bed of the aquifer is horizontal and thickness of the stratum is uniform.

(iii) there is no leakage from impervious layers, confining the stratum.

(iv) The flow towards the well is horizontal radial and symmetrical about the axis of the well and is in a steady state. There is no natural flow in the aquifer before pumping.

(b) **Sign Convention :**

In the case of pumped wells or discharging wells, the flow is towards the well. As such, for the sake of convenience, pumped discharges and velocities towards the well, have been treated as positive. Other parameters e.g., h, r, x and y have the normal sign conventions followed in Cartesian and Cylindrical co-ordinate systems.

(c) **Derivation of the flow equation :**

Let h be the height of the piezometric surface at any point reckoned above an arbitrary datum(fig. 2.10). Let r be the radial distance of the point from the centre of the well.

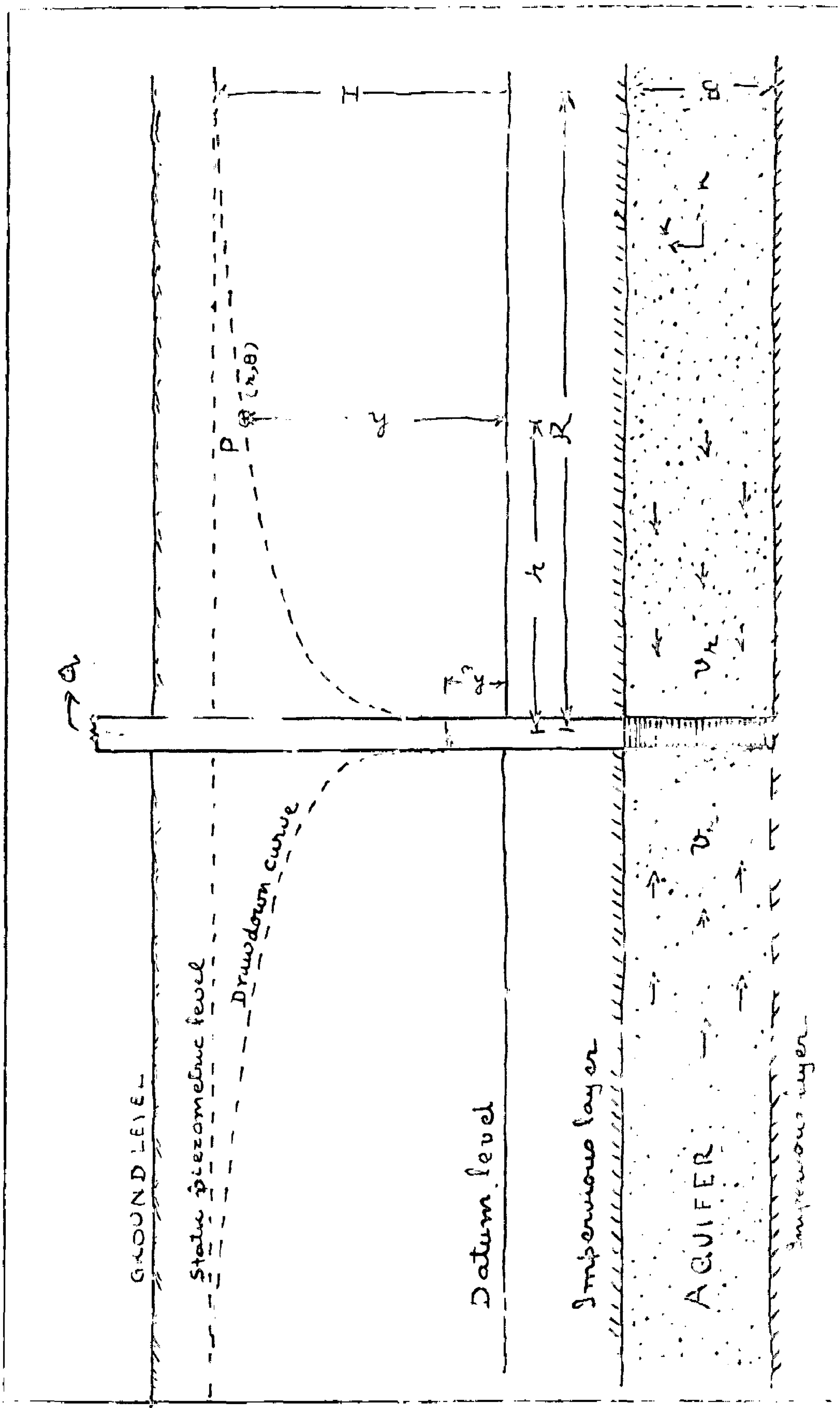

FIG 2.10 - Radial flow towards a well in a Confined aquifer

The Laplace's equation for flow through isotropic porous medium is given by,

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial h}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 h}{\partial \theta^2} + \frac{\partial^2 h}{\partial z^2} = 0 \quad \text{(Ref.eqn.2.34)}$$

Under the assumptions made, the flow through the confined layer is horizontal, radial and symmetrical about the axis of the well. There is no component of velocity either in the direction of Z or θ. As such, the derivates of h with respect to Z and θ, are zero. Consequently, the equation of steady radial flow towards a well in a confined aquifer reduces to

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial h}{\partial r}\right) = 0 \qquad \text{.......(2.41)}$$

On integration, we get,

$$r\frac{h}{r} = C_1 \quad \therefore \quad v_r = K\frac{\partial h}{\partial r} = \frac{KC_1}{r}$$

....(2.42a)

Integrating again, we get,

$$h = C_1 \log r + C_2 \qquad \text{.........(2.42b)}$$

where C_1 and C_2 are constants.

Considering the discharge flowing across a cylindrical ring of radius r and thickness B we get,

$$Q = \int_0^{2\pi} v_r \cdot B \cdot r \, d\theta$$

On substituting the value of v_r we get,

$$Q = \int_0^{2\pi} \frac{K.C_1}{r} B.r. \, d\theta$$

or $Q = 2 \pi K B . C_1$

or $C_1 = \dfrac{Q}{2 \pi KB}$ ...... (2.42 c)

Substituting the value of C_1 in equation (2.42 b) we get,

$h = \dfrac{Q}{2 \pi KB} \log r + C$ ....(2.43).

This is the basic equation for steady radial flow towards a well in confined aquifers. The value of C is determined from boundary conditions.

(d) <u>Equipotential lines and stream lines.</u>

Let the complex potential for flow towards the well be $W = \phi + i\psi$, where ϕ is the velocity potential and ψ is the stream function.

Where, $\phi = Kh$, and $\dfrac{\partial \phi}{\partial r} = K \dfrac{\partial h}{\partial r}$

Equation (2.43) can be rewritten as,

$Kh = \dfrac{Q}{2 \pi B} \log r + C'$

or $\phi = \dfrac{Q}{2 \pi B} \log r + C'$ ....(2.44)

Also , $\dfrac{\partial \phi}{\partial r} = \dfrac{1}{r} \dfrac{\partial \psi}{\partial \theta}$

$$\text{or} \quad \frac{\partial \psi}{\partial \theta} = r \frac{\partial \phi}{\partial r}$$

$$= \frac{Q}{2 \pi B}$$

or $\psi = \dfrac{Q}{2 \pi B} \theta + C''$, ...(2.46)

From equations (2.44) and (2.46) we get the value of the complex potential

$$\text{as} \quad W = \phi + i \psi$$

$$= \frac{Q}{2 \pi B} (\log r + i\theta) + C$$

$$= \frac{Q}{2 \quad B} \log Z + C \qquad \text{..........(2.46)}$$

Where $Z = x + iy = r.e.^{i\theta}$

Equation 2.44 implies that, when ϕ = consts, r = constant and therefore the equipotential lines for free radial flow towards a well are concentric circles with centres at the well.

Similarly, from equations (2.45) we can see that when ψ is constant, θ = constant and therefore flow lines are radius vectors converging towards the well.

2.35. Basic equations for Steady radial flow towards a well in an unconfined aquifer:

(a) Special Characteristics of flow:

Flow towards a well in an unconfined aquifer has following special chracteristics.

(i) The free surface is not known.

(ii) The free surface strikes the well at an elevation, which is slightly higher than the elevation of water in the well, thereby forming a seepage face. The height of this seepage face is not known.

(iii) The depth of flow varies according to distance from the well. Due to non uniform flow the velocity vectors are inclined and length of the path followed by individual fluid particles, varies with elevation.

(b) Assumptions:

The problem is solved with the help of simplifying assumptions made by Dupuit:-

(i) The medium is uniform homogeneous and isotropic. The well penetrates the entire depth of the ~~forms~~ porous medium.

(ii) The bed of the aquifer is horizontal and thickness of the aquifer is uniform.

(iii) The flow towards the well is horizontal, radial and symmetrical about the axis of the well and is in a steady state. There is no vertical recharge or percolation from the ground. There is no leakage from the bed supporting the aquifer. There is no natural flow along the aquifer.

(iv) Velocity is uniform over the full depth of flow and is given by $K \frac{\partial h}{\partial r}$. The lengths of path followed by individual particles are assumed to be constant.

(c) Derivation of the flow equations

Let h be the height of the free water surface at a distance r from the centre of the well. (Fig. 2.40). Under the assumptions made, there is no component of velocity either in the direction of Z or θ. Consequently the equation for steady radial flow towards the well is given by,

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial h}{\partial r} \right) = 0 \qquad \text{(Ref. Eqn. 2.34)}$$

On integration, we get,

$$r \frac{\partial h}{\partial r} = C_1$$

$$\text{Also,} \quad v_r = k \frac{\partial h}{\partial r} = K \frac{C_1}{r} \qquad \ldots\ldots(2.51)$$

Where C_1 and C_2 are constants.

Considering the discharge flowing across a cylindrical ring of radius r and thickness h we get,

$$Q = \int_0^{2\pi} V_r \,.\, h \,.\, r \, d\theta$$

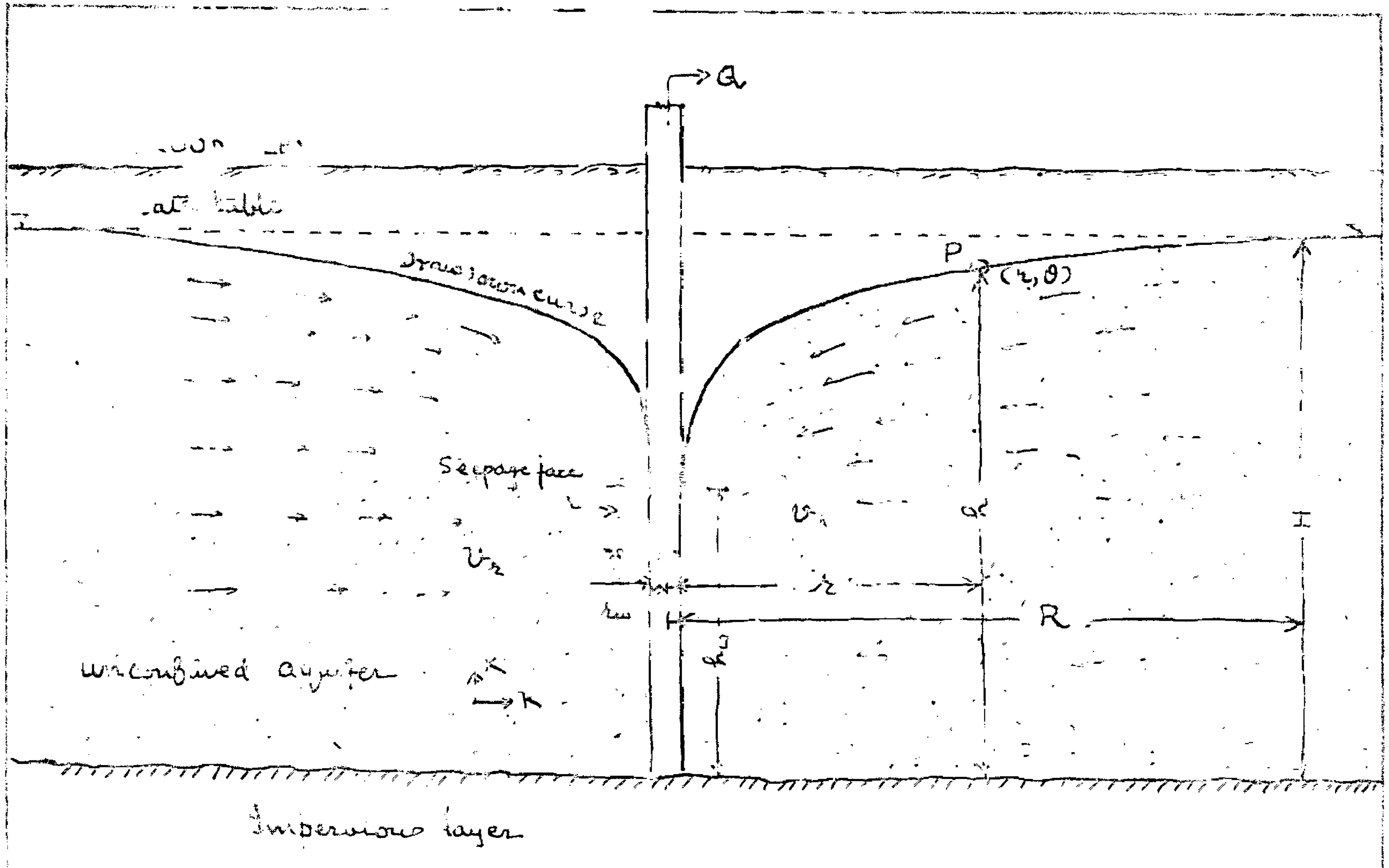

FIG 2.40 - Radial flow towards a well in an unconfined aquifer

On substituting the value of v_r we get,

$$Q = \int_0^{2\pi} \frac{K C_1}{r} . h r \, d\theta$$

Since, h is a constant for a given particular value of r

$$Q = 2\pi K h. C_1$$

$$\text{or } C_1 = \frac{Q}{2\pi Kh} \qquad \text{......(2.52)}$$

Substituting this value in the equation ......(2.52) we get,

$$r \frac{\partial h}{\partial r} = \frac{Q}{2\pi Kh}$$

$$\text{or } \frac{\partial (h^2)}{\partial r} = \frac{Q}{\pi Kr}$$

Integrating again we get,

$$h^2 = \frac{Q}{\pi K} \log r + c \qquad \text{........(2.53)}$$

This is the basic equation for steady radial flow towards a well in an unconfined aquifer.

(d) Applications and limitations of the equations:

The performance of a single well located in a confined aquifer has been studied in chapter III, under different conditions. (Ref. Para 3.0). Similarly the performance of groups of wells located in confined aquifers has been studied in chapter IV.

The basic equations for flow towards well in confined and unconfined aqufers are very similar,

$$h = \frac{Q}{2\pi KB} \log r + C \quad \text{(eqn.2.43)} \qquad \text{(For flow towards a well in a confined aquifer).}$$

$$h^2 = \frac{Q}{\pi K} \log r + C \quad \text{(eqn.2.53)} \qquad \text{(For flow towards a well in an unconfined aquifer.)}$$

It is therefore possible to apply all methods and derivations of Chapter III and IV to unconfined flow by using equation (2.53) in stead of equation (2.43). Qualitatively, the conclusions that have been drawn in individual cases for steady flow towards wells in confined aquifers, also apply to steady radial flow towards well in unconfined aquifers.

The main limitation of Dupuit's assumptions and the equation (2.53) are that the existence of the seepage face is ignored. For all practical purposes this is not a serious limitation, because the variation in the actual shape of the free surface and Dupuit's free surface occur, in the close vicinity of the well. As we move away from the well the difference is nominal.

2.36. Equation for unsteady flow in a confined aquifer

Suppose that the aquifer is extensive and that there are no lateral water boundaries to support the discharge of the well. In such a case the water will come from storage available within the aquifer and the discharge of the well will be equal to the product of the rate of decline in head and storage Co-efficient, integrated over the area of influence of the well. The differential equation governing unsteady radial flow to a well in a confined aquifer is given by,

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \quad \text{(Ref. eqn. 2.32 b.)}$$

Theis* obtained a solution for this equation based on

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*CV Theis - The relation between lowering of piezometric surface and rate of duration of discharge of a well, using ground water storage. Transactions of American Geophysical Union, Vol.16, P 519-524.

an analogy between ground waterflow and heat conduction. ~~The~~ He assumed the following conditions,

$$\lim_{r \to 0} \left(r \frac{\partial h}{\partial r} \right) = \frac{Q}{2 \pi T} \quad \text{for } t \geq 0$$

r 0

This signifies that the well is replaced by a sink of constant strength. Other boundary conditions are,

$$h = H \text{ for } t < 0 \quad \text{(Initial conditions)}$$

$$\text{and } h \to H \text{ when } r \to \infty \text{ for } t \geq 0$$

The solution obtained by Theis is,

$$H - h = \frac{Q}{4 \pi T} \int_{\frac{r^2 S}{4 Tt}}^{\infty} \frac{e^{-u} \, du}{u}$$

Where t is the time taken from the commencement of pumping and $u = \frac{r^2 S}{4 Tt}$.

The above exponential integral can be expanded in the form of a convergent series,

$$H - h = \frac{Q}{4 \pi T} \left[-0.5772 - \log (u) + u - \frac{u^2}{2 \lfloor 2} + \frac{u^3}{3 \lfloor 3} + \frac{u^4}{4 \lfloor 4} + \ldots\ldots \right]$$

For large values of t the above expression can be expressed very closely by the asymptotic expression

$$H - h = \frac{Q}{4 \pi T} \log \frac{2.25 \, Tt}{r^2 S} \quad \ldots\ldots (3.61).$$

This equation can be used for obtaining the values of aquifer constant T and S and when the aquifer constants are known, it can be utilised to obtain drawdown at any point and at any time for different discharges.

An examination of equation (3.61) will show that at a fixed interval after pumping, i.e. for a given value of t the equation is similar to equations 2.43 and as such the methods used in chapter III and IV for steady radial flow towards wells in confined aquifers can be applied in a limited manner to similar problems of unsteady flow. Moreover, the inferences and conclusions drawn about the behaviour of wells under steady flow and the effects of nutural interference between them, can be applied qualitatively to problems of unsteady flow under similar situations.

CHAPTER III

BEHAVIOUR OF A SINGLE WELL

3.0 BEHAVIOUR OF A SINGLE WELL.

If an isolated well is placed in a water bearing stratum, the flow towards the well is free and radial. Basic assumptions and flow equations for steady radial flow towards an isolated well in a confined aquifer have been given in para 2.34. In nature, the disposition of the natural boundaries e.g., bodies of water, geological discontinuities and impervious boundaries, may substantially influence the behaviour of the well. The following cases have been studied with a view to have a proper appreciation of the influence of natural boundaries and other factors on the behaviour of an isolated well.

(a) Single well at the Centre of a circular island or recharge boundary.

(b) Influence of eccentricity on a well located in a circular water boundary.

(c) Influence of irregular shape of a closed water boundary.

(d) Influence of straight line water boundaries, impervious boundaries or combinations of such boundaries in the neighbourhood of the well.

(e) Influence of unidirectional natural flow in the aquifer.

3.1 Single well located at the Centre of a Circular recharge Boundary:

When the well is located at the Centre of a recharge boundary, the flow is radial. The assumptions and basic equations have been given in para 2.34. The influence of different variables on the behaviour of the well has been studied and illustrated.

Flow Equations:

Suppose that the well is located at the centre of a circular island or any other circular recharge boundary with constant piezometric levels along the periphery. (Refer fig.3.10),

The basic equation for flow towards a well is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{Refer equation 2.43}$$

Considering a point on the external boundary where $h = H$, $r = R$,

$$H = \frac{Q}{2\pi KB} \log R + C \qquad \ldots\ldots\ldots\ldots(3.11)$$

Considering a point on the face of the well, where $h = h_w$, $r = r_w$.

$$h_w = \frac{Q}{2\pi KB} \log r_w + C \qquad \ldots\ldots\ldots\ldots(3.12)$$

From equations (3.11) and (3.12) we get

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{R}{r_w} \qquad \ldots\ldots\ldots\ldots(3.13a)$$

$$\text{or} \quad Q = \frac{2\pi KB\,(H-h_w)}{\log \frac{R}{r_w}} \qquad \ldots\ldots\ldots\ldots(3.13b)$$

From equations (2.43) and (3.11) we get,

$$H - h = \frac{Q}{2\pi KB} \log \frac{R}{r} \qquad \ldots\ldots\ldots\ldots(3.14a)$$

$$\text{or} \quad h = H - \frac{Q}{2\pi KB} \log \frac{R}{r} \qquad \ldots\ldots\ldots\ldots(3.14b)$$

Equation 3.13 gives the discharge for the well and equation 3.14 gives the piezometric heights for different points on the drawdown curve.

Equation for piezometric height can also be written in the following forms,

$$h - h_w = \frac{Q}{2\pi KB} \log \frac{r}{r_w} \qquad \text{..........(3.14c)}$$

$$\text{or} \quad h = h_w + \frac{Q}{2\pi KB} \log \frac{r}{r_w} \qquad \text{..........(3.14d)}$$

$$\text{or} \quad h = h_w + \frac{H-h_w}{\log \frac{R}{r_w}} \log \frac{r}{r_w} \qquad \text{..........(3.14e)}$$

Computations :

The following computations have been done to illustrate the influence of different variables on the flow of a well under a given set of conditions :

(a) Influence of radius of influence on discharge (Table 3.11 and Fig. 3.11)

(b) Influence of radius of well on discharge. (Table 3.12 and Fig. 3.12)

(c) Influence of discharge on drawdown curve (Assuming that drawdown curves for different values of discharges are geometrically similar Table 3.13 and Fig. 3.13).

(d) Influence of Radius of influence on drawdown curve. (Assuming that the drawdown remains constant. Table 3.14 and Fig. 3.14).

(e) Influence of change of drawdown on drawdown curve (Assuming that the radius of influence remains constant. Table 3.15 and Fig. 3.15).

Conclusions:

(a) The discharge increases as drawdown increases.

(b) Discharge increases as the radius of the well increases. Variation is however logarithmic. A tenfold increase in the diameter of the well increases the discharge by 35%. It is not economical to have large diameter wells.

(c) Discharge decreases as the radius of influence increases and vice versa. The variation is however logarithmic. A change of 100% in the value of R effects the discharge by less than 10%.

(d) Discharge is directly proportional to the transmissibility of the aquifer.

(e) Drawdown curve is a logarithmic curve with very steep gradients close to the well and flatter gradients away from the well. 75% of the drawdown occurs within 100 ft of the well.

(f) Flow lines are radius vectors converging towards the centre of the well. Equipotential lines are concentric circles with centre at the centre of the well i.e., the flow lines are concentric with the feed contour.

3.2 <u>Single well located eccentrically in a circular recharge Boundary:</u>

The behaviour of a well located centrally in a circular recharge boundary has been studied in para 3.1. This is an idealised conditions. In practice, the wells, particularly groups of wells may have to be located away from the Centre. The influence of eccentricity, on the behaviour of the well, has been studied by the application of method of images (refer to para 2.2).

<u>Location of the image well:</u>

Suppose that the well is located at M_1 with an eccentricity 'e' with respect to the centre of a circular island or a circular recharge boundary (Refer to fig. 3.20). Let the piezometric levels along the external boundary be constant.

It has been shown (Refer to para 2.34d) that the equipotential lines for free flow towards a well are concentric circles. In the case of a well, located at the centre of an island or circular recharge boundary, the flow lines are also concentric with the recharge boundary, as such, the basic character of free flow towards a well is maintained.

It can be imagined that, if the well is located eccentrically in a circle and is pumping freely, the pressure distribution along the given circle will not be uniform. Conversely, if a constant pressure is maintained along the circular boundary, the equipotential lines of the well will not be concentric circles. This distortion in the pattern of flow, occurs due to the presence of the boundary. The problem is solved by using the method of images. If the given recharge boundary is removed and replaced by a recharging image well, with the same flow as that of the real well, and is located at point M_2, where M_2 is the inverse reflection of M_1 about the given boundary, a constant potential is obtained along the given boundary. As such, the image well at M_2 replaces the hydraulic effects of the given boundary and the problem of a well located eccentrically in a circular feed contour is transformed into a problem of two wells located at M_1 and M_2.

Co-Ordinates of the Image Well :

Let R be the radius of the given circular boundary with centre at O. The real well is located at M_1 with co-ordinates $Z_1 = x_1 + iy_1$, and the image well be located at M_2, with co-ordinates $Z_2 = x_2 + iy_2$. (Refer fig. 3.20).

$$\text{Eccentricity } e = OM_1 = \sqrt{x_1^2+y_1^2} = |Z_1|$$

Since M_2 is the inverse reflection of point M_1 about the given boundary,

$$\frac{OM_1}{R} = \frac{R}{OM_2} \quad \text{or} \quad R^2 = OM_1 \cdot OM_2$$

It can be seen from fig. 3.20 that,

$$\frac{ON_2}{ON_1} = \frac{OM_2}{OM_1}$$

$$\text{or} \quad \frac{x_2}{x_1} = \frac{R^2}{OM_1} \cdot \frac{1}{OM_1} = \frac{R^2}{OM_1^2} = \frac{R^2}{x_1^2+y_1^2}$$

$$\text{or} \quad x_2 = x_1 \cdot \frac{R^2}{x_1^2+y_1^2}$$

$$\text{Similarly,} \quad \frac{M_2N_2}{M_1N_1} = \frac{OM_2}{OM_1}$$

$$\text{or} \quad \frac{y_2}{y_1} = \frac{R^2}{OM_1^2} = \frac{R^2}{x_1^2+y_1^2}$$

$$\text{or} \quad y_2 = y_1 \cdot \frac{R^2}{x_1^2+y_1^2}$$

$$\therefore \; Z_2 = x_2 + iy_2 = \frac{x_1+y_1}{x_1^2+y_1^2} \cdot R^2 = \frac{R^2}{x_1-iy_1} = \frac{R^2}{\bar{Z}_1}$$

Flow Equations :

Let the discharge of the real well be +Q and that of the image well be -Q. Let P be any point with complex co-ordinates $Z = x+iy$. Let PM_1 be equal to r_1 and PM_2 be equal to r_2.

The basic equation for flow to-wards a well is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{Ref. equation 2.43}$$

Combined flow equation for real well at M_1 and imaginary well at M_2 can be written as,

$$h = \frac{Q}{2\pi KB}\log r_1 - \frac{Q}{2\pi KB} \log r_2 + C \qquad (3.21a)$$

$$= \frac{Q}{2\pi KB} \log |Z-Z_1| - \frac{Q}{2\pi KB} \log |Z_2-Z| + C$$

$$= \frac{Q}{2\pi KB} \log |Z-Z_1| - \frac{Q}{2\pi KB} \log \left| \frac{R^2}{\bar{Z}_1} - Z \right| + C$$

.......(3.21b)

Considering a point on the face of the real well at M_1,

$$Z = Z_1 + r_w, \quad r_1 = |Z - Z_1| = r_w$$

$$r_2 = Z_2 - Z_1 = \left| \frac{R^2}{\bar{Z}_1} - Z_1 \right| = \frac{R^2}{e} - e = \frac{R^2 - e^2}{e}$$

$$\therefore \quad h_w = \frac{Q}{2\pi KB} \log r_w - \frac{Q}{2\pi KB} \log \frac{R^2 - e^2}{e} + C \quad \ldots\ldots (3.22)$$

Considering a point on the external boundary, say at A,

$$h = H, \quad r_1 = AM_1 = OA - OM_1 = R - e$$

$$r_2 = AM_2 = OM_2 - OA = \frac{R^2}{e} - R = \frac{R(R-e)}{e}$$

$$\therefore \quad H = \frac{Q}{2\pi KB} \log (R-e) - \frac{Q}{2\pi KB} \log \frac{R(R-e)}{e} + C \quad \ldots\ldots (3.23)$$

From equations (3.22) and (3.23) we get,

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{R-e}{r_w} \cdot \frac{R^2 - e^2}{e} \cdot \frac{e}{R(R-e)}$$

$$= \frac{Q}{2\pi KB} \log \frac{R^2 - e^2}{R . r_w} \quad \ldots\ldots\ldots (3.24a)$$

$$\text{or} \quad Q = \frac{2\pi KB (H - h_w)}{\log \frac{R^2 - e^2}{R . r_w}} \quad \ldots\ldots\ldots (3.24b)$$

From equations (3.21a) and 3.23 we get,

$$H - h = \frac{Q}{2\pi KB} \log \frac{r_2}{r_1} \cdot \frac{e}{R} \quad \ldots\ldots\ldots (3.25a)$$

$$\text{or} \quad h = H - \frac{Q}{2\pi KB} \log \frac{r_2}{r_1} \cdot \frac{e}{R} \quad \ldots\ldots\ldots (3.25b)$$

Equation 3.24 can be utilised for computation of discharges and equation 3.25 can be used for computation of piezometric levels at different points on the drawdown curve.

Computations :

The following computations have been done to illustrate the influence of eccentricity of the well :

(a) Influence of eccentricity on discharge. (Table 3.21 and Fig. 3.21)

(b) Influence of eccentricity on drawdown curve. (Table 3.22 and Fig. 3.22).

Conclusions:

(a) The discharge increases as the eccentricity of the well increases. The increase in the discharge is of the order of 5% upto 50% eccentricity and of the order of 10% upto 70% eccentricity. Beyond that the increase is sharp but wide variations occur only when the eccentricity exceeds 90%.

(b) For a given eccentricity ($\frac{e}{R}$) the value of radius of influence has nominal effect on discharge. (Refer to fig. 3.21).

(c) Equivalent radius of influence R', is given by $\frac{R^2-e^2}{R}$. (Refer to equation 3.24a).

(d) In practice, the influence of eccentricity can be neglected without much loss of accuracy. This is particularly convenient in the case of group of wells located in a circular is-land or any other recharge boundary.

3.3 Well located in an island or recharge boundary of irregular shape:

The behaviour of a well located at the centre of a circular island has been studied in para 3.1. For all practical purposes, this is too idealised a condition to be met with in practice. It is rare to find a natural recharge boundary which is absolutely circular. Moreover, the well may not be located exactly in the centre of such a boundary.

The effect of eccentricity or displacement of the well from the centre of the boundary has been studied in para 3.2 and it has been observed that the variation in discharge becomes significant, only when the eccentricity exceeds 70%.

Evidently, the influence of the shape of the external water boundary on discharge can be studied only when the shape of the boundary is known. Polubarinova-Kochina* has suggested an analytical solution of the problem by conformal transformation of the irregular boundary into a circular boundary and then applying the results of para 3.1 and 3.2 to the problems.

She has also analysed the specific cases of elliptical boundaries and has obtained ~~the following~~ results, which can be summarised as follows :

Case (a) Let 'a' be the major axis and 'b' be the minor axis of the elliptical boundary. Let R be the radius of the circular boundary. If b = R and

*Polubarinova-Kochina: Theory of Ground Water Movement, p.365

a = 3R, the discharge of a well located at the centre of an elliptical boundary is more than 97% of the discharge of well located at the Centre of a circular boundary. There is no further reduction in discharge when $a > 3R$.

Case (b) Let the area of the elliptical boundary be equal to the area of circular boundary, or $R^2 = a.b.$ Upto a = 3b, the discharge of the well located at the centre of the elliptical boundary is 105% of the discharge of the well located at the centre of circular boundary. For a = 6b, the discharge is 110%.

Evidently, the influence of an irregular boundary on discharge, is nominal and can be ignored for all practical purposes. However, in exceptional cases, specific solutions can be obtained.

3.4 Well located on one side of an impervious boundary :

In nature, the aquifers are frequently intercepted by natural impervious boundaries or geological discontinuities, e.g., faults and folds. If the well is located on one side of such a discontinuity in the aquifer, the pattern of flow to-wards the well gets distorted and the discharge and shape of the draw-down curve are affected. The problem is solved by the method of images.

Location of the image well :

Let the impervious boundary lie along the axis of Y (Fig. 3.40). Let A(a,o) be the location of the well.

(Fig. 3.40). Let Q be the discharge of the well. The effects of the impervious boundary are :

(a) There is no flow across the boundary YOY', which means that it is a flow line.

(b) when the well is pumping, maximum drawdown will occur at O which is closest to the well. The drawdown will diminish gradually along OY and OY'.

Suppose that an image well with the same discharge +Q as that of the real well is located at B (-a,o), which is the reflection of point A on the other side of the impervious boundary. If wells at A and B are in operation, simultaneously, a water divide is obtained along YOY'. Water divide implies that there is no flow across it. Water divide is also a flow line. That satisfies the first condition. The maximum drawdown along the water divide shall be at O which is closest to the two wells with gradual reduction along OY and OY', thereby satisfying the second condition.

<u>Flow equations</u> :

Equation for free flow towards a well is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{(Refer to equation 2.43)}$$

Combined flow equation for real well at A and image well at B with a discharge of Q each, can be written as,

$$h = \frac{Q}{2\pi KB} \log r_1 + \frac{Q}{2\pi KB} \log r_2 + C$$

$$= \frac{Q}{2\pi KB} \log r_1 r_2 + C \qquad \text{.........(3.41)}$$

Considering a point on the face of the well at A,

$r_1 = r_w$, $r_2 = 2a$, $h = h_w$

$$\text{or } h_w = \frac{Q}{2\pi KB} \log 2ar_w + C \quad .....(3.42)$$

Considering a point on the external boundary of the region of influence,

$$r_1 \simeq r_2 \simeq R; \quad h = H$$

$$\text{or } \quad H = \frac{Q}{2\pi KB} \log R^2 + C \quad ....(3.43)$$

From equations (3.42) and (3.43) we get,

$$H - h_w = \frac{Q}{2\pi KB} \cdot \log \frac{R^2}{2\,a\,r_w} \quad ....(3.44a)$$

$$\text{or } Q = \frac{2\pi KB\,(H-h_w)}{\log \dfrac{R^2}{2\,a\,r_w}} \quad ....(3.44b)$$

From equations (3.41) and (3.43) we get,

$$H - h = \frac{Q}{2\pi KB} \log \frac{R^2}{r_1 r_2} \quad ....(3.45a)$$

$$\text{or } h = H - \frac{Q}{2\pi KB} \log \frac{R^2}{r_1 r_2} \quad ....(3.45b)$$

Equation 3.44 gives the discharge whereas equation 3.45 gives the piezometric heights for different points on the drawdown curve.

Computations :

The following computations have been done to illustrate the influence of impervious boundary on the behaviour of a well under a given set of conditions.

(a) Influence on discharge of the well.
(Table 3.41 and Fig. 3.41)

(b) Influence on drawdown curve
(Table 3.42 and Fig. 3.42)

Conclusions :

(a) The presence of the impervious boundary reduces the discharge available from the well.

(b) The discharge increases as the well moves away from the impervious boundary.

(c) the flow equation and drawdown curves are same as for a group of two wells placed inside a circular water boundary (Refer to para 4.1).

(d) Conversely, the presence of the impervious boundaries or other discontinuities can be located by studying the nature of drawdown curves from readings of observation wells.

(e) The equivalent radius of influence $R' = \frac{R^2}{2a}$

3.5 Well located on one side of an infinite water boundary or Line drive:

An infinite water boundary may appear in nature in the form of a river, drain, burried valley, canal, lake, reservoir or sea. The word infinite signifies that the lengths of the source is very much bigger than the space covered by the group of wells. Let us assume that the potential along the water boundary is constant and that the sands of the aquifer outcrop into the water boundary, so that free flow and recharge at constant head is available to the aquifer.

Location of the image well :

Let the water boundary lie along the axis of Y (Fig.3.50) A Let A (a,o) be the location of the well. (Fig. 3.50). Let Q be the discharge of the well. The effects of the water boundary are :

(a) Water is drawn by the well from the water boundary. As such the flow lines will originate at right angles to the water boundary and will converge gradually to-wards the well.

(b) The water boundary YOY' is a line of constant potentials.

Suppose that a recharging image well with the flow of -Q is located at B(-a,O), which is the reflection of point A on the other side of the water boundary. If the recharging well at B and real well at A are in operation simultaneously, the flow lines will originate radially from B and converge radially at A. On account of symmetry of the two wells the flow lines will cut YOY' at right angles. This satisfies the first condition. Pumping well at A will cause drawdown all along YOY' with maximum drawdown at O. Recharging well at B will cause identical build up along YOY' with maximum build up at O. Cumulative effect is that a constant potential is maintained along YOY', thereby satisfying the second condition.

Flow equation :

Equation for free flow towards a well is given by

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{Ref. equation 2.43}$$

The combined flow equation for the real well at A and image well at B can be written as,

$$h = \frac{Q}{2\pi KB} \log r_1 - \frac{Q}{2\pi KB} \log r_2 + C$$

$$= \frac{Q}{2\pi KB} \log \frac{r_1}{r_2} + C \qquad \ldots\ldots\ldots\ldots(3.51)$$

Considering a point on the face of the real well we get, $r_1 = r_w$, $r_2 = 2a$,

$$h_w = \frac{Q}{2\pi KB} \log r_w - \frac{Q}{2\pi KB} \log 2a + C \ldots\ldots(3.52)$$

Considering a point on the water boundary we get, $r_1 = a$, $r_2 = a$.

$$H = \frac{Q}{2\pi KB} \log a - \frac{Q}{2\pi KB} \log a + C$$

$$= C \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3.53)$$

From (3.52) and (3.53) we get,

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{2a}{r_w} \qquad \ldots\ldots\ldots(3.54a)$$

$$\text{or} \quad Q = \frac{2\pi KB\ (H - h_w)}{\log \frac{2a}{r_w}} \qquad \ldots\ldots\ldots(3.54b)$$

From equations(3.51) and 3.53 we get

$$H - h = \frac{Q}{2\pi KB} \log \frac{r_2}{r_1} \quad \text{........(3.55a)}$$

$$\text{or} \quad h = H - \frac{Q}{2\pi KB} \log \frac{r_2}{r_1} \quad \text{........(3.55b)}$$

Equation 3.54 gives the discharge and equation 3.55 can be used for computing the piezometric heights of different points on the drawdown curve.

Flow Pattern - Equipotential lines and Flow lines :

(a) Equipotential Lines :

Equation 3.55 can be rewritten as

$$h - H = \frac{Q}{2\pi KB} \log \frac{r_1}{r_2}$$

$$\text{or} \quad \left(\frac{r_1}{r_2}\right)^2 = e^{\frac{4\pi KB(h-H)}{Q}}$$

For equipotential lines h = consts, $\therefore e^{\frac{4\pi KB(h-H)}{Q}}$ = consts=m say

Converting r_1 and r_2 to cartesian Co-ordinates we get,

$$r_1^2 = (x - a)^2 + y^2$$

$$r_2^2 = (x + a) + y^2$$

$$\text{or} \quad \frac{(x-a)^2 + y^2}{(x+a) + y^2} = m,$$

$$\text{or} \quad \left[x - a\left(\frac{1+m}{1-m}\right)\right]^2 + y^2 = \left[\frac{2a\sqrt{m}}{1-m}\right]^2 \quad \text{......(3.56)}$$

The equation represents a family of circles with centres at $\left[a\left(\frac{1+m}{1-m}\right), 0\right]$ and radii = $\left[\frac{2a\sqrt{m}}{1-m}\right]$. Equipotential lines can be obtained by assigning different values to h.

(b) Flow Lines :

The stream function for a well can be written as,

$$\psi = \frac{Q}{2\pi B}\,\theta \qquad \text{Ref. equation 2.45}$$

The stream function for the combined effect of the real well at A and recharging well at B can be written as,

$$\psi_1 - \psi_2 = \frac{Q}{2\pi B}(\theta_1 - \theta_2)$$

Where $\theta_1 = \tan^{-1}\frac{y}{x-a}$ and $\theta_2 = \tan^{-1}\frac{y}{x+a}$

For obtaining the stream lines we can put the stream function $\psi_1 - \psi_2$ = consts.

$$\text{or } \theta_1 - \theta_2 = \frac{2\pi B}{Q}(\psi_1 - \psi_2) = \text{Consta.}$$

$$\text{or } \tan(\theta_1 - \theta_2) = \text{Constant} = \text{say, } p.$$

$$\text{where } p = \tan\frac{2\pi B}{Q}(\psi_1 - \psi_2)$$

$$\text{or } \frac{\tan\theta_1 - \tan\theta_2}{1+\tan\theta_1\tan\theta_2} = p$$

$$\text{or } \frac{\frac{y}{x-a} - \frac{y}{x+a}}{1+\frac{y}{x-a}\cdot\frac{y}{x+a}} = p$$

$$\text{or } x^2 + \left(y - \frac{a}{p}\right)^2 = \left(a\sqrt{1+\frac{1}{p^2}}\right)^2 \quad \ldots\ldots(3.57)$$

This equation represents a family of circles with centres at $\left(0, \frac{a}{p}\right)$ and radii = $a\sqrt{1+\frac{1}{p^2}}$ The flow lines can be obtained by assigning different values to $(\psi_1 - \psi_2)$. It can be seen that the family of circles pass through the points A (a,0) and B (-a,0).

Computations :

The following computations have been done to illustrate the influence of the water boundary on the behaviour of the well:

(a) Influence on discharge of the well (Table 3.51. Fig. 3.51).

(b) Co-ordinates of centres and radii of equipotential circles for a given set of conditions (table 3.52).

(c) Influence of water boundary on drawdown curve. (Table 3.53. Fig. 3.52).

Conclusions :

(a) Discharge decreases as the well moves away from the water boundary and vice versa.

(b) Equivalent radius of influence R' = 2a.

(c) Drawdown curve has a comparatively steeper gradient from O to A. Drawdown curve extends to infinity along Ax, i.e. as we move away from the water boundary.

(d) The equipotential lines are almost concentric circles, close to the well. The gradients are steep in this region, and absorb 75% of the drawdown. Beyond that, the drawdown curve becomes flatter and eccentricity and radii of equipotential circles, increase sharply, till they reach infinity. (Ref to Table 3.52)

3.6 Influence of Combinations of natural boundaries on the performance of a Single Well :

The problems are solved by the application of method of images. Curved boundaries are usually replaced by planes or straight lines. The image wells may be discharging wells or recharging wells and the number image of wells may vary from one to infinity depending on the nature of natural boundary and the accuracy desired.

3.61 Well located in a quadrant formed by the intersection of a Water boundary and an impervious boundary :

Let the water boundary be along OY and impervious boundary along OX. (Fig.3.61). Let the well with discharge +Q be located at A (a, b). An image well with discharge -Q will be needed at B (-a, b). (Refer to para 3.5) to replace the hydraulic effects of water boundary. Similarly, an image well with discharge +Q will be needed at D(a, -b) (Refer to para 3.4) to replace the impervious boundary. Further, another image well with a recharge Q, will be needed at C(-a, -b) to balance the drawdowns caused by image wells B and D, along the extensions of natural boundaries.

The combined flow equation for the group of wells can be written as,

$$h = \frac{Q}{2\pi KB} \log \frac{r_1 r_4}{r_2\, r_3} + C \qquad \ldots\ldots\ldots (3.61a)$$

Considering the point O, the junction of the two boundaries,

$$r_1 = r_2 = r_3 = r_4 = \sqrt{a^2 + b^2} \quad , h = H$$

$\therefore H = C$ ....(3.61b)

Considering a point on the face of the real well at A,

$r_1 = r_w$, $r_2 = 2a$, $r_3 = 2\sqrt{a^2+b^2}$, $r_4 = 2b$, $h = h_w$

$$\therefore h_w = \frac{Q}{2\pi KB} \log \frac{b.\ r_w}{2a\sqrt{a^2+b^2}} + C \quad \text{........(3.61c)}$$

Equations (3.61b) and (3.61c) give,

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{2a\sqrt{a^2+b^2}}{b.\ r_w} \quad \text{......(3.61d)}$$

$$\text{or} \quad Q = \frac{2\pi KB\,(H - h_w)}{\log \frac{2a\sqrt{a^2+b^2}}{b.\ r_w}} \quad \text{.......(3.61e)}$$

Equation (3.61a) and (3.61b), give,

$$H - h = \frac{Q}{2\pi KB} \log \frac{r_2\ r_3}{r_1\ r_4} \quad \text{........(3.61f)}$$

$$\text{or} \quad h = H - \frac{Q}{2\pi KB} \log \frac{r_2\ r_3}{r_1\ r_4} \quad \text{.........(3.61g)}$$

Equation (3.61e) gives the discharges and equation (3.61g) gives the piezometric heights for the drawdown curve.

The equation 3.64 indicates that the discharge increases as the water boundary moves closer to the well and impervious boundary moves away from the well. The equivalent radius of influence

$$R' = \frac{2a\sqrt{a^2+b^2}}{b}$$

3.62: <u>Well located in a quadrant formed by the intersection of two water boundaries</u> :

Let OX and OY be the water boundaries (Fig. 3.62). Let the well with a discharge Q be located at A (a, b).

An image well with discharge -Q is needed at B(-a, b) to replace the boundary OY. (Refer to para 3.5). Similarly, another image well with a discharge -Q is needed at D(a, b) to replace the water boundary OX. Another image well with a discharge +Q is needed at C (-a, -b) to balance the drawdown caused by the image wells B and D along the extentions of the water boundaries .

The combined flow equation for the group of wells can be written as,

$$h = \frac{Q}{2\pi KB} \log \frac{r_1 \, r_3}{r_2 \, r_4} + C \qquad \ldots\ldots\ldots\ldots(3.62a)$$

Considering the point O, the junction of the two water boundaries,

$$r_1 = r_2 = r_3 = r_4 = \sqrt{a^2 + b^2} \quad ; \; h = H,$$

$$\therefore \quad H = C \qquad \ldots\ldots\ldots\ldots(3.62\ b)$$

Considering a point on the face of the well at A,

$r_1 = r_w$, $r_2 = 2a$, $r_3 = 2\sqrt{a^2+b^2}$, $r_4 = 2b$, and $h = h_w$

$$h_w = \frac{Q}{2\pi KB} \log \frac{r_w\sqrt{a^2+b^2}}{2\ ab} \qquad \ldots\ldots(3.62c)$$

From equation (3.62b) and (3.62c) we get,

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{2ab}{r_w\sqrt{a^2+b^2}} \qquad \ldots\ldots\ldots(3.62d)$$

$$\text{or} \quad Q = \frac{2\pi KB(H - h_w)}{\log \frac{2ab}{\lambda_w \cdot \sqrt{a^2+b^2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.62e)$$

From equations(3.62a) and (3.62b) we get

$$H - h = \frac{Q}{2\pi KB} \log \frac{r_2 \; r_4}{r_1 \; r_3} \quad \ldots\ldots\ldots (3.62f)$$

$$\text{or } h = H - \frac{Q}{2\pi KB} \log \frac{r_2 \; r_4}{r_1 \; r_3} \quad \ldots\ldots\ldots\ldots (3.62g)$$

Equation (3.62e) gives the discharges and equation (3.62g) gives the piezometric levels. The discharge increases as the well moves closer to the boundaries. The equivalent radius of influence is given by $R' = \frac{2\,ab}{\sqrt{a^2+b^2}}$

3.63 <u>Well located in a quadrant formed by the intersection of two impervious boundaries</u> :

Let OX and OY be the impervious boundaries (Fig. 3.63). Let the well with a discharge Q be located at A (a, b).

An image well with a discharge Q is needed at B (-a, b) to replace the boundary OY. Similarly an image well with discharge Q is needed at D (a, -b) to replace the boundary OX. Another image well with a discharge Q is needed at C (-a,-b) to balance the drawdown caused by the image wells B and O along the extensions of the impervious boundaries OX and OY.

The combined flow equation for the group of wells can be written as,

$$h = \frac{Q}{2\pi KB} \log r_1, r_2, r_3, r_4 + C \quad \ldots\ldots (3.63a)$$

Considering a point on the external recharge boundary $h = H$, $r_1 \simeq r_2 \simeq r_3 \simeq r_4 \simeq R$

$$\text{or } H = \frac{Q}{2\pi KB} \log R^4 + C \qquad \text{.........(3.63b)}$$

Considering a point on the face of the real well, $h = h_w$, $r_1 = r_w$, $r_2 = 2a$, $r_3 = 2\sqrt{a^2+b^2}$, $r_4 = 2b$

$$\text{or } h_w = \frac{Q}{2\pi KB} \log 8\, r_w\, ab.\sqrt{a^2+b^2} + C \qquad \text{.....(3.63c)}$$

From equations (3.63b) and (3.63c) we get,

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{R^4}{8ab\sqrt{a^2+b^2} . r_w} \qquad \text{.......(3.63d)}$$

$$\text{or } Q = \frac{2\pi KB(H - h_w)}{\log \dfrac{R^4}{8ab\sqrt{a^2+b^2}.\ r_w}} \qquad \text{..........(3.63e)}$$

From equations (3.63a) and (3.63b) we get

$$H - h = \frac{Q}{2\pi KB} \log \frac{R^4}{r_1 . r_2 . r_3 . r_4} \qquad \text{.......(3.63f)}$$

$$\text{or } h = H - \frac{Q}{2\pi KB} \log \frac{R^4}{r_1 . r_2 . r_3 . r_4} \qquad \text{.......(3.63g)}$$

Equation (3.63e) gives the discharges and equation (3.63g) gives the piezometric levels.

The discharges increases as a and b increase. The equivalent radius of influence is $R' = \dfrac{R^4}{8ab\sqrt{a^2+b^2}}$. The problem is similar to the problem of a group of four wells placed in a circular water boundary.

3.64 <u>Influence of other natural boundaries</u> :

The pattern of image wells has been indicated in figure 3.64 for wells located close to the following types of boundaries:

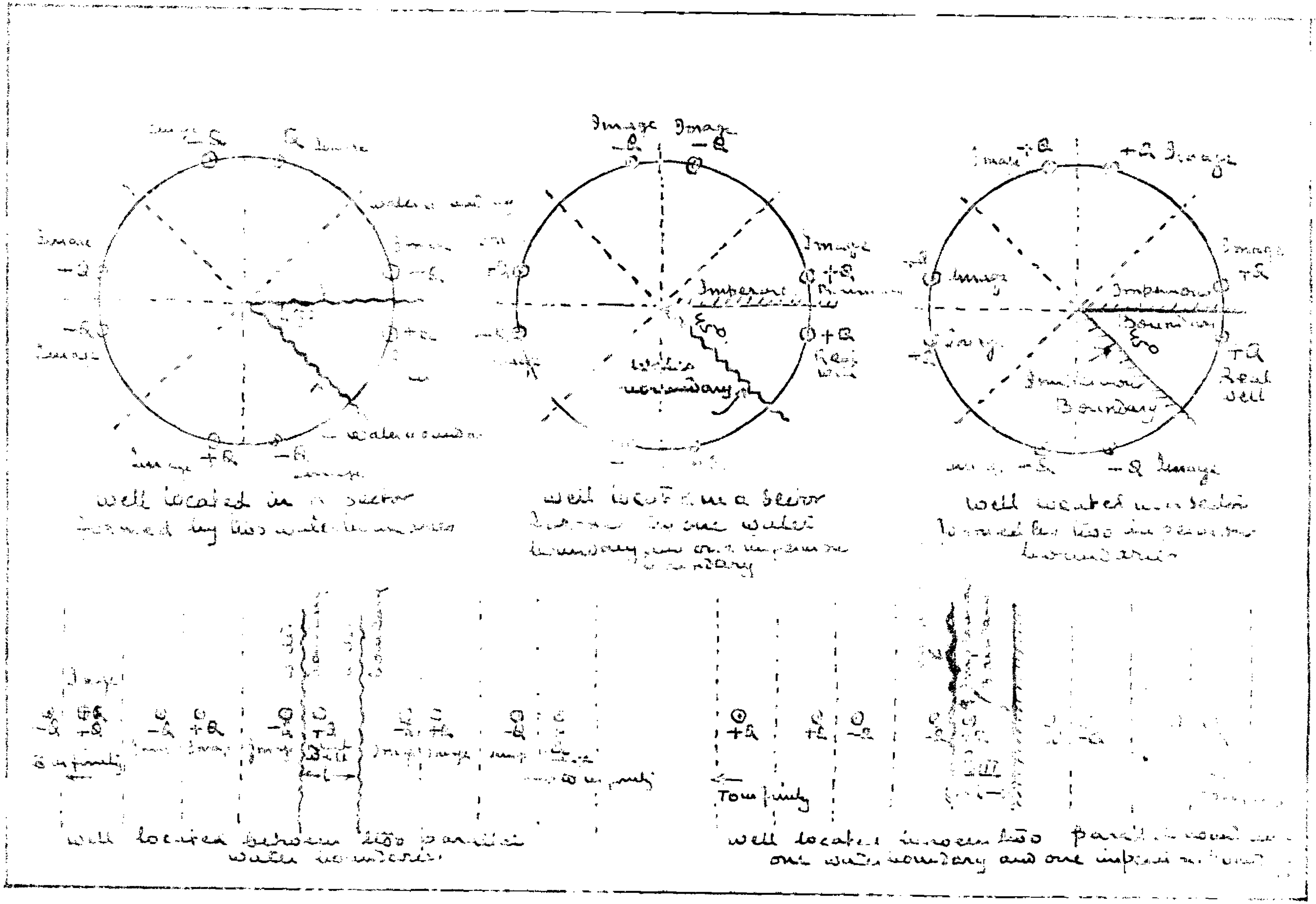

FIG - 3·64 - Disposition of image wells for real wells located in the area of natural boundaries

(a) Well located in a sector formed by two water boundaries intersecting at an acute angle.

(b) Well located in a sector formed by a water boundary meeting an impervious boundary at an acute angle.

(c) Well located in a sector formed by intersection of two impervious boundaries.

(d) Well lying in between two parallel water boundaries.

(e) Well lying in between one water boundary and one impervious boundary running parallel to each other.

Similarly, patterns of image wells can be formed to replace other closed or open areas formed by the intersections of water boundaries and impervious boundaries.

3.7 Influence of Natural flow in an aquifer on the behaviour of well :

All cases discussed earlier are based on the assumption that piezometric levels are static, when the well is not in operation. This assumes recharge at a constant potential, or under reservoir conditions. In nature, the ground water is under a continuous movement. It should therefore be of interest to study the influence of natural flow in an aquifer, on the behaviour of a well.

Flow equations :

Let the well be located at 0 (Fig.3.70). Let there be uniform flow with a velocity U parallel to the x-axis.

The complex potential for free flow towards a well is given by (Refer to para 2.34d)

$$W_1 = \phi_1 + i\psi_1 = \frac{Q}{2\pi B} \log z_1 + C_1$$ (Refer to eq. 2.46)

Let W_2 be the complex potential due to uniform velocity U in the aquifer,

$$\therefore \quad \frac{\partial \phi_2}{\partial x} = U \quad \text{or} \quad \phi_2 = Ux + \text{Const.}$$

$$\text{also} \quad \frac{\partial \psi_2}{\partial y} = U \quad \text{or} \quad \psi_2 = Uy + \text{Const.}$$

$$\therefore \quad W_2 = U.Z + C_2$$

The combined potential is gigen by,

$$W = W_1 + W_2 = U.Z + \frac{Q}{2\pi B} \log Z + C \quad \ldots\ldots \quad (3.71)$$

$$\text{or } \phi = U.x + \frac{Q}{2\pi B} \log r + C' \quad \ldots\ldots\ldots\ldots \quad (3.72)$$

$$\text{and } \psi = U.y + \frac{Q}{2\pi B} \theta + C'' \quad \ldots\ldots\ldots\ldots \quad (3.73)$$

<u>Stagnation Point:</u>

Stagnation point is the place where the natural velocity in the aquifer is balanced by radial velocity towards the well combined velocity is given by,

$$u = \frac{\partial \phi}{\partial x} = U + \frac{Q}{4\pi B} \cdot \frac{2x}{x^2+y^2} \quad \ldots\ldots\ldots \quad (3.74)$$

At the stagnation point $u = 0$, $y=0$, $x=x_0$

$$\therefore \quad U + \frac{Q}{4\pi B} \cdot \frac{2x_0}{x_0^2} = 0$$

$$\text{or} \quad x_0 = -\frac{Q}{2\pi BU} \quad \ldots\ldots\ldots \quad (3.75)$$

For Q = 1.5 cfs, B = 100 feet, U = 50 ft/year, x_0 =1510 feet.

<u>Water divide:</u> is the extreme limit or boundary upto which water is drawn by the well. There is no flow across the water divide. Naturally the water divide is a flow line passing through the stagnation point.

The stream function is given by

$$\psi = U.y + \frac{Q}{2\pi B}\,\theta + C'' \qquad \text{Ref. equation 3.73)}$$

At the stagnation point, $y = 0$ and $\theta = \pm\pi$

$$\therefore \quad \psi - C'' = \pm \frac{Q}{2B}$$

The equation of the water divide is therefore given by,

$$U.y + \frac{Q}{2\pi B}\,\theta = \pm \frac{Q}{2\ B} \qquad \text{........(3.76)}$$

For intercept of the water divide on the y - axis,

$$\theta = \pm \frac{\pi}{2}, \quad y = y_1$$

$$\text{or } y_1 = \pm \frac{Q}{4\ BU} \qquad \text{........(3.77)}$$

When Q = 1.5 cfs, B = 100 ft, U= 50 ft./year,

$$y = \pm \ 2370 \text{ ft.}$$

<u>Conclusions:</u> (a) Natural flow in aquiters serves as a source of recharge. It narrows down the region of influence and increases the discharge of the well. The increase in discharge is directly proportional to the velocity of natural flow in the aquifer. Incidentally, natural flow in the aquifer helps in stabilising the region of influence and establishing steady state conditions, quickly.

(b) Ground water velocities are generally of a very small order. Under normal conditions, velocities of the order of 50 ft. to 100 ft./year will have nominal influence in the flow pattern and discharge of the well. If the velocities are of a higher order, flow pattern may undergo substantial distortion and the influence of natural velocities may be analysed under the given set of conditions.

(c) When the ground water velocities are of a high order, the region of influence is in the form of a narrow strip. In such cases the wells can be placed very close to each other, at right angles to the direction of flow, without causing mutual interference between them. Whereas, the spacing in the direction of flow, will have to be very much larger to reduce the effects of mutual interference.

SINGLE WELL LOCATED AT THE CENTRE OF A CIRCULAR RECHARGE BOUNDARY

TABLE 3.11

INFLUENCE OF RADIUS OF INFLUENCE ON DISCHARGE

Data : ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft,
$KB = 0.107$ ft^2/sec.

Notes: ... Refer to equation 3.13.
Q_o refers to discharge for $R = 2000$ ft.
Results plotted in figure 3.11

R	$\text{Log} \frac{R}{r_w}$	Q (cfs)	$\frac{Q}{Q_o}$
200	6.68	2.03	1.35
500	7.60	1.78	1.19
1000	8.30	1.63	1.09
2000	8.98	1.50	1.00
3000	9.40	1.43	0.96
5000	9.90	1.36	0.91

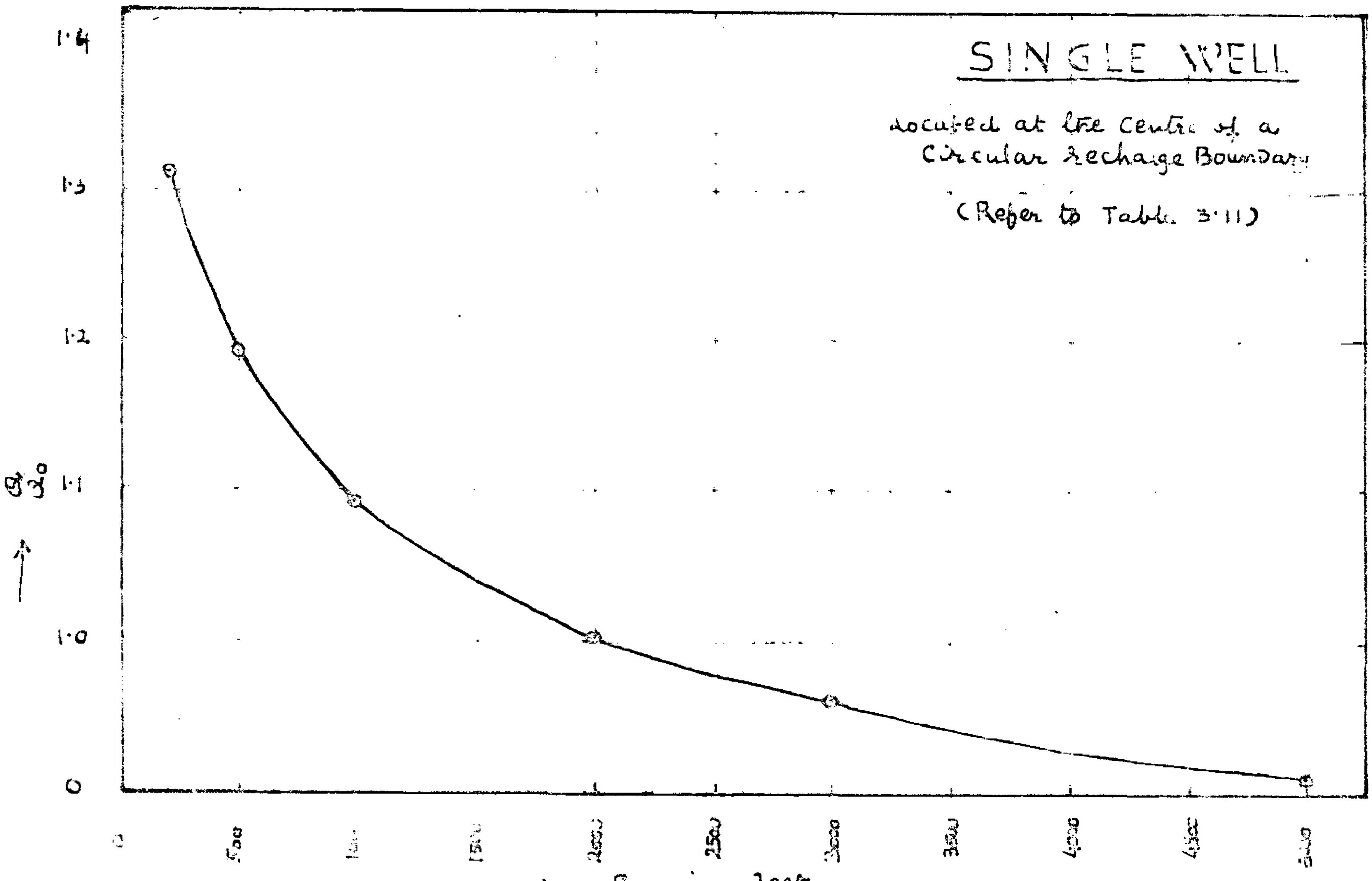

FIG 3.11 - Influence of Radius of Influence on Discharge

SINGLE WELL LOCATED AT THE CENTRE OF A CIRCULAR RECHARGE BOUNDARY

TABLE 3.12

INFLUENCE OF RADIUS OF WELL ON DISCHARGE

Data : ... R = 2000 ft, KB = 0.107 ft^2/sec

H = 20 ft, h_w = 0, r_w = 0.25 ft.

Note: ... Refer to equation 3.13

Q_o refers to discharge for r_w = 0.25 ft.

r_w' = radius of well.

Results plotted in fig. 3.12

r_w'	r_w'/r_w	$\log \frac{R}{r_w'}$	Q (cfs)	$\frac{Q}{Q_o}$
0.25	1.0	8.98	1.50	1.000
0.50	2.0	8.29	1.63	1.085
1.25	5.0	7.37	1.81	1.205
2.50	10.0	6.68	2.02	1.345
5.00	20.0	6.00	2.25	1.500
12.50	50.0	4.97	2.72	1.810
25.00	100.0	4.38	3.08	2.050

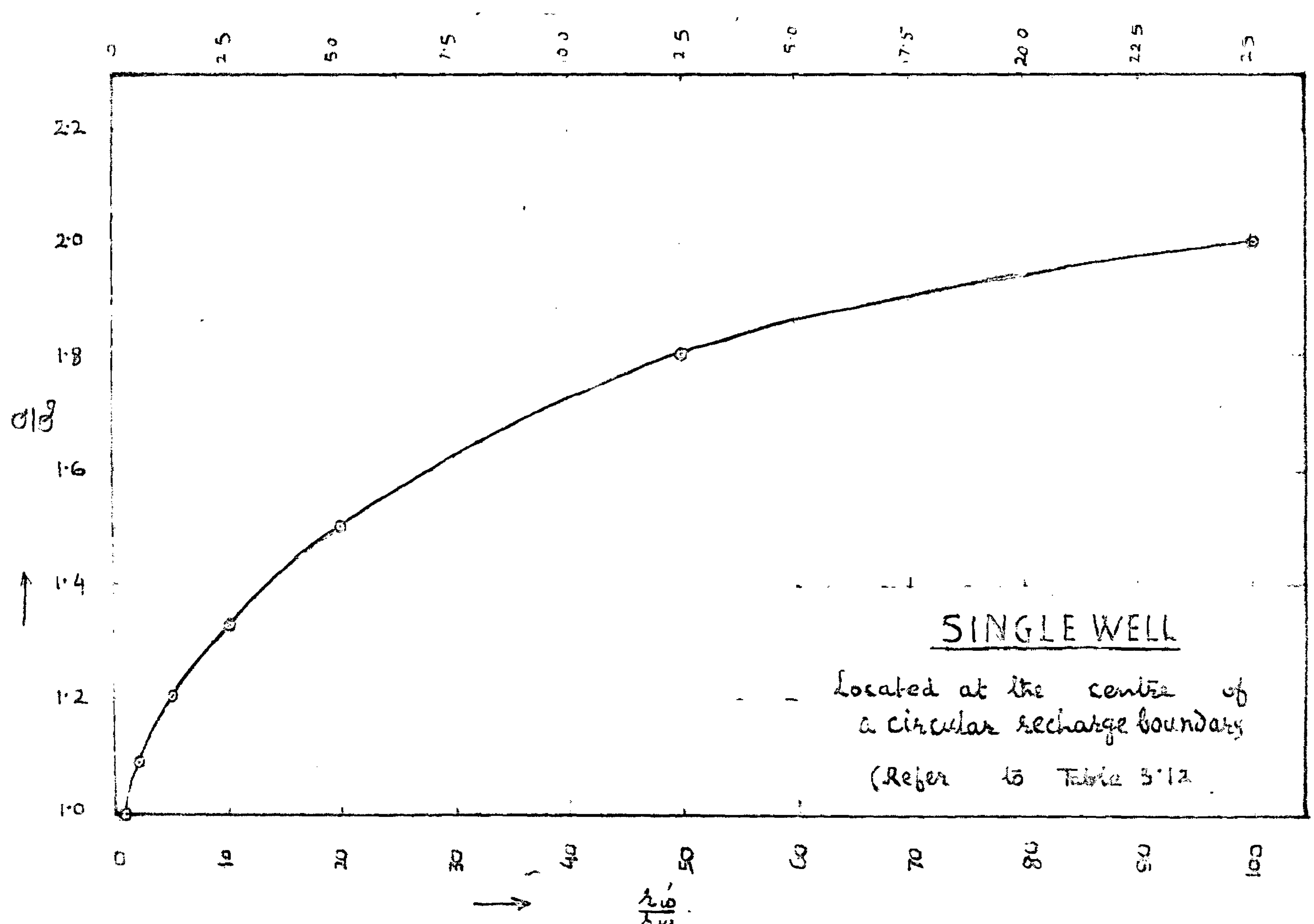

FIG 3·12 - Influence of radius of well on discharge

SINGLE WELL LOCATED AT THE CENTRE OF A CIRCULAR RECHARGE BOUNDARY

TABLE 3.13

INFLUENCE OF DISCHARGE ON DRAWDOWN CURVE
(Assuming that drawdown curves for different values of discharges are geometrically similar)

Data : ... $(H - h_w)_r = (R)_r$

$KB = 0.107$ ft^2/sec, $r_w = 0.25$ ft.

Notes ... Refer to equations 3.13 and 3.14.

r refers to radial distances along the radius of recharge boundary. Results plotted in fig.3.13

Q = 1.5 cfs, $H-h_w$ = 20 ft, R = 2000 ft		Q = 1.23 cfs, $H-h_w$ = 16 ft, R = 1600 ft		Q = 0.96 cfs, $H-h_w$ = 12 ft, R = 1200 ft		Q = 0.66 cfs, $H-h_w$ = 8 ft, R = 800 ft	
r (feet)	h (feet)	r (feet)	h (feet)	r (feet)	h (feet)	r (feet)	h (feet)
1	2	3	4	5	6	7	8
2000	20.0	1600	20.0	1200	20.0	-	-
1000	18.5	1000	19.2	1000	19.8	800	20.0
500	16.9	500	17.9	500	18.8	500	19.48
200	15.3	200	16.2	200	17.5	200	18.57
100	13.4	100	15.1	100	16.82	100	17.90
50	11.8	50	13.7	50	15.52	50	17.22
0.25	0	0.25	4.0	0.25	8.00	0.25	12.00

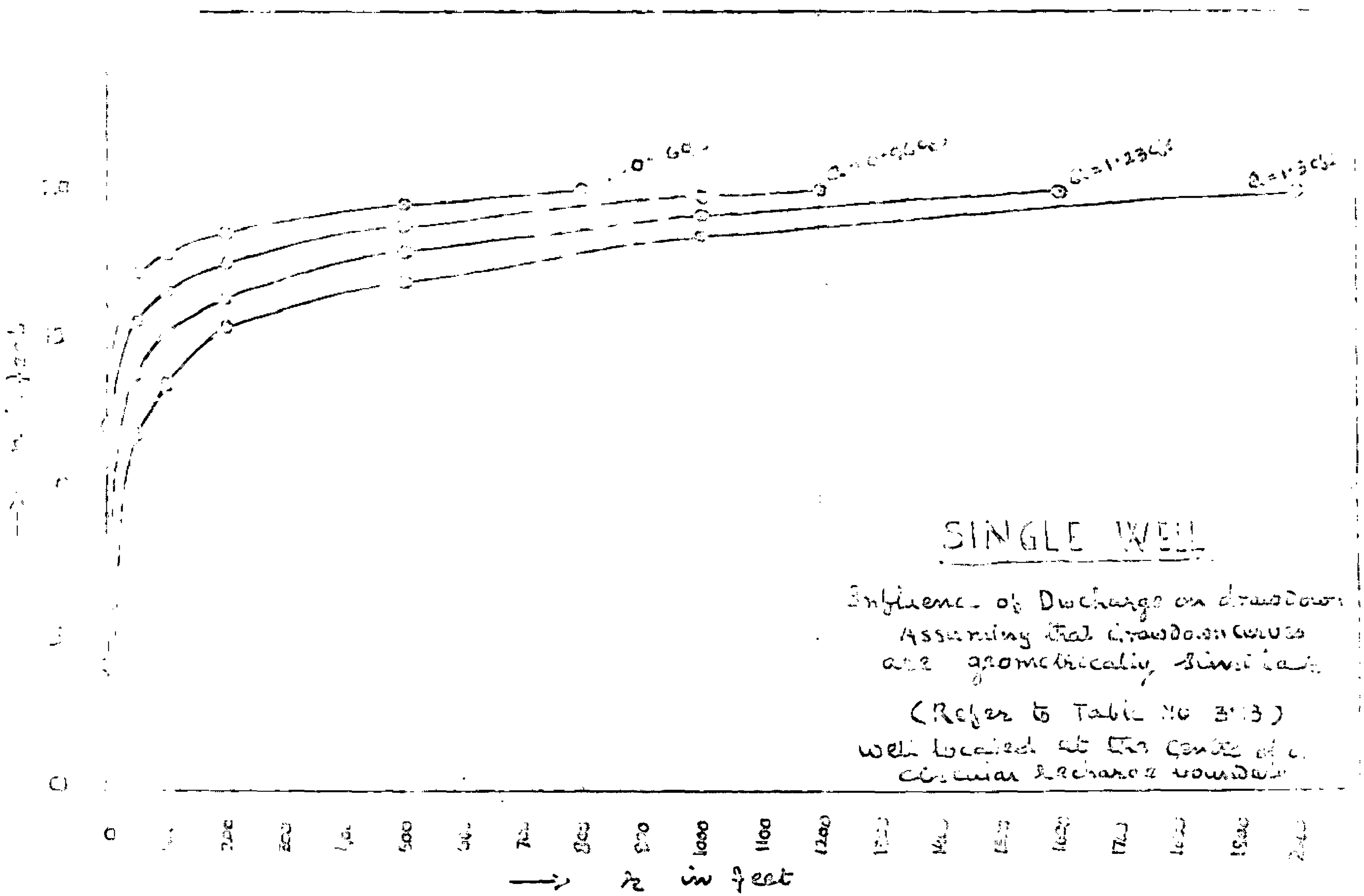

FIG 3.13 — SINGLE WELL- Drawdown Curves

SINGLE WELL LOCATED AT THE CENTRE OF A CIRCULAR RECHARGE BOUNDARY

TABLE 3.14

INFLUENCE OF RADIUS OF INFLUENCE ON DRAWDOWN CURVE

Data : ... $H = 20$ ft, $h_w = 0$, $KB = 0.107$ ft^2/sec

$r_w = 0.25$ ft.

Note: ... Refer to equation 3.14

Results plotted in Fig. 3.14

r refers to radial distances along the radius of recharge boundary

R = 2000 ft Q = 1.5 cfs		R = 1000 ft Q = 1.63 cfs		R = 500 ft Q = 1.78 cfs		R = 200 ft Q = 2.03 cfs	
r (feet)	h (feet)	r (feet)	h (feet)	r (feet)	h (Feet)	r (feet)	h (feet)
1	2	3	4	5	6	7	8
2000	20.0	-	-	-	-	-	-
1000	18.5	1000	20.0	-	-	-	-
500	16.9	500	18.3	500	20.0	-	-
200	15.3	200	16.1	200	17.6	200	20.0
100	13.4	100	14.5	100	15.8	100	18.0
50	11.8	50	12.8	50	14.0	50	15.9
0	0	0	0	0	0	0	0

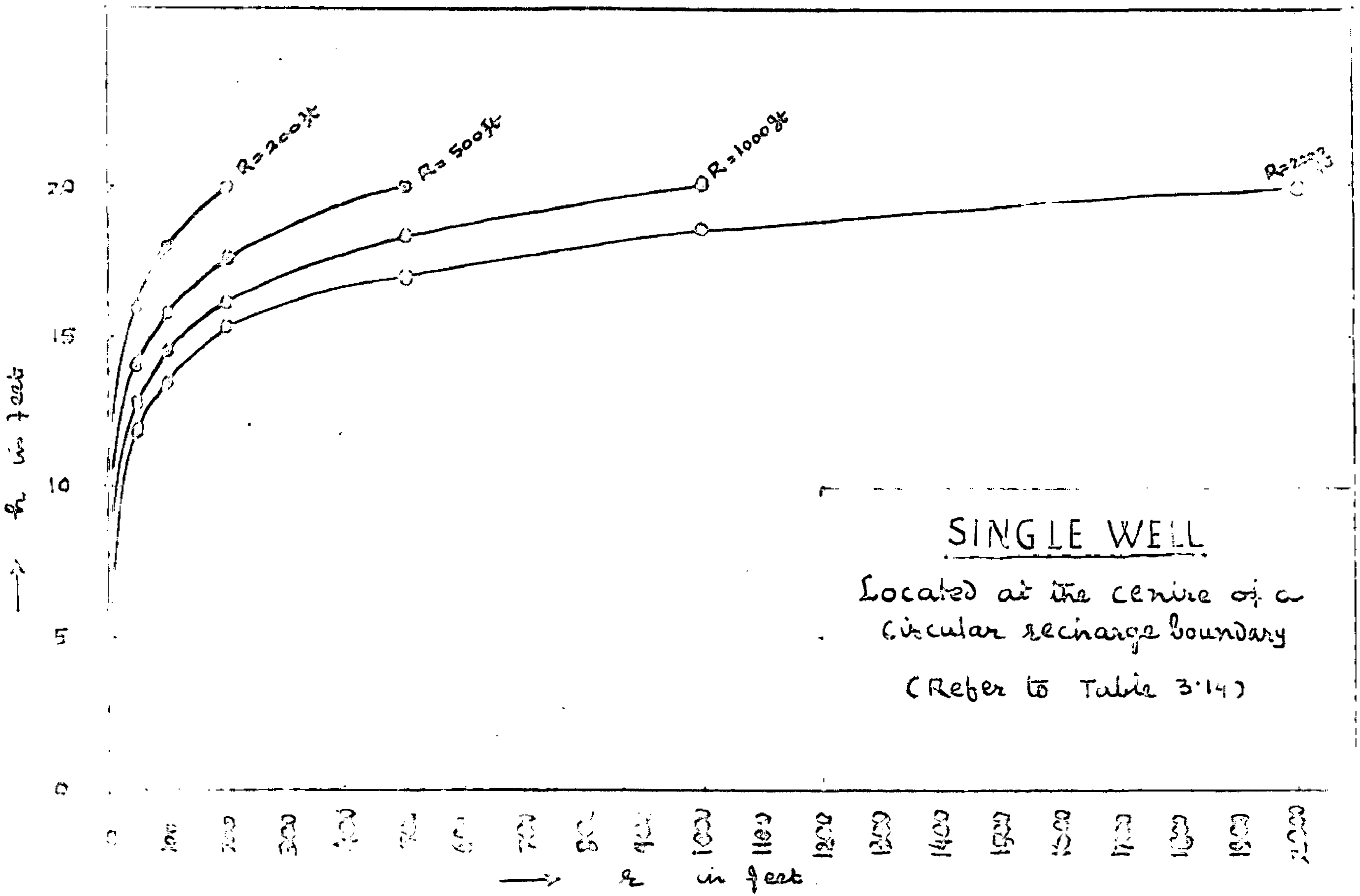

FIG 3·14 - Influence of radius of influence on drawdown curves. Maximum drawdown H-hw is same for all cases.

SINGLE WELL LOCATED AT THE CENTRE OF A CIRCULAR RECHARGE BOUNDARY

TABLE 3.16

INFLUENCE OF CHANGE OF DRAWDOWN ON DRAWDOWN CURVE

Data : ... $R = 2000$ ft, $H = 20$ ft, $KB = 0.107$ ft^2/sec.

$r_w = 0.25$ ft.

Note: ... Refer to equation 3.14

Results plotted in Fig. 3.16

r Refers to radial distances along the radius of recharge boundary.

$H-h_w$ = 20 ft, Q = 1.5 cfs		$H-h_w$ = 16 ft, Q = 1.2 cfs		$H-h_w$ = 12 ft, Q = 0.9 cfs		$H-h_w$ = 8 ft, Q = 0.6 cfs	
r (feet)	h (feet)	r (feet)	h (feet)	r (feet)	h (feet)	r (feet)	h (feet)
1	2	3	4	5	6	7	8
2000	20.0	2000	20.0	2000	20.0	2000	20.0
1000	18.5	1000	18.8	1000	19.1	1000	19.4
500	16.9	500	17.5	500	18.2	500	18.8
200	15.3	200	15.9	200	16.9	200	18.0
100	13.4	100	14.7	100	16.0	100	17.3
50	11.8	50	13.5	50	15.1	50	16.7
0	0	0	4.0	0	8.0	0	12.0

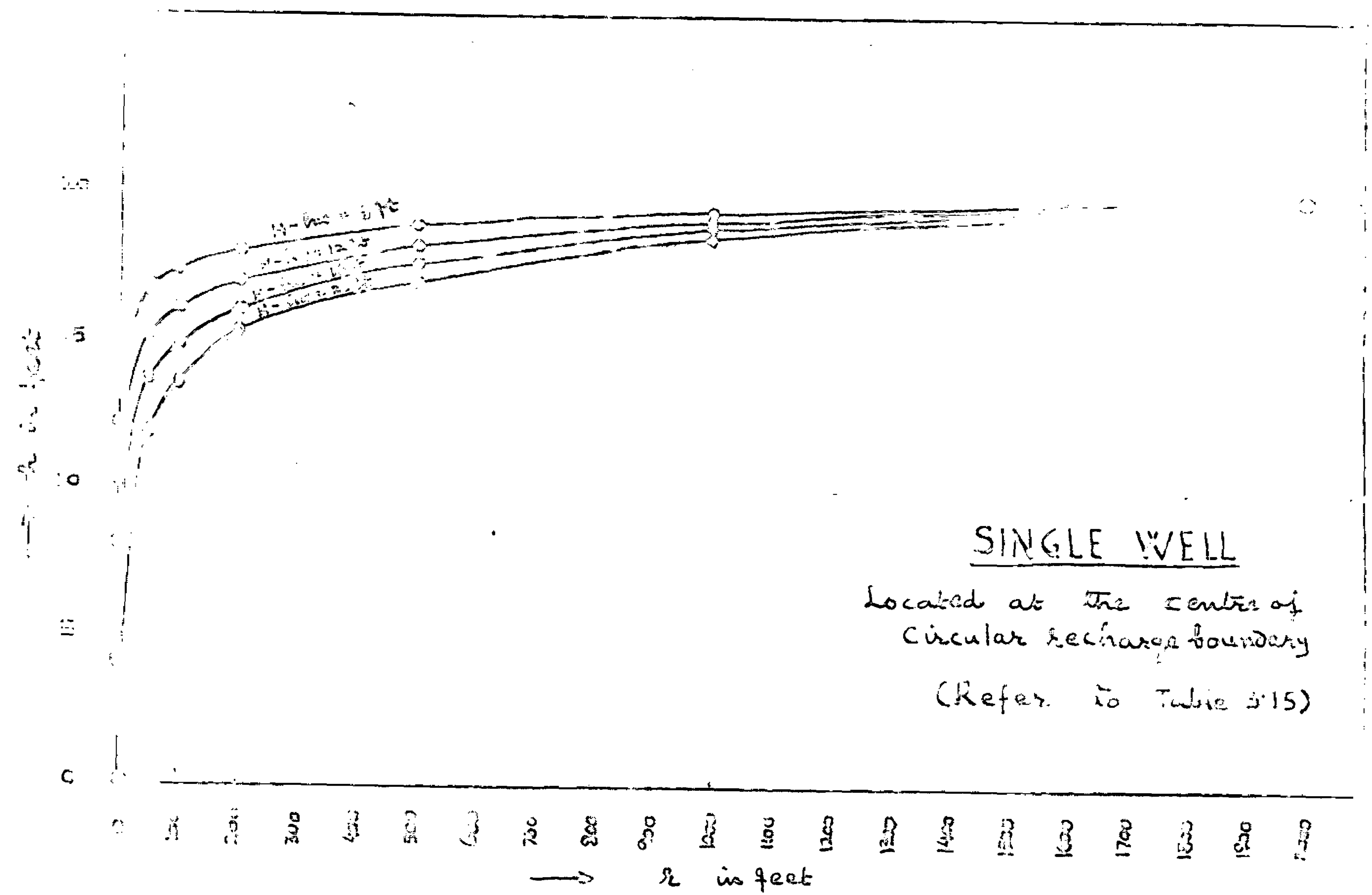

FIG 3·15 – Drawdown Curves for different values of (H-hw)

Table 3.21

Influence of Eccentricity on discharge

Data ... H = 20 ft, hw = 0 , rw = 0.25 ft.
KB = 0.107 ft.^{2}/sec.,

Note ... Refer to equation 3.24
Qo refers to discharge of a well located centrally in an island under same conditions. Results plotted in Fig.3.21.

e/R	R = 2000 ft. Qo = 1.5 cfs.		R = 1000 ft. Q = 1.63 cfs.		R = 500 ft. Q = 1.78 cfs.	
	Q (cfs.)	Q/Qo	Q (cfs.)	Q/Qo	Q (cfs.)	Q/Qo
0	1.50	1.00	1.63	1.00	1.78	1.00
0.1	1.50	1.00	1.63	1.00	1.78	1.00
0.2	1.51	1.00	1.63	1.00	1.78	1.00
0.3	1.52	1.01	1.64	1.01	1.80	1.01
0.4	1.53	1.02	1.66	1.02	1.82	1.02
0.5	1.55	1.03	1.69	1.04	1.85	1.04
0.6	1.58	1.05	1.72	1.06	1.89	1.06
0.7	1.62	1.08	1.77	1.09	1.95	1.10
0.8	1.70	1.13	1.86	1.14	2.05	1.15
0.9	1.84	1.23	2.04	1.25	2.27	1.28
0.95	2.03	1.35	2.26	1.38	2.56	1.44

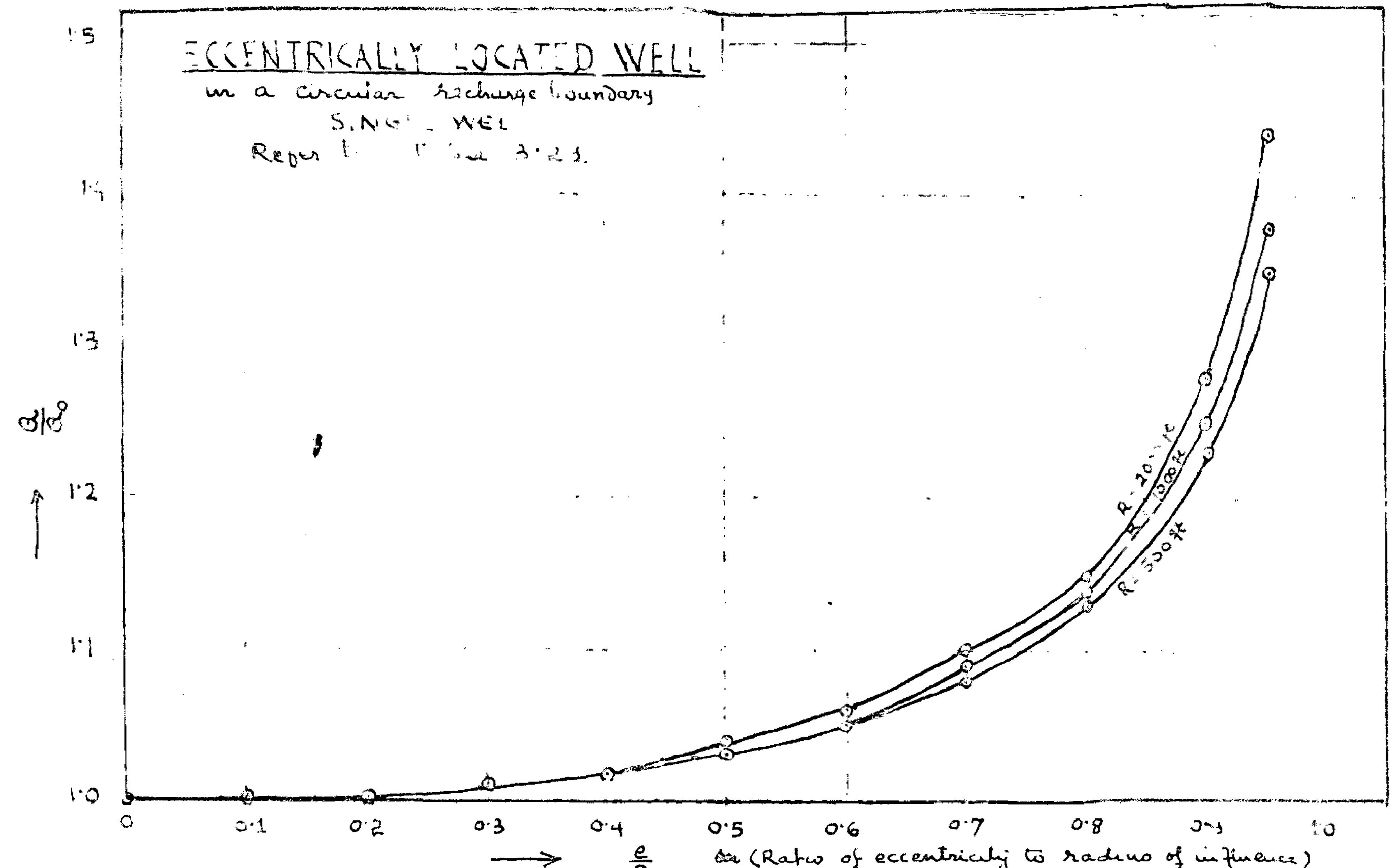

FIG 3.21 – Influence of eccentricity on discharge

Table 3.22

Influence of eccentricity on drawdown curve

Data ... $H = 20$ ft, $hw = 0$, $KB = 0.107\ ft^2/sec.$

$e = 800$ ft, $R = 2000$ ft, $Q = 1.53$ cfs.

$OM_2 = \frac{R^2}{e} = 5000$ ft.

Note ... Refer to equation 3.25.

Piezometric levels have been computed along B O M_1 A M_2 C

Draw down curve plotted in Fig.3.22.

r (feet)	r_2 (feet)	r_1 (feet)	h (feet)
1	2	3	4
2000	7000	2800	20.00
1200	6200	2000	19.51
200	5200	1000	18.13
0	5000	800	17.92
500	4500	300	15.94
700	4300	100	13.55
800	4200	0.25	0
900	4100	100	13.65
1000	4000	200	15.39
1500	3500	700	18.48
2000	3000	1200	20.0
4000	1000	3200	24.71
4500	500	3700	26.62
4750	250	3950	28.35

1	2	3	4
5000	0.25	4200	44.20
5250	250	4450	28.05
5500	500	4700	27.20
6000	1000	5200	25.80
7000	2000	6200	24.70
8000	3000	7200	24.05

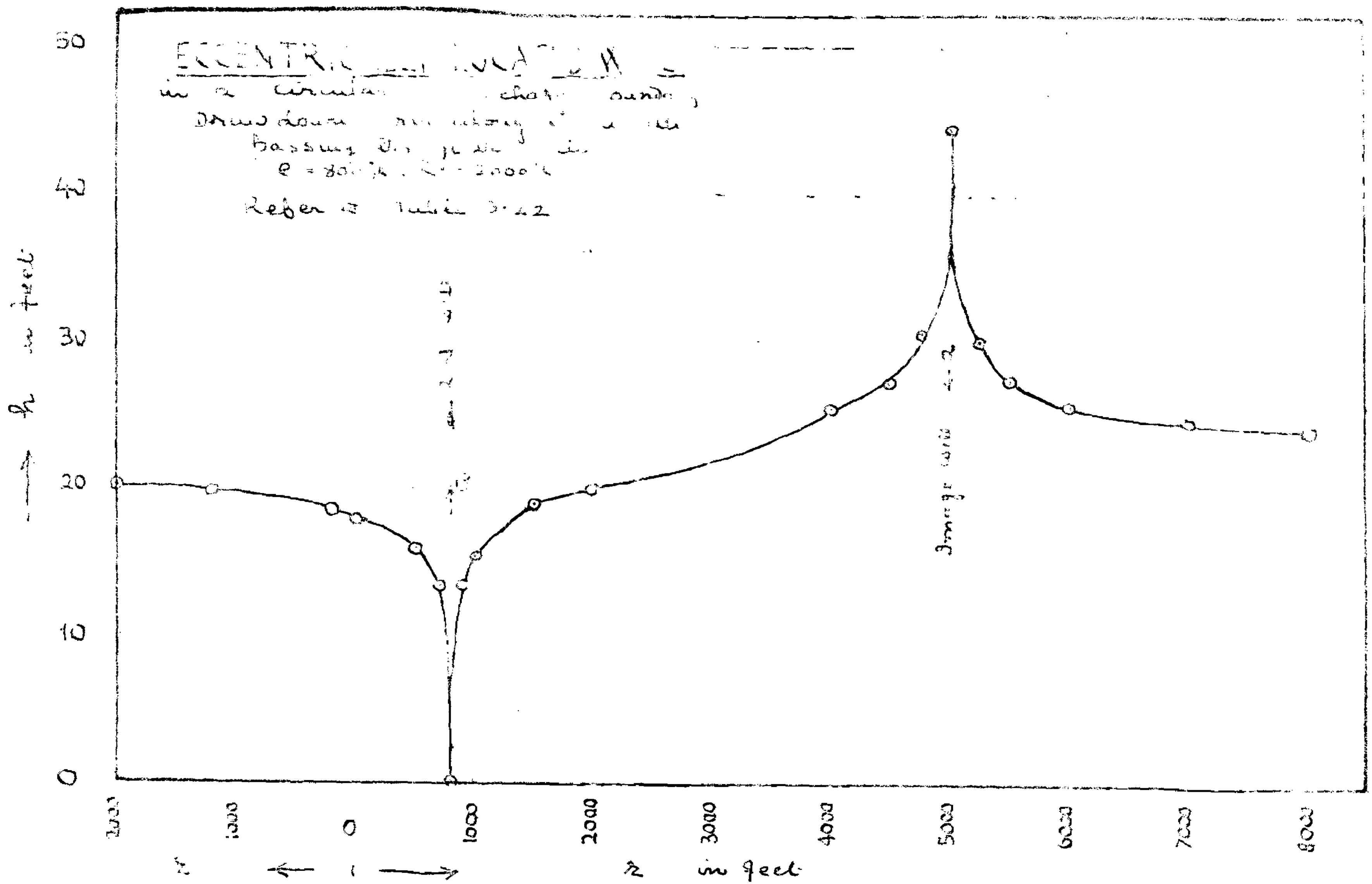

FIG 3·22 - Influence of eccentricity on drawdown curve.

WINGLE WELL LOCATED ON ONE SIDE OF AN IMPERVIOUS BOUNDARY

Table 3.41

Influence of boundary on discharge of the well

Data: ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft.

$KB = 0.107$ ft.^{2}/sec.

Note ... Refer to equation 3.44

Qo refers to disch·rge of a well located in a circular water boundary with R = 2000 ft.

Results plotted in figure 3.41.

a = distance of well from impervious boundary.

a (feet.)	R = 2000 feet.		R = 1000 ft.	
	Q (cfs.)	$\frac{Q}{Qo}$	Q (Cfs.)	$\frac{Q}{Qo}$
50	1.13	0.75	1.28	0.79
100	1.20	0.80	1.37	0.84
200	1.28	0.85	1.47	0.90
300	1.32	0.88	1.54	0.95
400	1.36	0.91	1.60	0.98
500	1.40	0.93	1.63	1.00

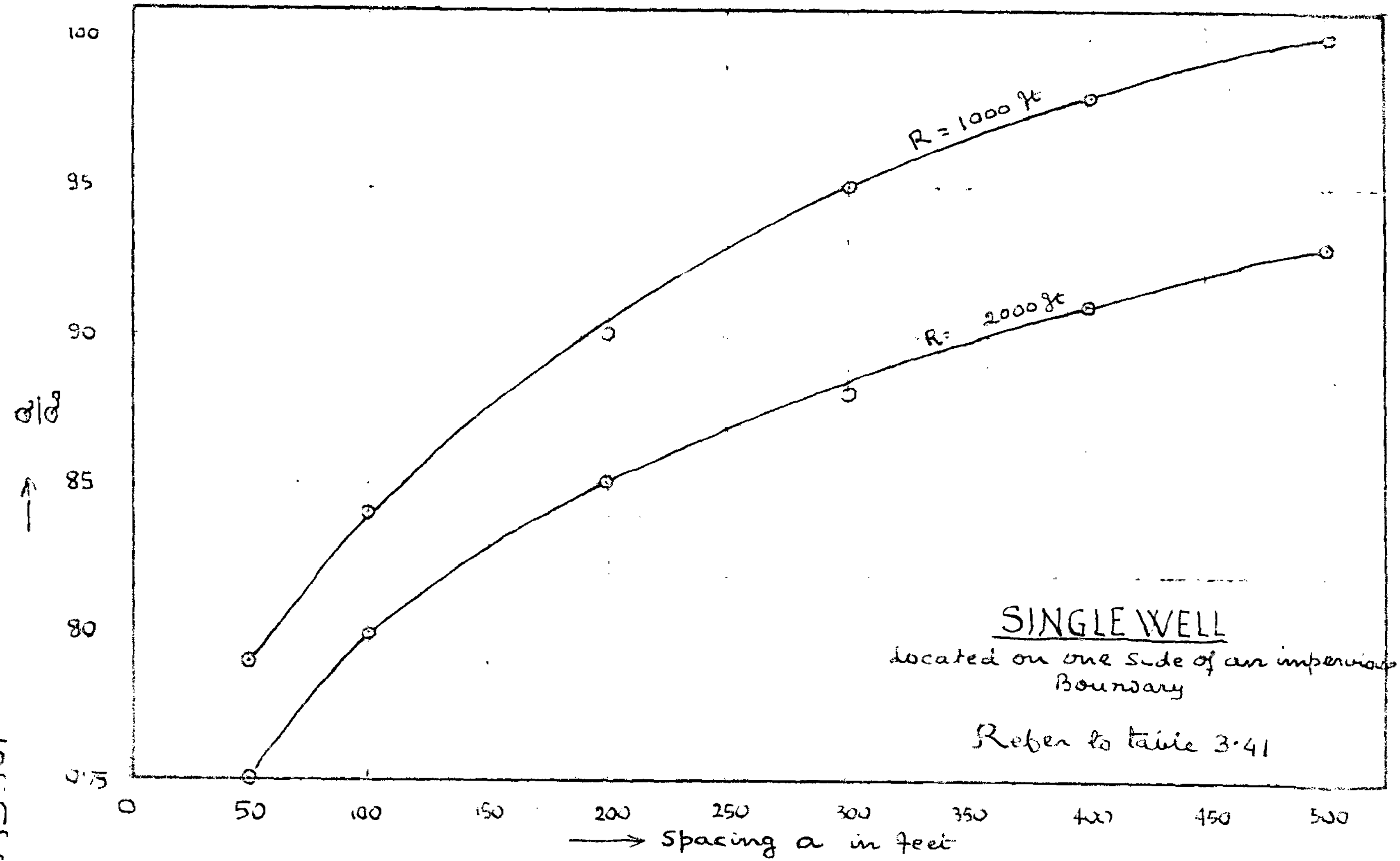

FIG 3·41 – Influence of impervious boundary on discharge of a well

Table 3.42

Influence of impervious boundary on drawdown curve

Data: ... H = 20 ft, hw = 0, rw = 0.25 ft, a = 50ft.
KB = 0.107 ft^2/sec., R = 2000 ft.

Note: ... Refer to equation 3.46
Piezometric levels have been computed along a line perpendicular to the impervious boundary and passing through the well.
Drawdown curve plotted in fig.3.41

x (feet)	r_1 (feet)	r_2 (feet.)	h
0	50	50	7.65
25	25	75	7.15
50	0.25	100	0
75	25	125	8.05
100	50	150	9.50
200	150	250	12.20
500	450	550	15.33
1000	950	1050	17.70
2000	1950	2050	20.00

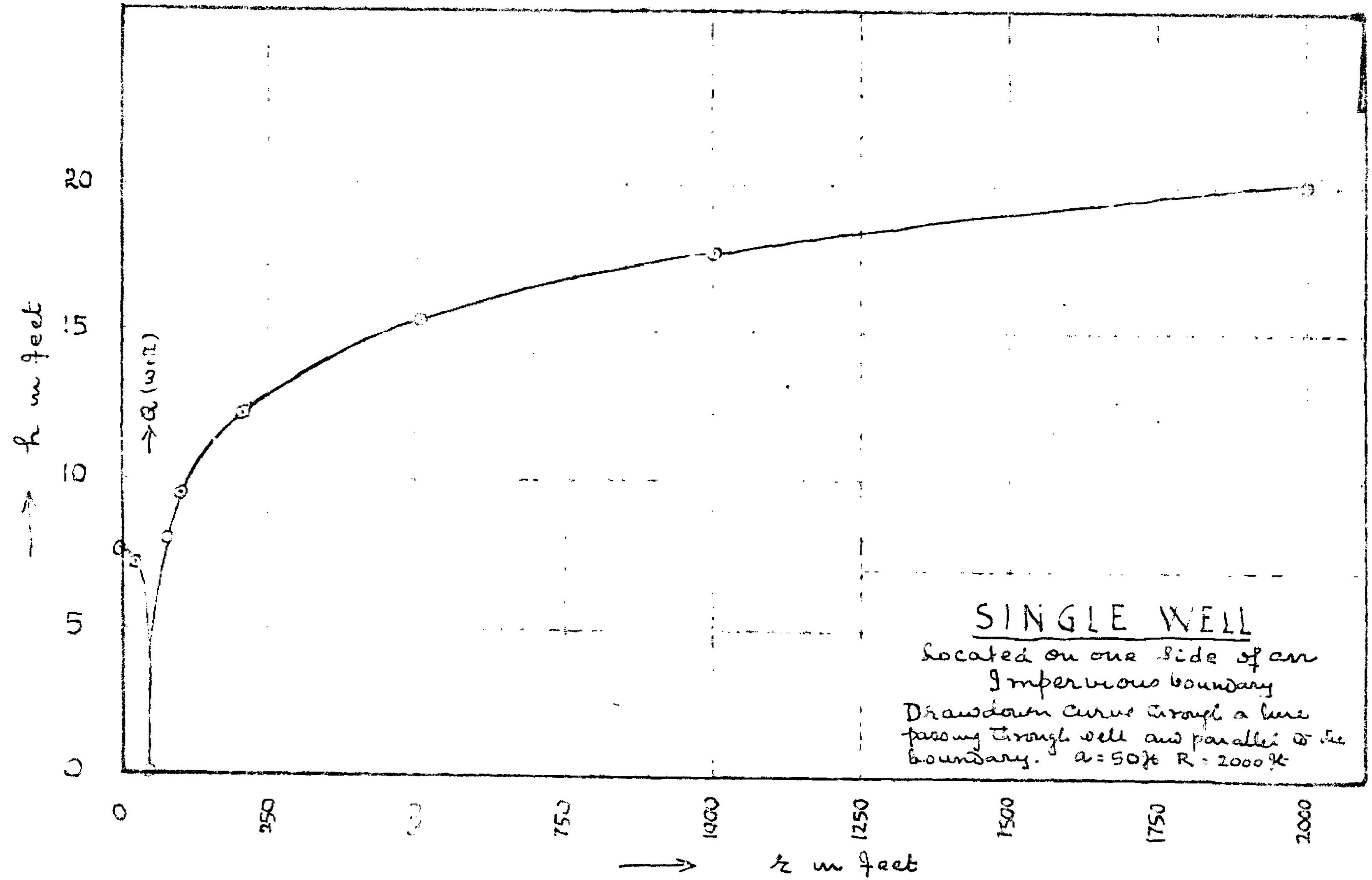

FIG. 3·42 Influence of impervious boundary on Drawdown Curve

SINGLE WELL LOCATED ON ONE SIDE OF AN INFINTE WATER BOUNDARY OR LINE DRIVE

Table 3.51

Influence of Water boundary on discharge

Data: ... H = 20 ft, hw = 0 , rw = 0.25 ft.

Note: ... Refer to equation 3.54

Qo refers to discharge of a well located in a circular island with R = 2000 ft.

Results plotted in Fig.3.51.

a = distance of a well from water boundary.

a (feet.)	100	200	500	1000	2000	5000
Q (cfs.)	2.02	1.83	1.63	1.50	1.40	1.28
$\frac{Q}{Qo}$	1.35	1.22	1.09	1.00	0.93	0.86

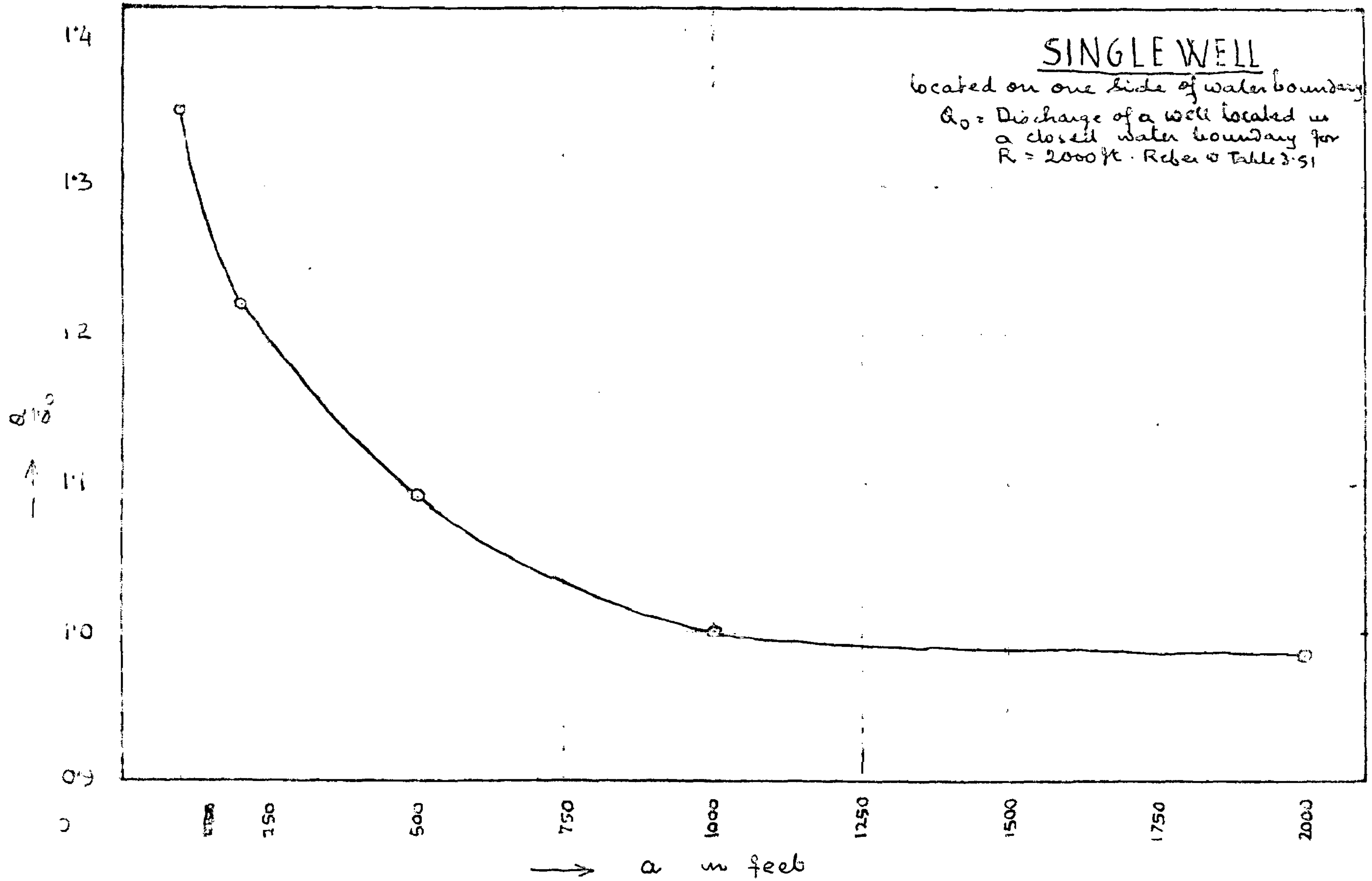

FIG - 3·51 Influence of distance from water boundary on discharges.

SINGLE WELL LOCATED ON ONE SIDE OF AN INFINITE WATER BOUNDARY OR LINE DRIVE

Table 3.52

Co-ordinates of Centres and radii of equipotential circles.

Data: ... $H = 20$ ft, $hw = 0$, $rw = 0.25$ ft., $Q = 1.5$ cfs.
$a = 1000$ ft, $KB = 0.107$ ft^2/sec.

Note: ... Refer to equation 3.56

h (feet)	m	Co-ordinates of centre (feet) $a(\frac{1+m}{1-m}), 0$	radius(feet) $\frac{2a\sqrt{m}}{1-m}$
20	1.0	∞ ,0	∞
19.5	0.637	4520,0	4380
19.0	0.407	2370,0	2180
18.0	0.165	1395,0	970
16.0	0.028	1055,0	339
14.0	0.0045	1010,0	135

SINGLE WELL LOCATED ON ONE SIDE OF ARE INFINITE WATER BOUNDARY OR LINE DRIVE

Table 3.53

Influence of water boundary on drawdown curve

Data: ... H = 20 ft, hw = 0, rw = 0.25 ft., Q = 1.6 cfs.
KB = 0.107 ft^2/sec., a = 1000 ft.

Note: ... Refer to equation 3.55 and 3.14.
Pierometric levels have been computed along axis of x.

h_1 = pierometric height of a point on the drawdown curve of real well.

h_2 = Pierometric height of a point on drawdown curve of image well.

h = pierometric height of a point on drawdown curve due to combined action.

Drawdown curves plotted in Fig.3.52.

x (feet)	r_1 (feet)	r_2 (feet)	h_1 (feet)	h_2 (feet.)	h (feet.)
1	2	3	4	5	6
-10000	11000	9000	23.78	16.67	20.45
- 5000	6000	4000	22.44	18.45	20.89
- 2000	3000	1000	20.88	21.54	22.30
- 1500	2500	500	20.46	23.11	23.57
- 1250	2250	250	20.22	24.65	24.87
- 1100	2100	100	20.11	26.66	26.77
- 1050	2050	50	20.04	28.20	28.24
- 1000	2000	0.25	20.00	40.00	40.00
- 950	1950	50	19.96	28.20	28.16

1	2	3	4	5	6
- 900	1900	100	19.89	26.66	26.55
- 750	1750	250	19.67	24.65	24.32
- 500	1500	500	19.34	23.11	22.45
0	1000	1000	18.46	21.54	20.00
500	500	1500	16.89	20.66	17.55
750	250	1750	15.35	20.33	15.68
900	100	1900	13.34	20.11	13.45
950	50	1950	11.80	20.04	11.84
1000	0.25	2000	0	20.00	0
1050	50	2050	11.80	19.96	11.76
1100	100	2100	13.34	19.89	13.23
1250	250	2250	15.35	19.78	15.11
1500	500	2500	16.89	19.54	16.44
2000	1000	3000	18.46	19.12	17.58
5000	4000	6000	21.55	17.56	19.11
10000	9000	11000	23.33	16.22	19.55

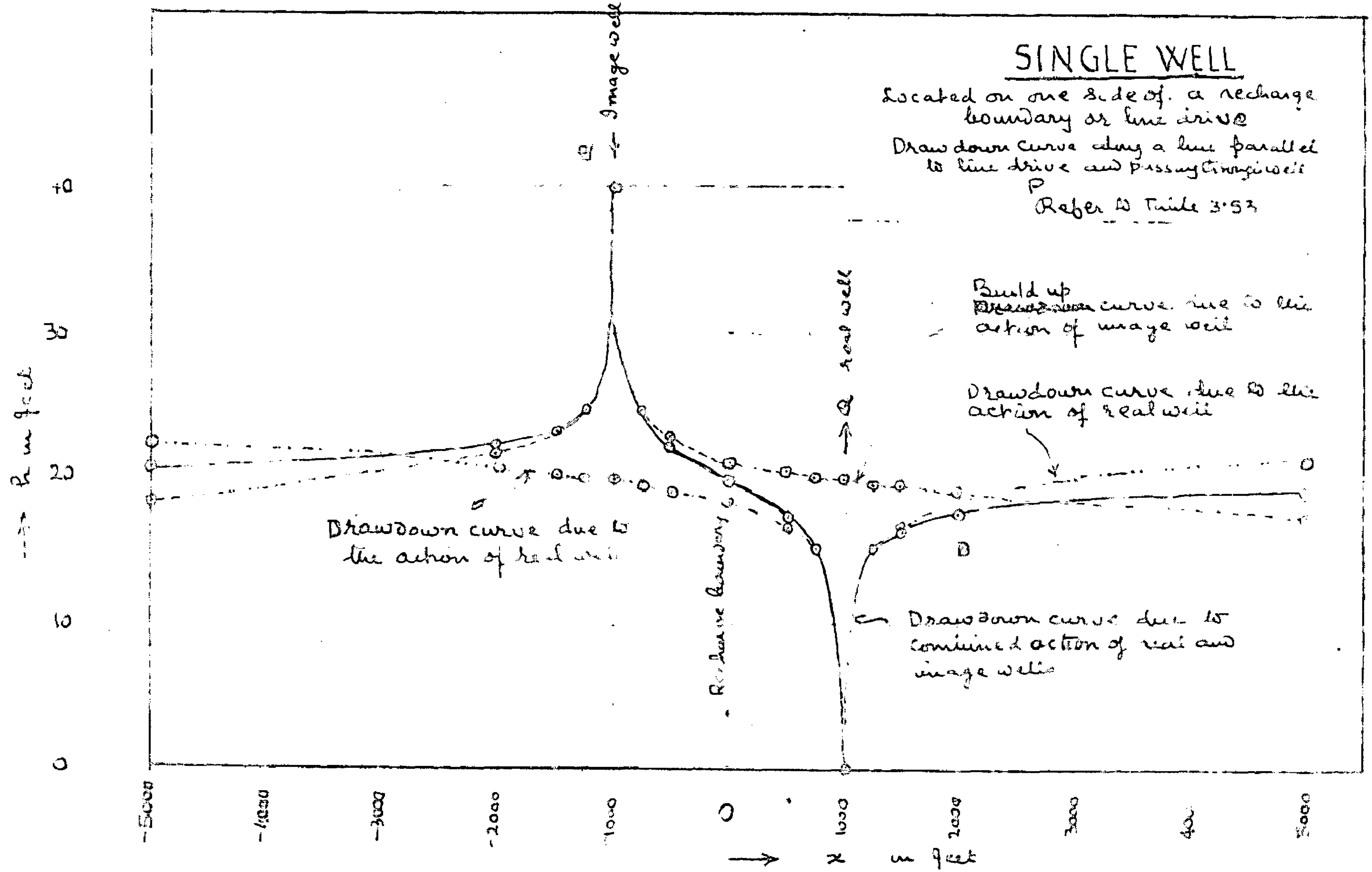

FIG-3·52 - Influence of water boundary on drawdown curve

CHAPTER - IV

MUTUAL INTERFERENCE BETWEEN WELLS LOCATED IN CONFINED AQUIFERS

4.0 When a single isolated well is placed in an aquifer and water is pumped out, it develops a region of influence. If another well is placed close to the first well, the regions of influence of the two wells overlap, leading to greater drawdown and reduction in discharge and overall efficiency of each well. Efficiency of the individual wells diminishes further, with the installation of every additional well in the area. This reduction in efficiency is due to mutual interference between wells. If a group of wells are placed in a straight line, the end wells suffer lesser interference than the intermediate wells, because the end wells are interfered with, from one side only, whereas, intermediate wells are intefered with, from both sides. If the group of wells are in the form of closed patterns, the wells located in the outer rings suffer lesser interference, than those in the inner rings. The interference increases, as the spacing of the well decreases and vice versa. Thus, the extent of interfernece depends on the spacing of the wells and their geometrical placing in the area.

Broadly the problem of interference between wells can be divided into following categories:

(a) Wells located in a closed water boundary-

Closed water boundary is in the form of a circular island or an alluvial aquifer with plentiful recharge at the boundary. The groups of wells in a closed boundary can further be classified into two categories-

(i) Small groups of wells, i.e. a group of wells occupying a small area of the closed water boundary. This normally happens in the earlier stages of development and drilling operations.

(ii) Group of wells spread over the whole area. This is the ultimate stage, and will occur in final stages of development.

(b) Wells located on one side of the straight recharge boundary or infinite line drive. The line drive may be in the form of a river canal, lake, reservoir or sea. The water - boundary is treated as infinite, if it very much longer than the total spread of the group of well.

The following cases have been analysed in the present study for steady flow in confined aquifers.

(a) Small group of wells in a closed water boundary-

(i) Two wells in a line

(ii) Three wells in a straight line,

(iii) Three wells forming a triangle,

(iv) Four wells forming a square

(v) Five wells - Four wells forming a square and one well at the centre.

(vi) Battery of 'n' wells arranged in a circle, with a given spacing with a given radius of circle.

(b) Groups of Wells on one side of a line drive,

(i) Two wells parallel to the line drive

(ii) Two wells at right angles to the line drive,

(iii) Three wells parallel to the line drive,

(iv) Single array of wells parallel to the line drive

(v) Double array of wells parallel ' ''ne drives,

with square placing

with staggered placing.

The implications of interforence between wells have been brought out in terms of reduction of discharge, increase in drawdown and influnece on the shape of the drawdown curve. Comparisons have been made with reference to a single well located in a circular boundary and the results have been illustrated by graphs.

Broadly the assumptions are the same as for steady radial flow towards a single well. In the case of wells located in a closed boundary the boundary has been assumed to be Circular or more or less circular with an average radius of influence R. The priermetric heights of points lying on the boundary are assumed to be equal or more or less equal with an average height H.

4.1. <u>Two wells located in an island or closed recharge boundary:</u>

Let the two wells he located at A $(\frac{a}{2}, 0)$ and B$(-\frac{a}{2}, 0)$ (Fig.4.10). Let the spacing between wells be a. Let r_1 and r_2 be the distances of any point P ~~given~~ from the centres of wells A and B respectively.

The Equation for steady radial flow towards a well in a confined aquifer is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{(Ref.Eqn.2.43)}$$

The combined flow equation for the two wells A and B can be written as,

$$h = \frac{Q_1}{2\pi KB} \log r_1 + \frac{Q_2}{2\pi KB} \log r_2 + C \quad \ldots.(4.11)$$

Considering a point on the face of well at A,

$$h_w = \frac{Q1}{2\pi KB} \log r_w + \frac{Q2}{2\pi KB} \log a + C \quad ----(4.12)$$

Considering a point on the face of well at B,

$$h_w = \frac{Q}{2 \quad KB} \log a + \frac{Q2}{2 \quad KB} \log r_w + C \ldots.(4.13)$$

Considering a point on the external boundary,

$$a << R, \quad r_1 \simeq r_2 \simeq R$$

$$H = \frac{Q1}{2\pi KB} \log R + \frac{Q2}{2\pi KB} \log R + C \quad \ldots\ldots.(4.14)$$

From equation (4.12) and (4.13) we get,

$$Q_1 = Q_2 \quad \ldots\ldots(4.15)$$

From equation (4.12) and (4.14) we get

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{R^2}{a\ r_w} \quad \ldots.(4.16)$$

$$\text{or } Q = \frac{2\pi KB\ (H - hw)}{\log \frac{R^2}{a\ r_w}} \quad \ldots\ldots(4.16\ b)$$

From equation (4.11) and (4.14) we get,

$$H - h = \frac{Q}{2\pi KB} \log \frac{R2}{r_1 r_2} \quad \ldots..(4.17a)$$

$$\text{or } h = H - \frac{Q}{2\pi KB} \log \frac{R^2}{r_1\ r_2} \quad \ldots..(4.17\ b).$$

Equation 4.16 gives the discharges ~~for different~~ and equation 4.17 can be used for computing the piezometric height for different points on the drawdown curve.

Computations:

Following computations have been done to illustrate the influence of different variables on mutual interference between two wells -

(a) Effect of Mutual interference of wells on discharge (table No.4.11, Fig. 4.11)

(b) Effect of mutual interference of wells on Draw-down curves (i) Draw down curve along a line passing through the two wells, (Table 4.12, Fig. 4.12).

(ii) Draw down curve along the water divide between the two wells. (Table 4.13, ~~Fig. 4.12~~).

~~(c) Disposition of the equipotential lines, (Fig.4.14)~~

Conclusions:

(a) Combined discharge of two wells placed in a group is more than the discharge of a single well, under identical conditions. Discharge of each well in the group is however less than the discharge of a single well.

(b) The efficiency of the wells diminishes as they come closer to each other and vice versa.

(c) The draw down caused by individual wells in the group, adds up linearly to give the draw down due to combined action of the two wells.

(d) A single well operating with a discharge equal to the combined discharge of two wells will have to a much greater drawdown.

(e) The equivalent radius of influence is given by $R' = \frac{R^2}{a}$ (Ref. equation 4.16)

4.2 Three wells located in an island or closed recharge boundary:

Case I :

Wells placed in a straight line with equal drawdown at the faces of all wells.

Let the three wells be located at A (a,0), D(0,0) and B (-a,0) (Refer to Fig.4.20). The discharge of the wells be Q_1, Q_2 and Q_3 respectively. Spacing between wells be 'a'. Let r_1, r_2, r_3 be the distances of any point $P(r, \theta)$ from the Centres of wells A, O and B respectively.

The equation for steady radial flow towards a well in a confined aquifer is given by

$$h = \frac{Q}{2\pi KB} \log r + C \quad \text{.....(ref. eqn. 2.43)}$$

The combined flow equation for the three wells can be written as :

$$h = \frac{Q}{2\pi KB} \log r_1 + \frac{Q}{2\pi KB} \log r_2 + \frac{Q}{2\pi KB} \log r_3 + C \quad ..(4.21)$$

Considering a point on the face of the well A,

$$h_w = \frac{Q_1}{2\pi KB} \log r_w + \frac{Q_2}{2\pi KB} \log a + \frac{Q_3}{2\pi KB} \log 2a + C \quad ...(4.22)$$

Considering a point on the face of the well at O,

$$h_w = \frac{Q_1}{2\pi KB} \log a + \frac{Q_2}{2\pi KB} \log r_w + \frac{Q_3}{2\pi KB} \log a + C \quad ....(4.23)$$

Considering a point on the face ot the well at B,

$$h_w = \frac{Q_1}{2\pi KB} \log 2a + \frac{Q_2}{2\pi KB} \log a + \frac{Q_3}{2\pi KB} \log r_w + C \quad \ldots\ldots (4.24)$$

Considering a point on the external boundary

$R >> a,\ r_1 \simeq r_2 \simeq r_3 = R,\ h = H;$

$$H = \frac{Q_1}{2\pi KB} \log R + \frac{Q_2}{2\pi KB} \log R + \frac{Q_3}{2\pi KB} \log R + C \quad \ldots\ldots (4.25)$$

Equation (4.22) and (4.24) give $Q_1 = Q_3$ ....(4.26)

Equations 4.22 and 4.23 give,

$$0 = \frac{Q_1}{2\pi KB} \log \frac{r_w}{a} + \frac{Q_2}{2\pi KB} \log \frac{a}{r_w} + \frac{Q_1}{2\pi KB} \log \frac{2a}{a}$$

$$= \frac{Q_1}{2\pi KB} \log \frac{2 r_w}{a} + \frac{Q_2}{2\pi KB} \log \frac{a}{r_w}$$

$$\text{or} \quad Q_1 = \frac{\log \frac{a}{r_w}}{\log \frac{a}{2 r_w}} \cdot Q_2 \quad \ldots\ldots\ldots\ldots\ldots (4.27)$$

Equation 4.23 and 4.25 give,

$$H - h_w = \frac{2Q_1}{2\pi KB} \log \frac{R}{a} + \frac{Q_2}{2\pi KB} \log \frac{R}{r_w} \quad \ldots\ldots\ldots\ldots (4.28)$$

Equation (4.26) and (4.27) give,

$$Q_1 = Q_3 \quad \frac{(H-hw)\ 2\pi KB \log \frac{a}{rw}}{2 \log\frac{R}{a} \cdot \log \frac{a}{r_w} + \log \frac{a}{2\ rw} \cdot \log\frac{R}{rw}} \quad \ldots\ldots\ldots (4.29a)$$

$$Q_2 = \frac{(H-hw)\ 2\pi KB \log \frac{a}{2rw}}{2 \log \frac{R}{a} \cdot \log \frac{a}{rw} + \log \frac{a}{2rw} \log \frac{R}{rw}} \quad \ldots\ldots\ldots (4.29b)$$

From equation 4.21 and 4.25 we get,

$$H - h = \frac{Q_1}{2\pi KB} \log \frac{R^2}{r_1 r_3} + \frac{Q_2}{2\pi KB} \log \frac{R}{r_2} \quad \ldots\ldots\ldots (4.210)$$

Equation 4.29 gives the discharges and equation 4.210 gives the piezometric heights for different points on the draw down curve.

Computations :

The following computations have been done to illustrate the effect of mutual interference between three wells in a straight line :

(a) Effect of mutual interference of wells on discharges (Table 4.21, Fig. 4.21)

(b) Effect of interference of wells on drawdown. Drawdown curve along a line passing through the wells. (Table 4.22, Fig. 4.22).

Conclusions :

(a) Combined discharge of the three wells placed in group is more than the discharge of a single well, under identical conditions. Discharge of each well in a group is however less than the discharge of a single well.

(b) The efficiency of the wells diminishes as they came closer to each other and vice versa. The reduction in the discharge of the end wells is less as compared to the central well. Radius of influence does not have much of effect on the ratio of discharges $\frac{Q_2}{Q_1}$.

(c) The draw down caused by individual wells adds up linearly to give the draw down due to combined action of the three wells.

(d) The area lying between the wells becomes a more or less level dewatered zone.

(e) A single well operating with a discharge equal to the combined discharge of three wells will have a much greater drawdown.

4.3 Three wells located in an island or closed recharge boundary:

Case II :

Wells placed in a straight line with equal discharge from all wells. Let the three wells be located at A(a, 0), O (0, 0) and B (-a, 0). The discharges of the wells be Q each. (Fig. 4.20) The heights of the piezometric levels at well faces be h_{w_1}, h_{w2} and h_{w_3} respectively. Spacing between wells be a. Let r_1, r_2 and r_3 be the distances of any point P from the centres of wells, A, O and B respectively.

The equation for steady radial flow towards a well in a confined aquifer is given by

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{(Refer equation 2.43)}$$

The combined flow equation for the wells can be written as,

$$h = \frac{Q}{2\pi KB} \log r_1 . r_2 . r_3 + C \quad \ldots\ldots\ldots\ldots (4.31)$$

Considering a point on the face of well A,

$$h_{w1} = \frac{Q}{2\pi KB} \log r_w + \frac{Q}{2\pi KB} \log a + \frac{Q}{2\pi KB} \log 2a$$

$$= \frac{Q}{2\pi KB} \log 2a^2 . r_w \quad \ldots\ldots\ldots\ldots (4.32)$$

Considering a point on the face of the well O,

$$h_{w2} = \frac{Q}{2\pi KB} \log a + \frac{Q}{2\pi KB} \log r_w + \frac{Q}{2\pi KB} \log a$$

$$= \frac{Q}{2\pi KB} \log a^2 . r_w \qquad \ldots\ldots\ldots\ldots(4.33)$$

Considering a point on the face of the well B,

$$h_{w3} = \frac{Q}{2\pi KB} \log 2a + \frac{Q}{2\pi KB} \log a + \frac{Q}{2\pi KB} \log r_w$$

$$= \frac{Q}{2\pi KB} \log 2a^2 r_w \qquad \ldots\ldots\ldots\ldots(4.34)$$

Considering a point on the external boundary we get,

$r >> a$, $r_1 \simeq r_2 \simeq r_3 \simeq R$, $h = H$

$$H = \frac{Q}{2\pi KB} \log R^3 \qquad \ldots\ldots\ldots\ldots\ldots\ldots(4.35)$$

Equations (4.32) and (4.34) give,

$$h_{w1} = h_{w3} \qquad \ldots\ldots\ldots\ldots\ldots(4.36)$$

From equations(4.32) and (4.33) we get,

$$h_{w1} - h_{w2} = \frac{Q}{2\pi KB} \log 2$$

or $$h_{w1} = \frac{Q}{2\pi KB} \log 2 + h_{w2} \qquad \ldots\ldots\ldots\ldots(4.37)$$

From equations (4.33) and (4.35) we get,

$$H - h_{w2} = \frac{Q}{2\pi KB} \log \frac{R^3}{a^2 r_w} \ldots\ldots(4.38)$$

From equations (4.31) and (4.35) we get,

$$H - h = \frac{Q}{2\pi KB} \log \frac{R^3}{r_1 r_2 r_3} \qquad \ldots\ldots\ldots(4.39)$$

Equation 4.38 gives the discharges and equation (4.39) gives the piezometric heights for different points on the drawdown curve . Equation 4.37 gives the drawdown in the side wells, when the draw down in the central well is known.

Computations:

Following computations have been done to illustrate the effect of mutual interference between wells -

(a) Effect of mutual interference of wells on discharges and drawdowns at faces of outer wells(Table 4.31 Fig. 4.31).

(b) Effect of mutual interference of wells on drawdown-drawdown curve along a line passing through wells-(Table 4.32, Fig. 4.32).

Conclusions:

(a) The discharge of the wells diminishes as they come closer to each other and vice versa.

(b) The drawdown of the central well is more than the drawdown of wells on the ends. The drawdown caused by individual wells, adds up linearly to give the combined drawdown of three wells.

(c) A single well operating with the combined discharge of the three wells in the group, gives three times the drawdown under identical conditions.

(d) The equivalent radius of influence is given by,

$$R' = \frac{R^3}{a^2} .$$

4.4 Three wells located in an island or closed recharge boundary:

Case III -

Wells forming a triangle. Drawdown equal for all wells.

Let the three wells be located at the verticles of a triangle (Fig.4.40). The spacing between the wells be 'a'. Let r_1, r_2 and r_3 be the distances of centres of wells from any point P. Let the discharges of the three wells be Q_1, Q_2 and Q_3 respectively.

The equation for steady radial flow toward a well, in a confined aquifer is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \text{ ....(Ref. equation 2.43)}$$

The combined flow equation for the three wells can be written as

$$h = \frac{Q_1}{2\pi KB} \log r_1 + \frac{Q_2}{2\pi KB} \log r_2 + \frac{Q_3}{2\pi KB} \log r_3 + C \text{ ....(4.41)}$$

Considering a point on the face of the well at A,

$$h_w = \frac{Q_1}{2\pi KB} \log r_w + \frac{Q_2}{2\pi KB} \log a + \frac{Q_3}{2\pi KB} \log a + C \text{ .....(4.42)}$$

Considering a point on the face of the well at B,

$$h_w = \frac{Q_1}{2\pi KB} \log rw + \frac{Q_2}{2\pi KB} \log rw + \frac{Q_3}{2\pi KB} \log a + C \text{ ....(4.43)}$$

Considering a point on the face of the well at C,

$$hw = \frac{Q_1}{2\pi KB} \log a + \frac{Q_2}{2\pi KB} \log a + \frac{Q_3}{2\pi KB} \log rw + C \text{ ......(4.44)}$$

Considering a point on the external boundary $R \gg a$,

$r_1 \simeq r_2 \simeq r_3 \simeq R$, $h = H$.

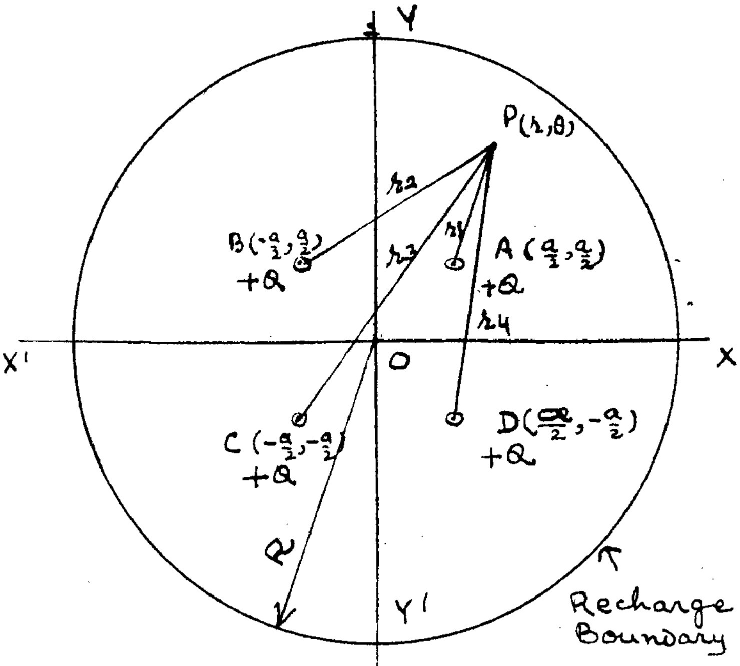
Y
P(r,θ)
r2
r1
B(-a/2, a/2)
+Q
r3
A(a/2, a/2)
+Q
r4
X'
O
X
C(-a/2, -a/2)
+Q
D(a/2, -a/2)
+Q
R
Y'
Recharge
Boundary

FIG - 4.50

P.T.O

Equation 4.48 is also identical to equation 4.39 for a group of three wells in a straight line. But equations 4.48 and 4.39 involve r_1, r_2 and r_3 for which the values in the two cases are different as such the extent of draw down and disposition of the equipotential lines in the two cases will be different.

Conclusions:

(a) If there are three wells in a group, drawing the same discharge, the extent of mutual interference depends on spacing and radius of influence. For a given spacing between wells, the geometry of the placing has no influence on discharge.

(b) For a given discharge from each well, the draw-down at the faces of individual wells, shape of the drawdown curve and disposition of equipotential lines, depends on the geometry of the placing.

4.5 Four Wells located in an island or closed recharge boundary:

Wells forming a square. Drawdowns at the faces of wells are equal.

Let the four wells be located at A($\frac{a}{2}$, $\frac{a}{2}$), B(- $\frac{a}{2}$, -$\frac{a}{2}$) C, (- $\frac{a}{2}$ - $\frac{a}{2}$), D($\frac{a}{2}$ - $\frac{a}{2}$). (Fig. 4.50). Let the side of the square be 'a'. Let r_1, r_2, r_3 and r_4 be the distance of any point from the centres of wells A, B, C and D respectively. Let the discharges of wells be Q_1, Q_2, Q_3 and Q_4.

The equation for steady radial flow towards a well in a confined aquifer is given by,

$$H = \frac{Q_1}{2\pi KB} \log R + \frac{Q_2}{2\pi KB} \log R + \frac{Q_3}{2\pi KB} \log R + C \quad \ldots\ldots (4.45)$$

From equation (4.42) and (4.43) we get $Q_1 = Q_2$

From equation (4.43) and (4.44) we get,

$Q_2 = Q_3$

or $Q_1 = Q_2 = Q_3$ ....(4.46)

From equations(4.42) and (4.45) we get,

$$H - hw = \frac{Q}{2\pi KB} \log \frac{R^3}{a^2 r_w} \quad \ldots\ldots (4.47a)$$

$$\text{or} \quad Q = \frac{2\pi KB (H - hw)}{\log \frac{R^3}{a^2 rw}} \quad \ldots\ldots\ldots (4.47b)$$

From equations (4.41) and (4.45) we get,

$$H - h = \frac{Q}{2\pi KB} \log \frac{R^3}{r_1 . r_2 . r_3} \quad \ldots\ldots\ldots (4.48a)$$

$$\text{or} \quad h = H - \frac{Q}{2\pi KB} \log \frac{R^3}{r_1 . r_2 . r_3} \quad \ldots\ldots\ldots (4.48b)$$

Equation (4.47) gives the discharges and equation 4.48 gives the peizometric heights of points on the drawdown curve.

It can be seen that equation 4.47 is identical to equation 4.38 which gives the discharges for a group of three wells in a straight line, drawing equal discharges. As such for a given data discharges of the two groups of wells will be identical. For effects of mutual interference on discharges refer to table 4.31 and Fig. 4.31.

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{(Ref. equation 2.43)}$$

The combined flow equation for the group of four wells is given by,

$$h = \frac{Q_1}{2\pi KB} \log r_1 + \frac{Q_2}{2\pi KB} \log r_2 + \frac{Q_3}{2\pi KB} \log r_3 + \frac{Q_4}{2\pi KB} \log r_4 + C \quad \ldots.(4.51)$$

Considering a point on the face of well at A,

$$h_w = \frac{Q_1}{2\pi KB} \log r_w + \frac{Q_2}{2\pi KB} \log a + \frac{Q_3}{2\pi KB} \log a\sqrt{2} \; \frac{Q_4}{2\pi KB} \log a + C \quad \ldots.(4.52)$$

Considering a point on the face of well at B,

$$h_w = \frac{Q_1}{2\pi KB} \log a + \frac{Q_2}{2\pi KB} \log r_w + \frac{Q_3}{2\pi KB} \log a + \frac{Q_4}{2\pi KB} \log a\sqrt{2} + C \quad \ldots(4.53)$$

Considering a point on the face of well at C,

$$h_w = \frac{Q_1}{2\pi KB} \log a\sqrt{2} + \frac{Q_2}{2\pi KB} \log a + \frac{Q_3}{2\pi KB} \log r_w + \frac{Q_4}{2\pi KB} \log a + C \quad \ldots(4.54)$$

Considering a point on the face of well at D,

$$h_w = \frac{Q_1}{2\pi KB} \log a + \frac{Q_2}{2\pi KB} \log a\sqrt{2} + \frac{Q_3}{2\pi KB} \log a + \frac{Q_4}{2\pi KB} \log r_w + C \quad \ldots(4.55)$$

From equations 4.52 and 4.54 we get, $Q_1 = Q_3$

From equations 4.53 and 4.55 we get, $Q_2 = Q_4$

From equations 4.52 and 4.53 we get, $Q_1 = Q_2$

or, $Q_1 = Q_2 = Q_3 = Q_4 = Q$ ....(4.56)

Considering a point on the external boundary,

$R \gg a, \; r_1 \simeq r_2 \simeq r_3 \simeq r_4 \simeq R$

$$H = \frac{Q}{2\pi KB} \log R^4 + C \quad \ldots\ldots\ldots\ldots(4.57)$$

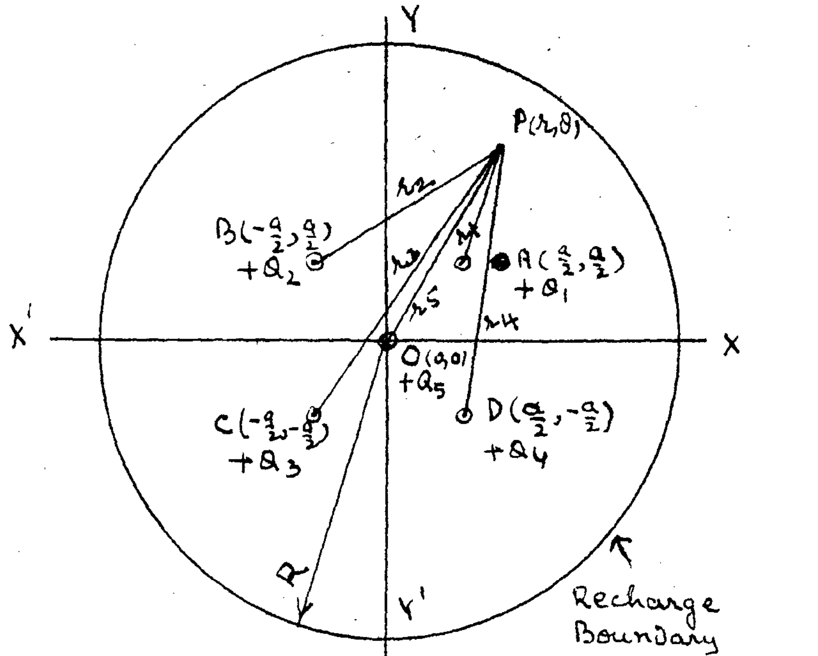
Y
P(r,θ)
r2
B(-a/2, a/2)
+Q2
r3
r1
A(a/2, a/2)
+Q1
r5
r4
X'
X
O(0,0)
+Q5
D(a/2, -a/2)
+Q4
C(-a/2, -a/2)
+Q3
R
Y'
Recharge
Boundary

FIG - 4·60

and spacing between wells remain unchanged.

If the wells are placed in any irregular pattern with non uniform spacing, the discharges from wells are different.

(d) The disposition of the equipotential lines, shape of the drawdown curve, and drawdown at the faces of wells depend on the discharge and geometrical placing of the wells.

(i) Wells with equal discharges and equal spacing between them can have different drawdowns at the faces of wells depending on the geometry of the placing.

(ii) Wells with equal discharges and non-uniform spacing will have different draw downs at the faces of wells.

(iii) Wells with different discharges, but equal spacing between them will have different drawdowns at the faces of wells.

(e) Equivalent radius of influence $R' = \frac{R^4}{a^3}$.

4.6 Five Wells located in an island or a closed recharge Boundary :

Four wells forming a square and one well at the Centre. Equal drawdown at the faces of all wells.

Let the wells be located at A $(+\frac{a}{2}, \frac{a}{2})$, B$(-\frac{a}{2}, \frac{a}{2})$ C $(-\frac{a}{2}, -\frac{a}{2})$, D$(\frac{a}{2}, -\frac{a}{2})$ and O(0,0)(Fig.4.60). Let the side of the square be 'a'. Let r_1, r_2, r_3, r_4 and r_5 be the distances of any point P from the Centres of wells A,B,C, D, O respecti-

From equations (4.52) and (4.57) we get,

$$H-h_w = \frac{Q}{2\pi KB} \log \frac{R^4}{a^{3/2}\ r_w} \qquad \text{......(4.58a)}$$

$$\text{or } Q = \frac{2\pi KB\ (H-h_w)}{\log \frac{R^4}{a^{3/2}\ r_w}} \qquad \text{......(4.58b)}$$

From equations (4.51) and (4.57) we get,

$$H - h = \frac{Q}{2\pi KB} \log \frac{R^4}{r_1 \cdot r_2 \cdot r_3 \cdot r_4} \qquad \text{......(4.59a)}$$

$$h = H - \frac{Q}{2\pi KB} \log \frac{R^4}{r_1 \cdot r_2 \cdot r_3 \cdot r_4} \qquad \text{......(4.59b)}$$

Equation 4.58 gives the discharges and equation 4.59 giv the piezometric heights for points on the draw down curve.

Computations:

Computations illustrating influence of mutual interference of wells on discharges have been given in Table 4.51 and the results have been plotted in Fig. 4.51.

Conclusions:

(a) For a given set of conditions, the discharge decreases with closer spacing and vice versa.

(b) For a given drawdown, the discharges of all wells in a group are equal, if placed in the form of a square. The geometrical placing of the square in the recharge boundary has no influence on discharge.

(d) If the wells are placed in an open geometrical pattern, the discharges of different wells in the group are different, even if the drawdown vely. Let the discharges of wells be Q_1, Q_2, Q_3, Q_4 and Q_5.

The equation for steady radial flow towards a well in a confined aquifer is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \quad \text{.........(Ref. eqn. 2.43)}$$

The combined flow equation for the group of five wells is given by,

$$h = \frac{Q_1}{2\pi KB} \log r_1 + \frac{Q_2}{2\pi KB} \log r_2 + \frac{Q_3}{2\pi KB} \log r_3 + \frac{Q_4}{2\pi KB} \log r_4 + \frac{Q_5}{2\pi KB} \log r_5 + C \quad \text{...........(4.61)}$$

Considering points on the faces of wells A, B, C, D, and O we get the following equations,

$$h_w = \frac{Q_1}{2\pi KB} \log r_w + \frac{Q_2}{2\pi KB} \log a + \frac{Q_3}{2\pi KB} \log a\sqrt{2} + \frac{Q_4}{2\pi KB} \log a + \frac{Q_5}{2\ \ KB} \log \frac{a}{\sqrt{2}} + C \quad \text{..............(4.62)}$$

$$h_w = \frac{Q_1}{2\pi KB} \log a + \frac{Q_2}{2\pi KB} \log rw + \frac{Q_3}{2\pi KB} \log a + \frac{Q_4}{2\pi KB} \log a\sqrt{2} + \frac{Q_5}{2\pi KB} \log \frac{a}{\sqrt{2}} + C \quad \text{..................(4.63)}$$

$$h_w = \frac{Q_1}{2\pi KB} \log a\sqrt{2} + \frac{Q_2}{2\pi KB} \log a + \frac{Q_3}{2\pi KB} \log r_w + \frac{Q_4}{2\pi KB} \log a + \frac{Q_5}{2\pi KB} \log \frac{a}{\sqrt{2}} + C \quad \text{.............(4.64)}$$

$$h_w = \frac{Q_1}{2\pi KB} \log a + \frac{Q_2}{2\pi KB} \log a\sqrt{2} + \frac{Q_3}{2\pi KB} \log a + \frac{Q_4}{2\pi KB} \log r_w + \frac{Q_5}{2\pi KB} \log \frac{a}{\sqrt{2}} + C \quad \text{..........(4.65)}$$

$$h_w = \frac{Q_1}{2\pi KB} \log \frac{a}{\sqrt{2}} + \frac{Q_2}{2\pi KB} \log \frac{a}{\sqrt{2}} + \frac{Q_3}{2\pi KB} \log \frac{a}{\sqrt{2}} + \frac{Q_4}{2\ \ KB} \log \frac{a}{\sqrt{2}} +$$

$$\frac{Q_5}{2\pi KB} \log r_w + C \quad \ldots\ldots\ldots\ldots\ldots(4.66)$$

From equations(2.62) and (2.64) we get, $Q_2 = Q_4$

From equations (2.63 and (2.65) we get, $Q_1 = Q_3$

From equations (2.62) and (2.63) we get, $Q_1 = Q_2$

$$\therefore Q_1 = Q_2 = Q_3 = Q_4 \quad \ldots\ldots\ldots\ldots(4.67a)$$

From equations (2.62) and (2.66) we get,

$$Q_1 = Q_5 \frac{\log \dfrac{a}{\sqrt{2}\ r_w}}{\log \dfrac{a}{4\sqrt{2}\ r_w}} \quad \ldots\ldots\ldots(4.67b)$$

Considering a point on the external boundary,

$h = H$, $r_1 \simeq r_2 \simeq r_3 \simeq r_4 \simeq r_5 \simeq R$.

$$H = \frac{Q_1}{2\pi KB} \log R^4 + \frac{Q_5}{2\ \ KB} \log R + C \quad \ldots\ldots\ldots(4.68)$$

From equations(2.68) and 2.66 we get,

$$H - h_w = \frac{Q_1}{2\pi KB} \log \frac{4R^4}{a^4} + \frac{Q_5}{2\pi KB} \log \frac{R}{r_w} \ldots\ldots(4.69)$$

Equations(2.67) and (2.68) give,

$$Q_1 = \frac{2\pi KB(H-h_w) \log \dfrac{a}{\sqrt{2}\ r_w}}{4 \log \dfrac{\sqrt{2}R}{a} \log \dfrac{a}{\sqrt{2}\ r_w} + \log \dfrac{R}{r_w} . \log \dfrac{a}{4\sqrt{2}\ r_w}} \quad \ldots\ldots(4.610a)$$

$$Q_5 = \frac{2\pi KB(H-h_w) \log \dfrac{a}{4\sqrt{2}\ r_w}}{4 \log \dfrac{\sqrt{2}\ R}{a} \log \dfrac{a}{\sqrt{2}\ r_w} + \log \dfrac{R}{r_w} \log \dfrac{a}{4\sqrt{2}\ r_w}} \quad \ldots\ldots(4.610b)$$

From equations (2.61) and (2.68) we get,

$$H-h = \frac{Q_1}{2\pi KB} \log \frac{R^4}{r_1 . r_2 . r_3 . r_4} + \frac{Q_5}{2\pi KB} \log \frac{R}{r_5} \quad \dots (4.611a)$$

$$\text{or } h = H - \frac{Q_1}{2\pi KB} \log \frac{R^4}{r_1 . r_2 . r_3 . r_4} + \frac{Q_5}{2\pi KB} \log \frac{R}{r_5} \quad \dots (4.611b)$$

Equation 2.610 gives the discharges and equation 2.611 gives the piezometric heights for points on the drawdown curve.

Computations :

Computations illustrating the influence of mutual interference of wells on discharges have been given in Table 4.61. ~~The results have been plotted in Fig. 4.61.~~

Conclusions :

(a) For equal drawdowns at the faces of wells, the discharges of outer wells are more than the discharge of well located at the centre.
The radius of influence does not have any influence on the ratio $\frac{Q_5}{Q_1}$.
The geometrical location of the group of wells in the recharge boundary does not have any influence on the discharges.

(b) The drawdown at any point, shape of the drawdown curve and disposition of equipotential lines depends on the geometry of the group of wells and its location in the recharge boundary.

4.70 Fi~~ve~~ Wells located in an island or a closed recharge Boundary:

~~From~~ Four wells forming a square and one well at the Centre. All wells have equal discharge.

Let the wells be located at A ($\frac{a}{2}$, $\frac{a}{2}$), B($-\frac{a}{2}$, $\frac{a}{2}$) C ($-\frac{a}{2}$, $-\frac{a}{2}$), D($\frac{a}{2}$, $-\frac{a}{2}$) and O (0,0)(Fig.4.70). Let the side of the square be 'a'. Let r_1, r_2, r_3, r_4, r_5 be the distances of any point P from the centres of wells A,B,C, D, O respectively. Let Q be the discharge of each of wells. Let h_{w1}, h_{w2}, h_{w3}, h_{w4}, h_{w5} be the drawdowns at the faces of wells.

The equation for steady radial flow towards a well in a confined aquifer is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \quad \text{.........(Ref. eqn. 2.43)}$$

The combined flow equation for the group of fine wells is given by,

$$h = \frac{Q}{2\pi KB} \log r_1 r_2 r_3 r_4 r_5 + C \quad \text{......(4.71)}$$

Considering points on the faces of wells, A, B, C, D, O we get the following equations,

$$h_{w1} = \frac{Q}{2\pi KB} \log a^4 r_w + C \quad \text{.....(4.72a)}$$

$$h_{w2} = \frac{Q}{2\pi KB} \log a^4 r_w + C \quad \text{.....(4.72b)}$$

$$h_{w3} = \frac{Q}{2\pi KB} \log a^4 r_w + C \quad \text{.....(4.72c)}$$

$$h_{w4} = \frac{Q}{2\pi KB} \log a^4 r_w + C \quad \text{.....(4.72d)}$$

$$hw_5 = \frac{Q}{2\pi KB} \log \frac{a^4}{4} rw + C \quad .....(4.73)$$

From equations 4.72 we get,

$$hw_1 = hw_2 = hw_3 = hw_4 \quad .....(4.74)$$

From equations (4.72a) and (4.73) we get,

$$h_{w1} = hw_5 + \frac{Q}{2\pi KB} \log 4 \quad .....(4.75)$$

Considering a point on the external boundary,

$$h = H, \; r_1 \simeq r_2 \simeq r_3 \simeq r_4 \simeq r_5 \simeq R$$

$$H = \frac{Q}{2\pi KB} \log R^5 \quad .....(4.76)$$

From equations (4.73) and (4.76) we get,

$$H-hw_5 = \frac{Q}{2\pi KB} \log \frac{4 R^5}{a^4 r_w} \quad .....(4.77a)$$

$$\text{or} \quad Q = \frac{2\pi KB (H-hw_5)}{\log \frac{4 R^5}{a^4 r_w}} \quad .....(4.77b)$$

From equations (4.71) and (4.76) we get,

$$H-h = \frac{Q}{2\pi KB} \log \frac{R^5}{r_1 \cdot r_2 \cdot r_3 \cdot r_4 \cdot r_5} \quad .....(4.78a)$$

$$\text{or} \; h = H - \frac{Q}{2\pi KB} \log \frac{R^5}{r_1 \cdot r_2 \cdot r_3 \cdot r_4 \cdot r_5} \quad .....(4.78b)$$

Equations 4.77 gives the discharges and equation 4.78 gives the piezometric heights for points on the draw-down curve. Equation (4.75) gives the drawdowns at outer wells when the drawdown at the Central well is known.

Computations:

Computations illustrating the influence of mutual interference of wells on discharges have been given in Table 4.71. ~~The results have been plotted in Fig. 4.71.~~

Conclusions :

(a) When the discharge of all wells is equal, the drawdown in the Central well is more than the drawdown in the outer wells. Other effects of interference are same as for groups of three and four wells.

(b) The extent of drawdown at the faces of wells, shapes of drawdown curves and dispositions of equipotential lines will vary with the geometry of location, even when the discharges of all wells and spacing between them continue to remain the same.

(c) The equivalent radius of influence $R' = \frac{4R^5}{a^4}$.

4.8 A Battery of wells located in a closed recharge boundary:

Let r be the radius of the battery circle (Fig.4.80). Let the number of wells be n, equally spaced along the circumberence of the battery circle. Let the spacing between adjoining wells be $a = 2\,r \sin\frac{\pi}{n}$. Let the drawdowns at the faces of wells be equal. Let r_1, r_2, r_3 ......r_n be the distances of any point P from the centres of wells. Let Q_1, Q_2, Q_3 ....Q_n be the discharges of wells.

The equation for steady radial flow towards a well in a confined aquifer is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{(Ref. eqn. 2.43)}$$

The combined flow equation for the group of n wells is given by,

$$h = \frac{Q_1}{2\pi KB} \log r_1 + \frac{Q_2}{2\pi KB} \log r_2 + \ldots\ldots \frac{Q_n}{2\pi KB} \log r_n + C \qquad \ldots\ldots(4.81)$$

By considering the points on the faces of wells n equations can be obtained to give, $Q_1 = Q_2 = Q_3 \ldots\ldots Q_n = \text{say } Q$ .....(4.82)

The combined flow equation can therefore be rewritten as

$$h = \frac{Q}{2\pi KB} \log r_1 . r_2 . r_3 \ldots\ldots r_n + C \qquad \ldots\ldots\ldots(4.83)$$

Considering a point on the face of the well at A we get,

$h = h_w,$

$r_1 = r_w$

$r_2 = AB = 2r \sin \frac{\pi}{n}$

$r_3 = AC = 2\, r \sin \frac{2\pi}{n}$

$r_4 = AD = 2\, r \sin \frac{3\pi}{n}$

$r_n = 2\, r \sin (n-1) \frac{\pi}{n}$

or $h_w = \frac{Q}{2\pi KB} \log rw.\ 2r \sin \frac{\pi}{n} .\ 2r \sin \frac{2\pi}{\pi} \ldots 2r \sin (n-1) \frac{\pi}{n} + C$

$$= \log rw. \sout{n-1.}r^{n-1}.2\sin.\frac{\pi}{n}\ .2\sin \frac{2\pi}{n} \ldots 2 \sin(n-1)\frac{\pi}{n} + C \qquad \ldots\ldots(4.84)$$

Considering a point on the external boundary,

$h = H,\ r_1 \simeq r_2 \ \ldots\ldots \simeq r_n \simeq R,$

$$H = \frac{Q}{2\pi KB} \log R^n + C \qquad \ldots\ldots\ldots\ldots\ldots\ldots(4.85)$$

From equations (2.84) and (2.85) we get,

$$H-h_w = \frac{Q}{2\pi KB} \log \frac{R^n}{r_w . r^{n-1} 2 \sin \frac{\pi}{n} . 2 \sin \frac{2\pi}{n} \ldots 2 \sin (n-1) \frac{\pi}{n}}$$

$$= \frac{Q}{2\pi KB} \log \frac{R^n}{r^n} . \frac{r}{r_w} \frac{1}{2 \sin \frac{\pi}{n} . 2 \sin \frac{2\pi}{n} . 2 \sin \frac{3\pi}{n} \ldots 2 \sin (n-1) \frac{\pi}{n}}$$

$$= \frac{Q}{2\pi KB} \left[n \log \frac{R}{r} + \log \frac{r}{r_w} - \sum_{m=1}^{m=n-1} 2 \sin \frac{m\pi}{n} \right] \ldots (4.86a)$$

$$\text{or } Q = \frac{2\pi KB (H - h_w)}{n \log \frac{R}{r} + \log \frac{r}{r_w} - \sum_{m=1}^{m=n-1} 2 \sin \frac{m\pi}{n}} \quad \ldots\ldots (4.86b)$$

From equations (2.83) and (2.85) we get,

$$H-h = \frac{Q}{2\pi KB} \log \frac{R^n}{r_1 . r_2 . r_3 . \ldots . r_n} \quad \ldots\ldots (4.87a)$$

$$\text{or } h = H - \frac{Q}{2\pi KB} \log \frac{R^n}{r_1 . r_2 . r_3 . \ldots\ldots . r_n} \quad \ldots\ldots. (4.87b)$$

Equation 4.86 gives the discharge and equation 4.87 gives the piezometric heights for points on the drawdown curve.

Computations :

The following computations have been done to illustrate the effect of mutual interference of battery of wells placed along the circumference of a circle -

(a) Effect of Mutual Interference on discharge

Case I - Constant spacing between wells (Table 4.81) and Fig 5.10

Case II-Constant radius of battery circle (Table 4.82 and Fig. 4.82)

(b) Effect of mutual interference of wells on drawdown - (Table 4.83 and Fig. 4.83).

Conclusions:

(a) Discharge diminishes as the number of wells in the battery increase, even when the spacing between wells remains unchanged.

(b) When 10 wells are placed in the battery, the total discharge from the wells is of the order of two and half to three times the discharge of a single well. Thus a battery of wells is not economical for drawing water for consumptive purposes.

(c) The drawdown curve along the diameter passing through wells becomes flatter as the number of wells in a battery increases. This is very useful for dewatering operations.

4.9 Two wells placed at right angles to a recharge boundary or infinite line drive :

Let the recharge boundary or line drive lie along the axis of x (Fig.4.90). Let the wells be located at A $(0, d_1)$ and B $(0, d_2)$. Let the discharges of wells at A be Q_1 and that at B be Q_2. Let one image well with a discharge $-Q_1$ be placed at C $(0, -d_1)$ and another image well with a discharge $-Q_2$ be placed at D$(0, -d_2)$ to replace the recharge boundary. Let r_1, r_2, r_3 and r_4 be the distances of any point P from the centres of wells A, C, B and D respectively. Let the drawdowns at the faces of the real wells A and B be equal.

The equation for steady radial flow towards a well is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{(Ref. eqn. 2.43)}$$

The combined flow equation for the group of real and image wells is given by,

$$h = \frac{Q_1}{2\pi KB} \log \frac{r_1}{r_2} + \frac{Q_2}{2\pi KB} \log \frac{r_3}{r_4} + C \quad \ldots\ldots (4.91)$$

Considering a point on the face of the well at A,

$h = hw$, $r_1 = rw$, $r_2 = 2d_1$, $r_3 = d_2-d_1$, $r_4 = d_1+d_2$

$$\text{or} \quad hw = \frac{Q_1}{2\pi KB} \log \frac{rw}{2d_1} + \frac{Q_2}{2\pi KB} \log \frac{d_2-d_1}{d_2+d_1} + C \quad \ldots (4.92)$$

Considering a point on the face of the well at B,

$h = hw$, $r_1 = d_2-d_1$, $r_2 = d_2+d_1$, $r_3 = rw$, $r_4 = 2d_2$

$$\text{or} \quad hw = \frac{Q_1}{2\pi KB} \log \frac{d_2-d_1}{d_2+d_1} + \frac{Q_2}{2\pi KB} \log \frac{rw}{2d_2} + C \quad \ldots (4.93)$$

Considering a point on the recharge boundary we get,

$r_1 = r_2$, $r_3 = r_4$, $h = H$

$$\text{or } H = C \quad \ldots\ldots\ldots\ldots (4.94)$$

From equation (4.92) and (4.93) we get,

$$0 = \frac{Q_1}{2\pi KB} \log\left(\frac{2d_1}{rw} \cdot \frac{d_2-d_1}{d_2+d_1}\right) + \frac{Q_2}{2\pi KB} \log\left(\frac{rw}{2d_2} \cdot \frac{d_2+d_1}{d_2-d_1}\right)$$

$$\text{or } Q_1 = Q_2 \; \frac{\log\left(\frac{2d_2}{rw} \cdot \frac{d_2-d_1}{d_2+d_1}\right)}{\log\left(\frac{2d_1}{rw} \cdot \frac{d_2-d_1}{d_2+d_1}\right)} \quad \ldots\ldots\ldots\ldots (4.95)$$

From equation 4.93 and 4.94 we get,

$$H - hw = \frac{Q_1}{2\pi KB} \log\left(\frac{d_2+d_1}{d_2-d_1}\right) + \frac{Q_2}{2\pi KB} \cdot \log \frac{2d_2}{rw} \quad \ldots\ldots\ldots (4.96)$$

From equations (4.95) and (4.96) we get,

$$Q_1 = \frac{2\pi KB(H-hw)\,\log\left[\frac{2d_2}{rw}\cdot\frac{d_2-d_1}{d_2+d_1}\right]}{\log\frac{d_2+d_1}{d_2-d_1}\log\left[\frac{2d_2}{rw}\cdot\frac{d_2-d_1}{d_2+d_1}\right]+\log\frac{2d_2}{rw}\log\left[\frac{d_2-d_1}{d_2+d_1}\cdot\frac{2d_1}{rw}\right]} \quad \ldots\ldots(4.97a)$$

and

$$Q_2 = \frac{2\pi KB(H-hw)\,\log\left[\frac{2d_1}{rw}\cdot\frac{d_2-d_1}{d_2+d_1}\right]}{\log\frac{d_2+d_1}{d_2-d_1}\log\left[\frac{2d_2}{rw}\cdot\frac{d_2-d_1}{d_2+d_1}\right]+\log\frac{2d_2}{rw}\cdot\log\left[\frac{2d_1}{rw}\cdot\frac{d_2-d_1}{d_2+d_1}\right]} \quad \ldots\ldots(4.97b)$$

From equation (4.91) and (4.94) we get,

$$H - h = \frac{Q_1}{2\pi KB}\log\frac{r_1 \cdot r_4}{r_1 \cdot r_3} \quad \ldots\ldots(4.98a)$$

$$\text{or } h = H - \frac{Q_1}{2\pi KB}\log\frac{r_2 \cdot r_4}{r_1 \cdot r_3} \quad \ldots\ldots(4.98b)$$

Equation 4.97 gives the discharges and equation 4.98 gives the piezometric heights for points on the draw down curve.

Computations :

Computations have been done in Table 4.91 to illustrate the effect of mutual interference of wells on discharges. Results have been plotted in fig 4.91

Conclusions:

(a) Discharge of each of the wells in the group is less than the discharge of a single well in identical conditions. Ratio of average discharge Q to discharge of a single well increases with the spacing between wells but decreases with the distance from the recharge boundary.

(b) Ratio of the discharge of second well Q_2 to discharge of first well Q_1, decreases as the spacing between wells increases. The ratio also increases as the distance from the recharge boundary increases.

4.10 Two Wells placed parallel to a recharge boundary or an infinite line drive

Let the recharge boundary or line drive lie along the axis of x (Fig. 4.100). Let the wells to be located A (0, d) and B (a, d). Let the drawdowns of two wells be equal. By the symmetry of location, the discharges of the two wells are equal, say Q each. Let the image well with a discharge - Q be located at C (0, d) and another image well with a discharge -Q be located at D(a, -d). Let r_1, r_2, r_3, r_4 be the distances of centres of wells A, C, B, D respectively from any point P. Let the spacing between wells be a .

The equation for steady radial flow towards a well is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{(Ref. eqn. 2.43)}$$

The combined flow equation for the group of realand image wells is given by,

$$h = \frac{Q}{2\pi KB} \log \frac{r_1 \, r_3}{r_2 \, r_4} + C \qquad \ldots\ldots.(4.101)$$

Considering a point on the face of well at A,

$h = hw$, $r_1 = rw$, $r_2 = 2d$, $r_3 = a$, $r_4 = \sqrt{a^2+4d^2}$

$$\text{or} \quad hw = \frac{Q}{2\pi KB} \log \frac{rw.\,a}{2d\sqrt{a^2+4d^2}} + C \qquad \ldots\ldots.(4.102)$$

Considering a point on the recharge boundary, say O,

$h = H$, $r_1 = r_2$, $r_3 = r_4$

or $H = C$ ....(4.103)

From equation (4.102) and (4.103) we get,

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{2d}{r_w} \frac{\sqrt{a^2+4d^2}}{a} \qquad \text{..........(4.104a)}$$

$$\text{or} \quad Q = \frac{2\pi KB\,(H - h_w)}{\log \frac{2d}{r_w} \cdot \frac{\sqrt{a^2+4d^2}}{a}} \qquad \text{..........(4.104b)}$$

From equations 4.101 and (4.103) we get,

$$H - h = \frac{Q}{2\pi KB} \log \frac{r_2 . r_4}{r_1 . r_3} \qquad \text{..........(4.105a)}$$

$$\text{or} \quad h = H - \frac{Q}{2\pi KB} \log \frac{r_2 . r_4}{r_1 . r_3} \qquad \text{..........(4.105b)}$$

Equation (4.104) gives the discharges and equation (4.105) gives the piezometric heights for points on the draw down curves.

Computations :

Computations have been done in Table 4.101 to illustrate the effect of mutual interference of wells on discharges. The results have been plotted in Fig. 4.101.

Conclusions :

(a) The discharges increase as the distance from the source decreases. The discharges also increase with the increase in spacing between wells.

(b) Equivalent radius of influence $R' = \frac{2d}{a}\sqrt{a^2+4d^2}$

4.11 Three wells placed parallel to a recharge boundary or infinite line drive:

Let the recharge boundary or line drive lie along the axis of x (Fig. 4.110). Let the wells be located at A(0,d), B (a, d) and C (2a, d). Let the drawdowns at the faces of three wells be equal. Let the discharges of wells be Q_1, Q_2 and Q_3 respectively. Let the image wells with discharges -$-Q_1$, $-Q_2$ and $-Q_3$ be located at D (0, -d), E (a, -d) and F (2a, -d). Let r_1, r_2, r_3, r_4, r_5, r_6 be the distances of any point P from wells at A, D, B, E, C, F respectively. The spacing between wells be a.

The equation for steady radial flow towards a well is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{.....(Ref. Eqn. 2.43)}$$

The combined flow equation for the group of real and image wells is given by,

$$h = \frac{Q_1}{2\pi KB} \log \frac{r_1}{r_2} + \frac{Q_2}{2\pi KB} \log \frac{r_3}{r_4} + \frac{Q_3}{2\pi KB} \log \frac{r_5}{r_6} + C \qquad \text{..........(4.111)}$$

Considering points on the faces of wells, A, B, and C we get,

$$hw = \frac{Q_1}{2\pi KB} \log \frac{rw}{2d} + \frac{Q_2}{2\pi KB} \log \frac{a}{\sqrt{a^2+4d^2}} + \frac{Q_3}{2\pi KB} \log \frac{a}{\sqrt{a^2+d^2}} + C \qquad \text{..........(4.112)}$$

$$hw = \frac{Q_1}{2\pi KB} \log \frac{a}{\sqrt{a^2+4d^2}} + \frac{Q_2}{2\pi KB} \log \frac{rw}{2d} + \frac{Q_3}{2\pi KB} \log \frac{a}{\sqrt{a^2+4d^2}} + C \qquad \text{..........(4.113)}$$

$$hw = \frac{Q_1}{2\pi KB} \log \frac{a}{\sqrt{a^2+d^2}} + \frac{Q_2}{2\pi KB} \log \frac{a}{\sqrt{a^2+4d^2}} + \frac{Q_3}{2\pi KB} \log \frac{rw}{2d} + C \qquad \text{..........(4.114)}$$

From equations (4.112) and (4.114) we get, $Q_1 = Q_3$ .....(4.115a)

From equations (4.112) and (4.113) we get,

$$Q_1 = \frac{\log \frac{2d}{rw} \cdot \frac{a}{\sqrt{a^2+4d^2}}}{\log \frac{2d}{rw} \cdot \frac{a}{a^2+4d^2}\sqrt{a^2+d^2}} \qquad \text{..........(4.115b)}$$

From equations (4.113) and (4.116) we get,

$$H - hw = \frac{Q_1}{2\pi KB} \log \frac{a^2+4d^2}{a^2} + \frac{Q_2}{2\pi KB} \log \frac{2d}{rw} \qquad \text{..........(4.117)}$$

From equations (4.115) and (4.117) we get,

$$Q_1 = \frac{4\pi KB(H-hw)\left\{ \log\left(\frac{2d}{rw}\right)^2 - \log\left(1+\frac{4d^2}{a^2}\right)\right\}}{\left\{\log\left(\frac{2d}{rw}\right)^2 \left\{\log\left(\frac{2d}{rw}\right)^2 \cdot \left(1+\frac{d^2}{a^2}\right)\right\} - 2\left\{\log\left(1+\frac{4d^2}{a^2}\right)\right\}^2\right]}$$

.........(4.118a)

$$Q_2 = \frac{4\pi KB(H-hw)\left[\log\left(\frac{2d}{rw}\right)^2 \times \left(1+\frac{d^2}{a^2}\right) - 2 \log\left(1+\frac{4d^2}{a^2}\right)\right]}{\left[\log\left(\frac{2d}{rw}\right)^2 \left\{\log\left(\frac{2d}{rw}\right)^2 \cdot \left(1+\frac{d^2}{a^2}\right)\right\} - 2\left\{\log\left(1+\frac{4d^2}{a^2}\right)\right\}^2\right]}$$

..........(4.118b)

From equations (4.111) and (4.116) we get,

$$H-h = \frac{Q_1}{2\pi KB} \log \frac{r_2 \cdot r_6}{r_1 \cdot r_5} + \frac{Q_2}{2\ KB} \log \frac{r_4}{r_3} \qquad \text{........(4.119a)}$$

$$\text{or } h = H - \frac{Q_1}{2\pi KB} \log \frac{r_2 \cdot r_6}{r_1 \cdot r_5} + \frac{Q_2}{2\ KB} \log \frac{r_4}{r_3} \qquad \text{.......(4.119b)}$$

Equation 4.118 gives the discharges and equations 4.119 gives the piezometric heights for points on the draw down curve.

Refer Table 4.111 for Computation

4.12 Infinite array of wells parallel to an infinite line drive or recharge boundary - Single array :

Let the recharge boundary or line drive lie along the axis of x. (Fig. 4.120). Let the wells be located at A(0,d), B (a, d), C (2a, d) ......(na, d)... Let the discharges of the wells be Q each. Let image wells with discharges -Q each, be placed at A' (0,-d), B' (a, -d), C' (2a, -d)....(na,-d).... Let r_1, r_2, r_3 ...... be the distances of any point P from the centres of real wells A, B, C, respectively. Let the draw-downs at the faces of all wells be equal. The spacing between wells be a and the distance of the array of wells from re-charge boundary be d.

The equation for steady radial flow towards a well in a confined aquifer is given by,

$$h = \frac{Q}{2\pi KB} \log r + C \qquad \text{(Refer eqn. 2.43)}$$

The combined flow equation for the group of real well is given by,

$$h = \frac{Q}{2\pi KB} \log r_1, r_2 . r_3 \quad + C$$

$$= \frac{Q}{4\pi KB} \sum_{-\infty}^{+\infty} \log\left[(x-na)^2 + (y-d)^2\right] + C$$

$$= \frac{Q}{4\pi KB}\left[\log \quad \text{Cos h} \; \frac{2\pi (y-d)}{a} - \text{Cos} \; \frac{2\ x}{a}\right] + C$$

....(4.121)*

Equation 4.111 is a basic equation for solution of problems involving infinite array of wells just as equation 2.43 is basic equation for flow towards a single well. The special features of the equation are : (i) It satisfies Laplace's equation,

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* For the derivation of infinite integral refer to Flow of Homogeneous fluids through porous media by M.Muskat, Secn 4.9 page 189-190.

(ii) It is a periodic function. The argument of the logarithm vanishes at centres of wells (na, d).

(iii) Pressure distribution is symmetrical about the axis of y.

The combined flow equation for the infinite array of real wells and image wells is given by,

$$h = \frac{Q}{4\pi KB} \log \left[\frac{\cosh 2\pi\frac{(y-d)}{a} - \cos 2\pi\frac{x}{a}}{\cosh 2\pi\frac{(y+d)}{a} - \cos 2\pi\frac{x}{a}} \right] + C \quad \ldots.(4.122)$$

For a point on the line drive say (0,0),

$$H = C \quad \ldots\ldots.(4.123)$$

For a point on the face of well A,

$h = h_w$, $y = d + r_w$, $x = 0$

$$\text{or } h_w = \frac{Q}{4\pi KB} \log \left(\frac{\cosh \frac{2\pi r_w}{a} - 1}{\cosh \frac{2\pi\, 2d}{a} - 1} \right) + C$$

$$= \frac{Q}{4\pi KB} \log \left[\frac{e^{\left(\frac{2\pi r_w}{a}\right)} + e^{\left(\frac{-2\pi r_w}{a}\right)} - 2}{e^{\left(\frac{2\pi\, 2d}{a}\right)} + e^{\left(\frac{-2\pi\, 2d}{a}\right)} - 2} \right] + C \quad \ldots.(4.124) \quad = \frac{Q}{2\pi KB} \log \left[\frac{\sinh \frac{\pi r_w}{a}}{\sinh \frac{2\pi d}{a}} \right] \text{ - 4.12[illegible]}$$

From equations (4.123) and (4.124) we get,

$$H - h_w = \frac{Q}{2\pi KB} \log \frac{\sinh\left(\frac{2\pi d}{a}\right)}{\sinh\left(\frac{\pi r_w}{a}\right)} \quad \ldots\ldots\ldots.(4.125a)$$

$$\text{or } Q = \frac{2\pi KB\,(H - h_w)}{\log \dfrac{\sinh \frac{2\pi d}{a}}{\sinh \frac{\pi r_w}{a}}} \quad \ldots\ldots\ldots.(4.125b)$$

From equations (4.122) and (4.123) we get,

$$H-h = \frac{Q}{4\pi KB} \log \left[\frac{\text{Cos h}.2\pi\left(\frac{y+d}{a}\right) - \text{Cos } 2\pi\frac{x}{a}}{\text{Cos h } 2\pi\left(\frac{y-d}{a}\right) - \cos 2\pi\frac{x}{a}} \right] \quad \ldots\ldots\ldots (4.126a)$$

$$\text{or } h = H - \frac{Q}{4\;KB} \log \left[\frac{\text{Cos h } 2\pi\left(\frac{y+d}{a}\right) - \cos 2\pi\frac{x}{a}}{\text{Cos h } 2\pi\left(\frac{y-d}{a}\right) - \cos 2\pi\frac{x}{a}} \right] \quad \ldots\ldots\ldots (4.126b)$$

Equation 4.125 gives the discharges of wells in the array and equation 4.126 gives the piezometric heights for points on the drawdown curve.

Computations:

The following computations have been done to illustrate the effect of mutual interference in any infinite array of wells placed parallel to an infinite line drive.

(a) Influence on discharges Table 4.121 and Fig. 4.121.

(b) Influence on drawdown. Tables 4.122 and 4.123 Fig. 4.122 and 4.123.

Conclusions:

(a) Discharges increase with an increase in spacing between wells and vice versa.

(b) Discharges decrease with an increase in distance from the line drive and vice versa.

(c) The equipotential lines are straight lines, parallel to the line drive except within a distance equal to spacing 'a' from the centres of wells. This is indicated by a uniform gradient of the drawdown curves upto 500 ft to 750 ft ~~for~~ from the line drive.

4.13 Infinite Arrays of wells parallel to an infinite line drive or a recharge boundary - Double Array of wells in square setting.

Let the recharge boundary or line drive lie along the axis of x. (Fig. 4.130). Let the distance of first array of wells from the line drive be d_1 and distance of second array from line drive be d_2. Let the spacing between the wells along the arrays be 'a' and the setting of the two arrays of wells be in a square pattern. Let the discharge of wells in first array be Q_1 and that in the second array Q_2. Let the drawdowns of all wells be equal. Let two infinite arrays of image wells with discharges $-Q_1$ and $-Q_2$ be placed, at distances d_1 and d_2 respectively, on the opposite side of the line drive.

The combined flow equation for the two arrays of real wells and two arrays of image wells is given by (Refer to equation 4.121).

$$h=\frac{Q}{4\pi KB}\log\left(\frac{\cosh 2\pi\left(\frac{y-d_1}{a}\right)-\cos\frac{2\pi x}{a}}{\cosh 2\pi\left(\frac{y+d_1}{a}\right)-\cos\frac{2\pi x}{a}}\right)+\frac{Q}{4\pi KB}\log\left(\frac{\cosh 2\pi\left(\frac{y-d_2}{a}\right)-\cos\frac{2\pi x}{a}}{\cosh 2\pi\left(\frac{y+d_2}{a}\right)-\cos\frac{2\pi x}{a}}\right)+C \quad \ldots.(4.131$$

Considering a point on the face of a well in first array, say $(0, d_1)$ we get,

$$h_w=\frac{Q_1}{4\pi KB}\log\left(\frac{\cos 2\pi\frac{r_w}{a}-1}{\cosh 2\pi\frac{2d_1}{a}-1}\right)+\frac{Q_2}{4\pi KB}\log\left(\frac{\cosh 2\pi\frac{(d_1-d_2)}{a}-1}{\cosh 2\pi\frac{d_1+d_2}{a}-1}\right)+C$$

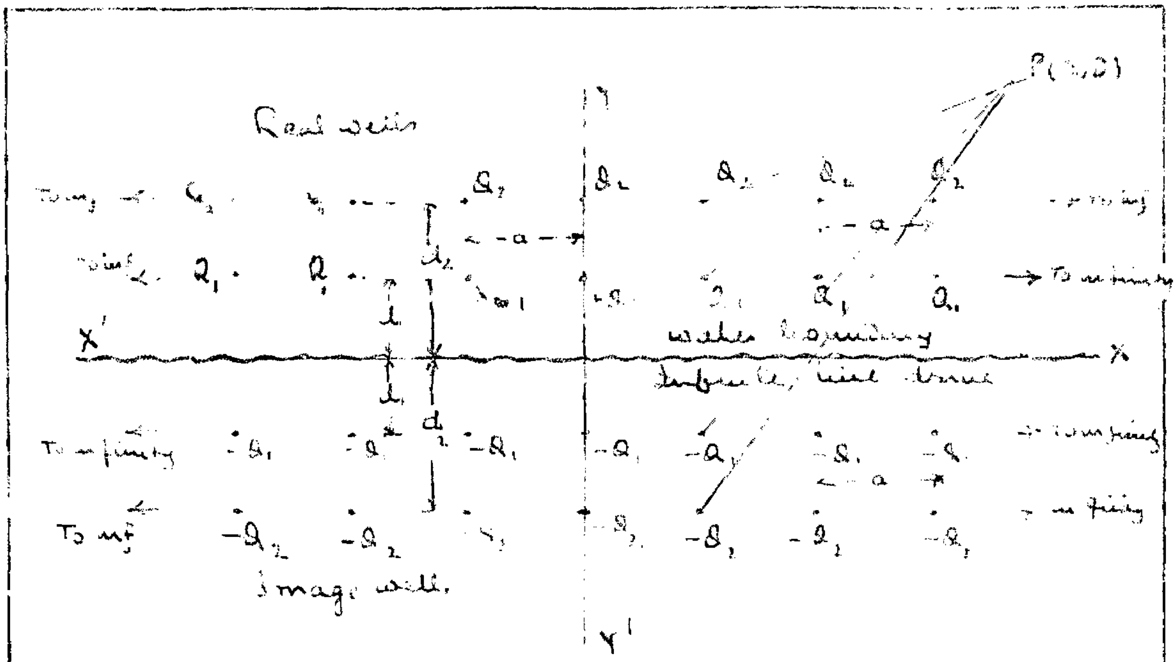


FIG - 4.130

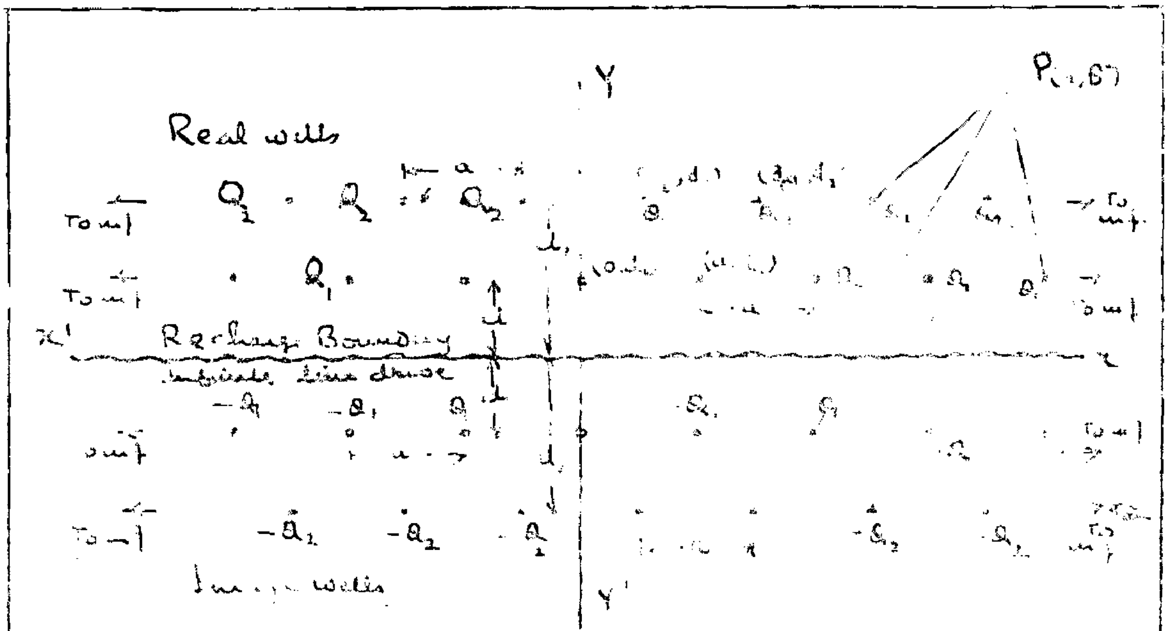


FIG - 4.140

$$= \frac{Q_1}{2\pi KB} \log \left[\frac{\sinh \pi \frac{r_w}{a}}{\sinh 2\pi \frac{d_1}{a}} \right] + \frac{Q_2}{2\pi KB} \log \left[\frac{\sinh \frac{\pi(d_2-d_1)}{a}}{\sinh \frac{\pi}{a}(d_2+d_1)} \right] + \quad \ldots (4.132)$$

Similarly considering a point on the face of a well on second array, say $(0, d_1)$ we get,

$$h_w = \frac{Q_1}{4\pi KB} \log \left[\frac{\cosh 2\pi \left(\frac{d_2 - d_1}{a} \right) - 1}{\cosh 2\pi \left(\frac{d_2 + d_1}{a} \right) - 1} \right] + \frac{Q_2}{4\pi KB}$$

$$+ \frac{Q}{4\pi KB} \left[\log \frac{\cos 2\pi \frac{r_w}{a} - 1}{\cos 2\pi \, 2 \frac{d_2}{a} - 1} \right] + C$$

$$\text{or } h_w = \frac{Q_1}{2\pi KB} \left[\log \frac{\sinh \pi \left(\frac{d_2 - d_1}{a} \right)}{\sinh \pi \frac{(d_2 + d_1)}{a}} \right] + \frac{Q_2}{2\pi KB}$$

$$+ \frac{Q_2}{2\pi KB} \left[\log \frac{\sinh \pi \frac{r_w}{a}}{\sinh \frac{2\pi d_2}{a}} \right] + C \quad \ldots\ldots (4.133)$$

From equation (4.132) and (4.133) we get,

$$\frac{Q_1}{Q_2} = \frac{\log \left[\frac{\sinh \pi \frac{r_w}{a} \cdot \sinh \pi \frac{(d_2+d_1)}{a}}{\sinh 2\pi \frac{d_2}{a} \cdot \sinh \pi \frac{(d_2-d_1)}{a}} \right]}{\log \left[\frac{\sinh \frac{r_w}{a} \quad \sinh \pi \frac{(d_2+d_1)}{a}}{\sinh 2 \frac{d_1}{a} \cdot \sinh \pi \frac{(d_2-d_1)}{a}} \right]} \quad \ldots\ldots (4.134)$$

Considering a point on the line drive we get,

$$H = C \quad \ldots\ldots\ldots\ldots (4.135)$$

From equation (4.132) and (4.135) we get,

$$H-h_w = \frac{Q_1}{2\pi KB} \log \left[\frac{\sinh \frac{2\pi d_1}{a}}{\sinh \cdot \pi \frac{r_w}{a}} \right] + \frac{Q_2}{2\pi KB} \log \left[\frac{\sinh \pi \frac{(d_2+d_1)}{a}}{\sinh \pi \frac{(d_2-d_1)}{a}} \right] \quad \ldots\ldots\ldots(4.136)$$

Equations (4.134) and (4.136) give,

$$Q_1 = \frac{2\pi KB\,(H-h_w)\,\log A}{\log \left[\frac{\sinh \frac{2\pi d_1}{a}}{\sinh \frac{\pi r_w}{a}} \right] \log A + \log \left[\frac{\sinh \pi \frac{(d_2+d_1)}{a}}{\sinh \pi \frac{(d_2-d_1)}{a}} \right] \log B} \quad \ldots\ldots(4.137a)$$

and

$$Q_2 = \frac{2\pi KB\,(H-h_w)\,\log B}{\log \left[\frac{\sinh \frac{2\pi d_1}{a}}{\sinh \frac{\pi r_w}{a}} \right] \log A + \log \left[\frac{\sinh \pi \frac{(d_2+d_1)}{a}}{\sinh \pi \frac{(d_2-d_1)}{a}} \right] \log B} \quad \ldots(4.137)$$

Where

$$A = \left[\frac{\sinh \pi \frac{r_w}{a} \cdot \sinh \pi \frac{(d_2+d_1)}{a}}{\sinh \frac{2\pi d_2}{a} \cdot \sinh \pi \frac{(d_2-d_1)}{a}} \right]$$

and

$$B = \left[\frac{\sinh \pi \frac{r_w}{a} \cdot \sinh \pi \frac{(d_2+d_1)}{a}}{\sinh \frac{\pi 2 d_1}{a} \cdot \sin \pi \frac{(d_2-d_1)}{a}} \right].$$

From equations (4.135) and (4.131) we get

$$h = H - \frac{Q_1}{4\pi KB} \log \left[\frac{\cosh 2\pi \left(\frac{y+d_1}{a}\right) - \cos \frac{2\pi x}{a}}{\cosh 2\pi \left(\frac{y-d_1}{a}\right) - \cos \frac{2\pi x}{a}} \right] - \frac{Q_2}{4\pi KB} \log \left[\frac{\cosh 2\pi \left(\frac{y+d_2}{a}\right) - \cos \frac{2\pi x}{a}}{\cosh 2\pi \left(\frac{y-d_2}{a}\right) - \cos \frac{2\pi x}{a}} \right] \quad (4.138)$$

$$\log \frac{\cosh \frac{2(y+d_2)}{a} - \cos \frac{2x}{a}}{\cosh \frac{2(y-d_2)}{a} - \cos \frac{2x}{a}} \quad \ldots (4.138$$

Equation 4.137 gives the discharge and equation 4.138 give the piezometric heights for points on the draw down curve.

Computations:-

The following computations have been done to illustrate the effect of mutual interference of wells in double array of wells parallel to an infinite line drive.

(a) Discharges of wells in the two arrays and shielding characteristics of the first array of wells. (Table 4.131. Fig. 4.131 and 4.132)

(b) Influence of spacing between arrays on shielding characteristics. (Table 4.132. Fig. 4.133)

(c) Drawdowns along a line at right angles to the line drive and,

(i) Passing through the wells,

and(ii) Passing midway between wells, i.e. along the water divide.

Conclusions :

(a) The discharge increases with increase in spacing between wells and decrease in distance from the line drive.

(b) The shielding effect of first array of wells decreases with increase in spacing between wells. For larger spacings the value of $\frac{Q_1}{Q_1+Q_2}$ is of the order of 2/3.

(c) The shielding effect become constant for values of $\frac{d_1}{a}$ exceeding 0.5.

(d) The shielding effect increases with an increase in th spacing between arrays of wells.

(e) The draw down curve along a line ~~of~~ at right angles to line drive is a straight line from the line drive upt a distance 'a' from the centres of the wells. Again, there is a uniform gradient for some distance between the two arrays of wells. Finally, the drawdown curve becomes a horizontal straight line beyond the second array of wells. This is due to the fact that equipotential lines are more or less parallel to line drive except in close vicinity of the wells.

(f) The potential from the line drive can be made to drop to any ~~denied~~ desired extent by the variation of spacing between wells and discharges of wells.

4.14 Infinite array of wells parallel to an infinite line drive - Double array of wells in staggered setting:

Suppose that the two arrays of wells discussed in para 4.13 are staggered by a distance $a/2$ along the axis of x and are placed as shown in figure 4.140. Let the drawdowns at the faces of all wells be equal.

The combined flow equation for the arrays of real and image wells is given by:

$$h = \frac{Q_1}{4\pi KB} \log \left[\frac{\cosh 2\pi \frac{(y - d_1)}{a} - \cos \frac{2\pi x}{a}}{\cosh 2\pi \frac{(y+d_1)}{a} - \cos \frac{2\pi x}{a}} \right] + \frac{Q_2}{2\pi KB} \log \left[\frac{\cosh 2\pi \left(\frac{y-d_2}{a}\right) + \cos \frac{2\pi x}{a}}{\cosh 2\pi \left(\frac{y+d_2}{a}\right) + \cos \frac{2\pi x}{a}} \right] + C \quad \text{..(4.141)}$$

Refer to para 4.12 for basic equation. The plus sign before $\cos \frac{2\pi x}{a}$ for second array of wells indicates advance in period by π relative to first array of wells.

Considering a point on the face of a well in first array, say at $(0, d_1)$, we get

$x = 0$, $y = (d_1 + r_w)$, $h = h_w$

$$\text{or } h_w = \frac{Q_1}{4\pi KB} \log \left[\frac{\cosh 2\frac{\pi r_w}{a} - 1}{\cosh 2\pi \frac{2d_1}{a} - 1} \right] + \frac{Q_2}{2\pi KB} \log \left[\frac{\cosh 2\pi \left(\frac{d_1 - d_2}{a}\right) + 1}{\cosh 2\pi \left(\frac{d_2 + d_2}{a}\right) + 1} \right] + C$$

$$= \frac{Q_1}{2\pi KB} \log \frac{\sinh \pi \frac{r_w}{a}}{\sinh \frac{2\pi d_1}{a}} + \frac{Q_2}{2\pi KB} \left[\log \frac{\cosh \pi \frac{(d_1 - d_2)}{a}}{\cosh \pi \frac{(d_2 + d_1)}{a}} \right] + C \quad \text{......(4.142}$$

Considering a point on the face of a well in second array, say at $\left(\frac{a}{2}, d_2\right)$ we get,

$$x = \frac{a}{2},\quad y = d_2,\quad h = h_w,$$

$$\text{or}\quad h_w = \frac{Q_1}{4\pi KB}\log\left[\frac{\cosh 2\pi\left(\frac{d_2-d_1}{a}\right)+1}{\cosh 2\pi\left(\frac{d_2+d_1}{a}\right)+1}\right] + \frac{Q_2}{4\pi KB}\log\left[\frac{\cosh 2\pi\frac{r_w}{a}-1}{\cosh 2\pi\frac{d_2}{a}-1}\right] + C$$

$$= \frac{Q_1}{2\pi KB}\log\left[\frac{\cosh \pi\left(\frac{d_2-d_1}{a}\right)}{\cosh \pi\frac{(d_2+d_1)}{a}}\right] + \frac{Q_2}{2\,KB}$$

$$+ \frac{Q_2}{2\pi KB}\log\left[\frac{\sinh \pi\frac{r_w}{a}}{\sinh 2\pi\frac{d_2}{a}}\right] + C \quad \text{.........(4.143)}$$

From equations(4.142) and (4.143) we get,

$$Q_1 = \frac{\log\left[\dfrac{\sinh \pi\frac{r_w}{a}}{\sinh 2\pi\frac{d_2}{a}}\cdot\dfrac{\cosh \pi\frac{(d_2+d_1)}{a}}{\cosh \pi\frac{(d_2-d_1)}{a}}\right]}{\log\left[\dfrac{\sinh \pi\frac{r_w}{a}}{\sinh 2\pi\frac{d_1}{a}}\cdot\dfrac{\cosh \pi\frac{(d_2+d_1)}{a}}{\cosh \pi\frac{(d_2-d_1)}{a}}\right]}\,Q_2 \quad \text{.(4}$$

Considering a point on the infinite line drive we get,

..........(4.145)

n equation (4.142) and (4.145) ow we get d_2+d_1

$$H - h_w = \frac{Q_1}{2\pi KB}\left[\log\left(\frac{\sinh \frac{2\pi d_1}{a}}{\sinh \frac{\pi r_w}{a}}\right) + \frac{Q_2}{2\pi KB}\log\left(\frac{\cosh \frac{\pi(d_2+d_1)}{a}}{\cosh \frac{\pi(d_2-d_1)}{a}}\right)\right] \quad \ldots\ldots(4.146)$$

From equation 4.141 and 4.145 we get,

$$H-h = \frac{Q_1}{2\pi KB}\log\left[\frac{\cosh 2\pi\left(\frac{y+d_1}{a}\right) - \cos\frac{2\pi x}{a}}{\cosh 2\pi\left(\frac{y-d_1}{a}\right) - \cos\frac{2\pi x}{a}}\right] + \frac{Q_2}{4\pi KB}\log\left[\frac{\cosh 2\pi\left(\frac{y+d_2}{a}\right) + \cos\frac{2\pi x}{a}}{\cosh 2\pi\left(\frac{y+d_1}{a}\right) + \cos\frac{2\pi x}{a}}\right] \quad \ldots\ldots(4.147)$$

Equations 4.144 and 4.146 give the discharges and equation (4.147) gives the piezometric height at any point.

Computations:-

Computations have been made in Table 4.141 to give the shielding effect of first array of wells for different values of (d_2-d_1).

Conclusion:- Equation 4.144 which gives the ratio of Q_1 to Q_2 is similar to equation 4.134. Since the values of $\cosh \pi \frac{d_2-d_1}{a}$ and $\sinh \pi \frac{d_2-d_1}{a}$ are almost equal for values of $\frac{d_2-d_1}{a} = 0.5$ and above, the shielding characteristics of double array of wells with square setting and staggered setting are almost the same. Other conclusions are the same as given in para 4.13,

TWO WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

TABLE 4.11

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON

Data: ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft.
$KB = 0.10$ ft^2/sec.

Note: ... Refer to equation 4.16
Q_o refers to discharge of a single well pumping alone under similar conditions.
Results plotted in fig. 4.11

a (feet)	R = 5000 ft Q_o= 1.36 cfs		R = 2000 ft Q_o= 1.5 cfs		R = 1000 ft Q_o= 1.6 cfs	
	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$
1	2	3	4	5	6	7
50	0.93	0.69	1.06	0.71	1.20	0.74
100	0.98	0.72	1.12	0.75	1.28	0.79
200	1.03	0.76	1.20	0.80	1.36	0.84
300	1.06	0.78	1.24	0.83	1.42	0.87
400	1.09	0.80	1.27	0.85	1.47	0.90
500	1.11	0.81	1.30	0.87	1.50	0.92

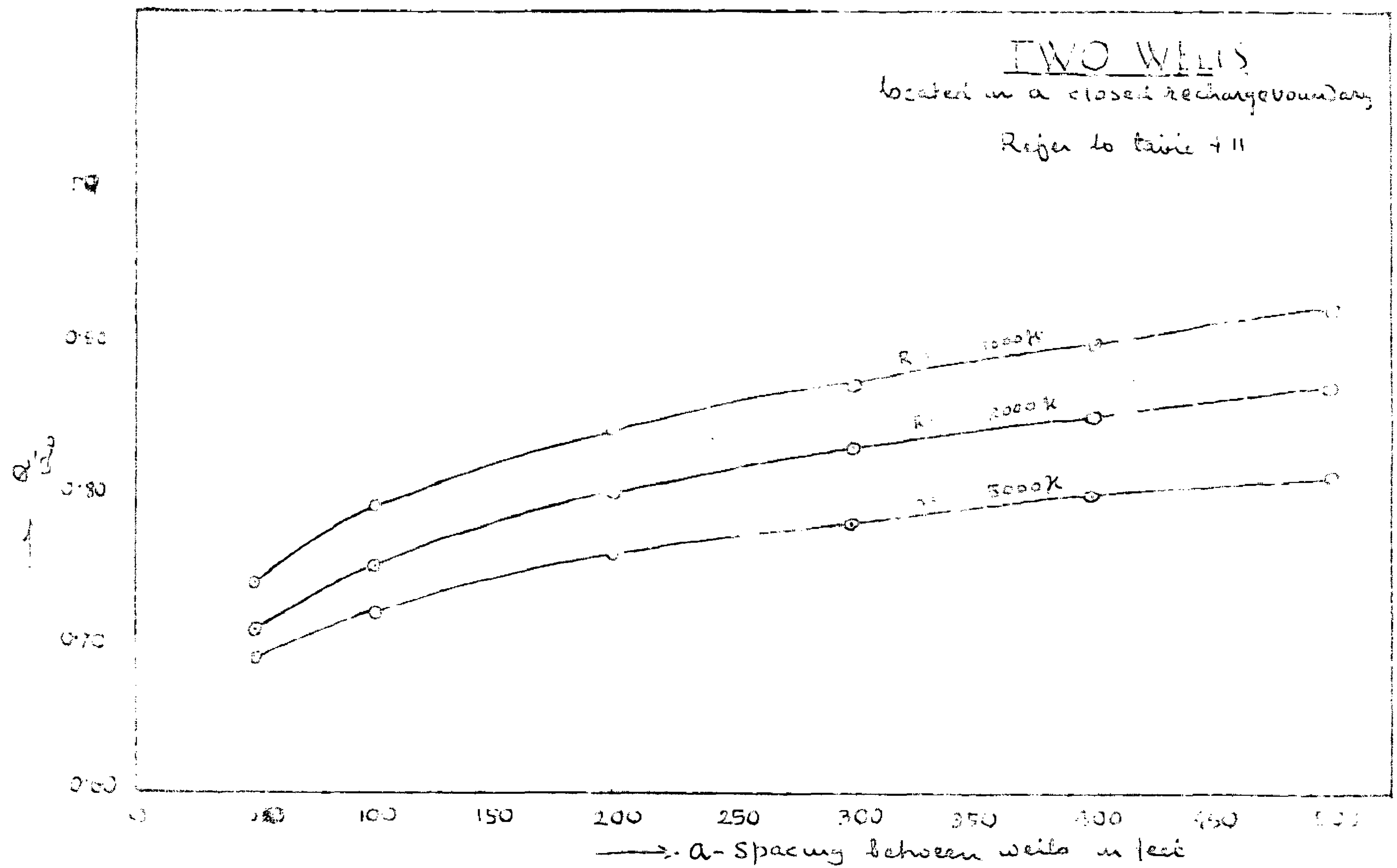


FIG - 4.11 Influence of spacing between wells and radius of influence on discharges

TWO WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

TABLE 4.12

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DRAW DOWN CURVE

Data : ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft.

$KB = 0.107$ ft^2/sec.

$a = 100$ ft, $R = 2000$ ft, $Q = 1.12$ cfs.

Notes: ... Refer to equation 4.17

Piezometer height have been computed along a line passing through the two wells.

h_1 and h_2 refer to piezometric heights due to the action of individual wells.

h - refers to piezometric height due to the combined action of two wells.

Draw down curve plotted in Fig. 4.12

x (feet)	Effect of well at A r_1 (feet)	h_1 (ft)	Effect of well at B r_2 (ft)	h_2 (ft)	Combined effect of two wells h (ft)
0	50	13.85	50	13.85	7.70
25	25	12.70	75	14.55	7.25
50	0.25	5.00	100	15.00	0
75	25	12.70	125	15.40	8.10
100	50	13.85	150	15.70	9.55
200	150	15.70	250	16.50	12.20
500	450	17.50	550	17.82	15.32
1000	950	18.80	1050	18.90	17.70
2000	1950	20.00	2050	20.00	20.00

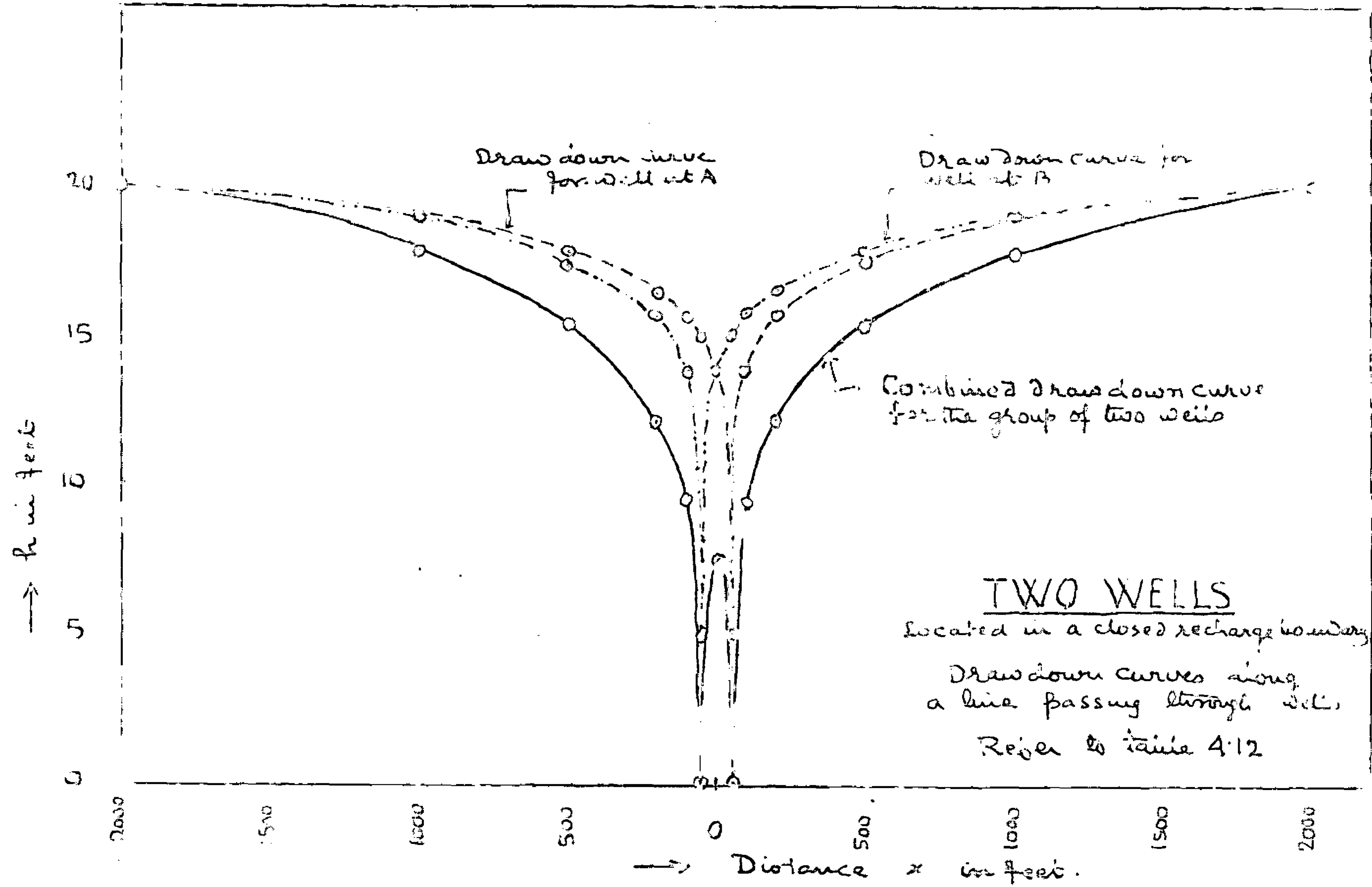


FIG- 4·12 · Drawdown curves for a group of two wells

TWO WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

TABLE 4.13

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DRAW DOWN CURVE

Data: ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft KB=0.107 ft^2/sec.

$a = 100$ ft, $R = 2000$ ft.

Note: ... Refer to equation 4.17

Piezometric heights have been computed along the water divide between the two wells (o,o')

h_1 and h_2 refer to piezometrid height due to the action of individual wells. h refers to piezometric height due to the combined action of two wells.

~~Draw down curve plotted in Fig.4.13~~

x (feet)	Effect of well at A r_1 (feet)	h_1 (feet)	Effect of well of B r_2 (feet)	h_2 (feet)	Combined effect of the two wells h (feet)
0	50	13.85	50	13.85	7.70
100	112	15.32	112	15.32	10.64
200	412	17.38	412	17.38	14.76
500	510	17.76	510	17.76	15.52
1000	1006	18.96	1006	18.96	17.92
1500	1500	19.50	1500	19.50	19.00
2000	2000	20.00	2000	20.00	20.00

THREE WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

Case I- Wells placed in a straight line.

Equal drawdown at the faces of wells.

TABLE 4.21

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DISCHARGES

Data : ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft,
$KB = 0.107$ ft^2/sec.

Note: ... Refer to equation 4.29

Q = Mean discharge of three wells

$$= \frac{Q_1 + Q_2 + Q_3}{3}$$

Q_0 = Discharge of a single well in identical conditions.

Results plotted in Fig. 4.21.

	R = 5000 ft Q_0 = 1.36 cfs				R = 2000 ft Q_0 = 1.5 cfs			
(feet)	Q_1 (cfs)	Q_2 (cfs)	$\frac{Q_2}{Q_1}$	$\frac{Q}{Q_0}$	Q_1 (cfs)	Q_2 (cfs)	$\frac{Q_2}{Q_1}$	$\frac{Q}{Q_0}$
50	0.76	0.66	0.87	0.54	0.89	0.77	0.87	0.57
100	0.82	0.72	0.88	0.58	0.97	0.85	0.88	0.62
200	0.88	0.79	0.90	0.63	1.07	0.96	0.89	0.69
300	0.94	0.84	0.90	0.67	1.13	1.02	0.90	0.73
400	0.97	0.87	0.90	0.69	1.19	1.08	0.90	0.77
500	0.99	0.90	0.91	0.71	1.23	1.11	0.90	0.80

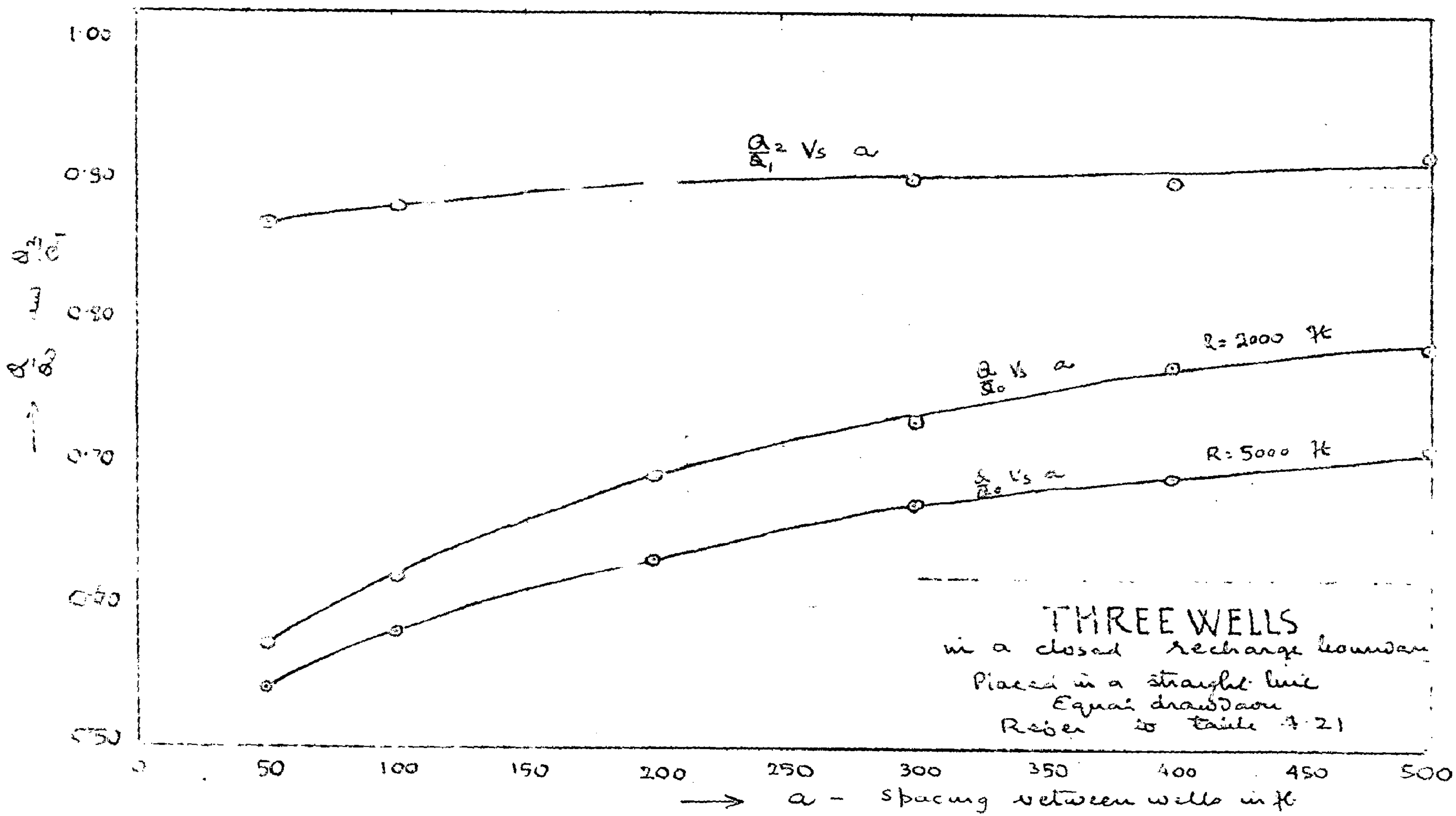


FIG - 4·21 - Influence of spacing and radius of influence on discharges.

THREE WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

Case I - Wells placed in a straight line.

Equal drawdown at the faces of wells.

TABLE 4.22

EFFECT OF INTERFERENCE OF WELLS ON DRAWDOWN CURVE

Data: ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft.

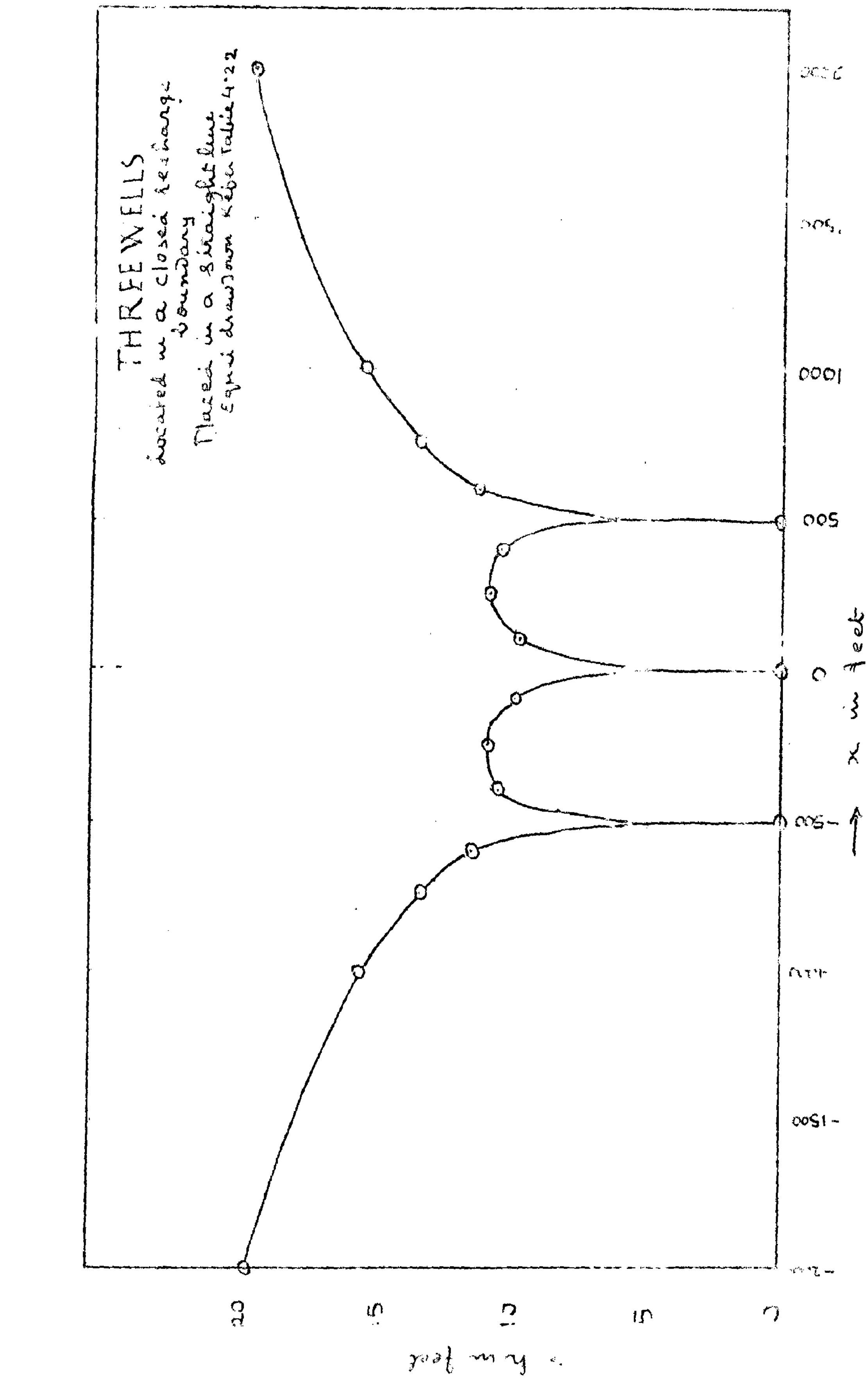
$KB = 0.107$ ft^2/sec.

$a = 500$ ft, $R = 2000$ ft, $Q_1 = 1.23$ cfs, $Q_2 = 1.11$ cfs.

Note: ... Refer to equation 4.210

Piezometric heights have been computed along a line passing through the wells.

x (feet)	r_1 (feet)	r_2 (feet)	r_3 (feet)	h (feet)
0	500	0.25	500	0
100	400	100	750	9.87
250	250	250	750	10.98
400	100	400	900	10.45
500	0.25	500	1000	0
600	100	600	1100	11.48
750	250	750	1250	13.69
1000	500	1000	1500	15.75
2000	1500	2000	2500	20.00



Drawdown Curve through a line passing through the wells

FIG 4·22

THREE WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

Case II Wells placed in a straight line Equal Discharge from all wells.

TABLE 4.31

EFFECT OF MUTUAL INTERFERENCE ~~ON~~ OF WELLS ON DISCHARGES AND AND DRAWDOWNS AT FACES OF OUTER WELLS

Data : ... $H = 20$ ft, $hw_2 = 0$, $r_w = 0.25$ ft,

$KB = 0.107$ ft^2/sec.

Note: ... Refer to equation 4.38

Q_o= Discharge of a single well in identical conditions.

~~Results plotted in Fig. 4.31.~~

a (feet)	R = 5000 ft Q_o= 1.36 cfs			R = 2000 ft Q_o= 1.50 cfs		
	Q (cfs)	$\frac{Q}{Q_o}$	hw_1 (feet)	Q (cfs)	$\frac{Q}{Q_o}$	hw_1 (feet)
50	0.71	0.52	0.72	0.83	0.55	0.85
100	0.76	0.56	0.78	0.90	0.60	0.93
200	0.83	0.61	0.85	1.00	0.67	1.02
300	0.87	0.64	0.89	1.06	0.71	1.09
400	0.90	0.66	0.93	1.11	0.74	1.14
500	0.93	0.69	0.96	1.15	0.77	1.18

THREE WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

Case II - Wells placed in a straight line
Equal discharge from all wells.

TABLE 4.32

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DRAWDOWN CURVE

Data: ... $H = 20$ ft, $h_{w_2} = 0$, $r_w = 0.25$ ft

$KB = 0.107\ ft^2/sec$ $a = 500$ ft

$R = 2000$ ft $Q = 1.5$ cfs.

Note: ... Refer to equation 4.39

Piezometric heights have been computed along a line passing through the wells.

x (feet)	r_1 (feet)	r_2 (feet)	r_3 (feet)	h (feet)
0	500	0.25	500	0
100	400	100	600	10.12
250	250	250	750	11.20
400	100	400	900	10.80
500	0.25	500	1000	1.18
600	100	600	1100	11.83
750	250	750	1250	13.95
1000	500	1000	1500	15.91
2000	1500	2000	2500	20.00

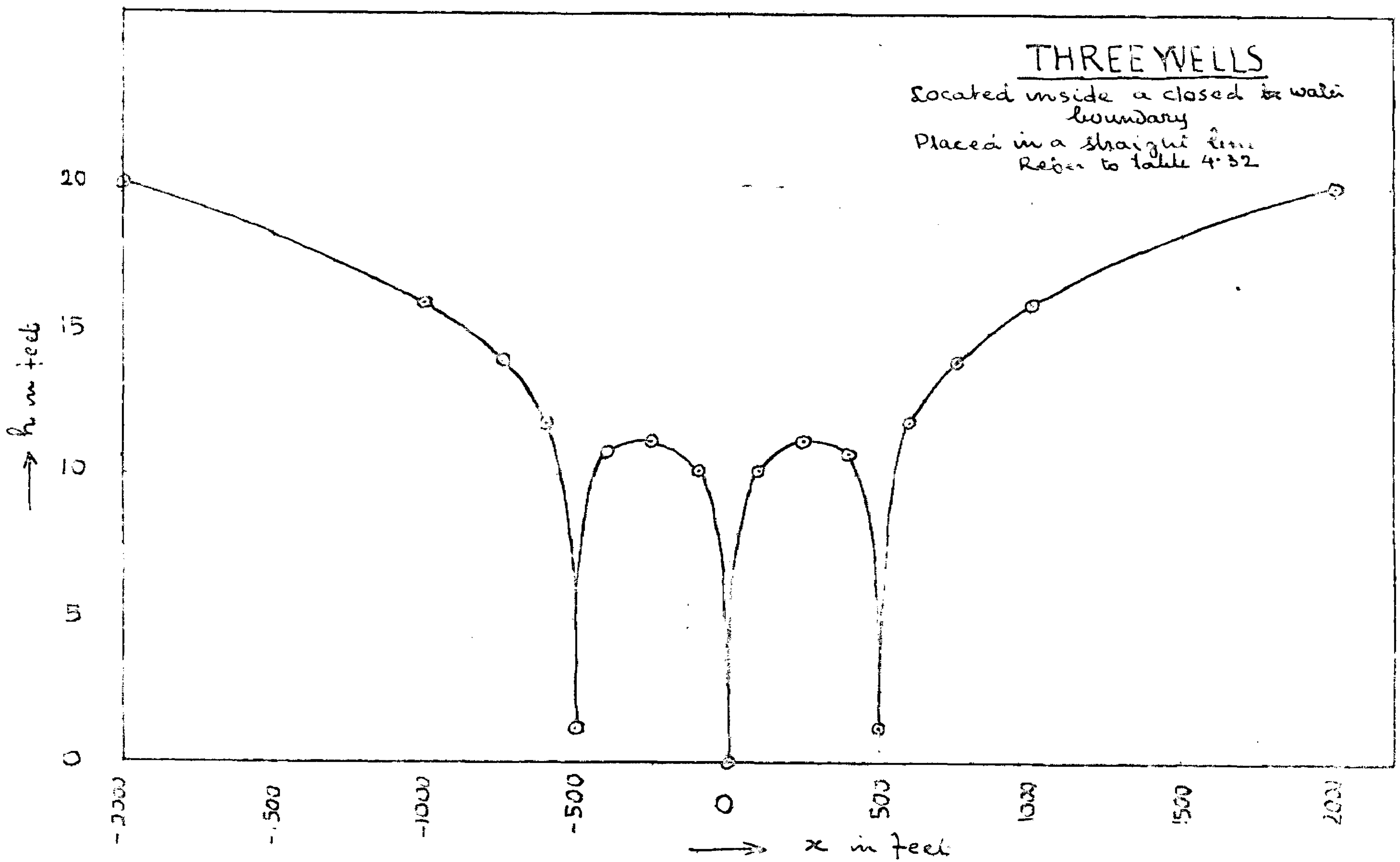


FIG- 4·32 - Drawdown Curve along a line passing through the wells - Discharge same for all wells

FOUR WELLS LOCATED IN AN ISLAND OR CLOSED RECHARGE BOUNDARY
Wells forming a square. Same drawdown at the faces of wells.

TABLE 4.51

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DISCHARGES

Data : ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft

$KB = 0.107\ ft^2/sec.$

Notes ... Refer to equation 4.58

$Q_1 = Q_2 = Q_3 = Q_4 = Q$ (Eqn. 4.56)

Q_o refers to discharge from a single well under identical conditions.

	R = 5000 ft, Q_o = 1.36 cfs		R = 2000 ft, Q_o = 1.5 cfs	
(feet)	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$
50	0·43	0.685	0.69	0·46
100	0·47	0.720	0.77	0·51
200	0·52	0.757	0.87	0·53
300	0·55	0.780	0.95	0·58
400	0·58	0.800	1.00	0·67
500	0·61	0.815	1.05	0·70

FIVE WELLS LOCATED IN AN ISLAND OR A CLOSED RECHARGE BOUNDARY
Four wells forming a square and the fifth well in the Centre. Equal drawdown at the faces of all wells.

TABLE 4.61

EFFECT OF MUTUAL INTERFERENCE BETWEEN WELLS ON DISCHARGES AND DRAWDOWNS AT FACES OF WELLS

Data ... $H = 20$ ft, $hw = 0$, $r_w = 0.25$ ft

$KB = 0.107\ ft^2/sec.$

Notes ... Refer to equation 4.610

$$Q = \frac{Q_1+Q_2+Q_3+Q_4+Q_5}{5} = \frac{4Q_1 + Q_5}{5}$$

Q_o = Discharge from a single well under identical conditions.

~~Results plotted in Fig. 4.61.~~

a (feet)	R = 5000 ft, Q_o = 1.36 cfs				R = 2000 ft, Q_o = 1.5 cfs			
	Q_1 (cfs)	Q_5 (cfs)	$\frac{Q_5}{Q_1}$	$\frac{Q}{Q_o}$	Q_1 (cfs)	Q_5 (cfs)	$\frac{Q_5}{Q_1}$	$\frac{Q}{Q_o}$
50	0.51	0.36	0.71	0.32	0.60	0.43	0.72	0.38
100	0.55	0.42	0.76	0.35	0.67	0.50	0.75	0.43
200	0.61	0.48	0.79	0.39	0.77	0.60	0.78	0.49
300	0.66	0.52	0.79	0.42	0.83	0.66	0.79	0.53
400	0.69	0.56	0.80	0.44	0.89	0.71	0.80	0.57
500	0.72	0.58	0.81	0.46	0.94	0.76	0.81	0.60

FIVE WELLS IN AN ISLAND OR A CLOSED RECHARGE BOUNDARY
Four wells forming a square and one well at the Centre.
All wells have equal discharge

TABLE 4.71

EFFECT OF MUTUAL INTERFERENCE BETWEEN WELLS ON DISCHARGES AND DRAWDOWNS AT FACES OF WELLS

Data : ... $H = 20$ ft, $hw_5 = 0$, $r_w = 0.25$ ft. $KB = 0.107$ ft^2/sec.

Notes: ... Refer to equation 4.77

Q_o = Discharge of a single well in identical conditions.

a (feet)	R = 5000 ft, Q_o = 1.36 cfs			R = 2000 ft, Q_o = 1.5 cfs		
	Q (Cfs)	$\frac{Q}{Q_o}$	hw_1 (feet)	Q (cfs)	$\frac{Q}{Q_o}$	hw_1 (feet)
50	0.46	0.338	0.92	0.54	0.360	1.11
100	0.50	0.368	1.02	0.60	0.400	1.23
200	0.55	0.405	1.13	0.69	0.460	1.42
300	0.60	0.442	1.23	0.75	0.500	1.54
400	0.64	0.470	1.31	0.80	0.534	1.64
500	0.67	0.492	1.37	0.85	0.566	1.75

A BATTERY OF WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

TABLE 4.81

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DISCHARGES

Case I : Spacing between adjoining wells remains constant.

Data: ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft.
$KB = 0.107\ ft^2/sec.$

Note: ... Refer to equation 4.86

Q_o refers to the discharge of a single well in identical conditions.

n	R = 5000 ft						R = 2000 ft					
	a=50 ft		a=100 ft		a=200 ft		a=50 ft		a=100 ft		a=200 ft	
	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$
1	1.36	1.0	1.36	1.0	1.36	1.00	1.50	1.00	1.50	1.00	1.50	1.00
2	0.93	0.68	0.98	0.72	1.03	0.75	1.06	0.71	1.12	0.75	1.20	0.80
3	0.71	0.52	0.76	0.56	0.83	0.61	0.83	0.55	0.90	0.60	1.00	0.67
4	0.58	0.43	0.64	0.47	0.71	0.52	0.69	0.46	0.78	0.52	0.87	0.58
5	0.49	0.36	0.55	0.40	0.62	0.46	0.59	0.39	0.68	0.45	0.78	0.52
6	0.43	0.32	0.49	0.36	0.56	0.41	0.53	0.35	0.61	0.41	0.72	0.48
7	0.39	0.29	0.45	0.33	0.52	0.38	0.48	0.32	0.56	0.37	0.68	0.45
8	0.35	0.26	0.41	0.30	0.48	0.35	0.44	0.29	0.52	0.35	0.64	0.43
9	0.33	0.24	0.38	0.28	0.43	0.32	0.41	0.27	0.49	0.33	0.61	0.41
10	0.30	0.20	0.35	0.26	0.42	0.31	0.38	0.25	0.46	0.31	0.59	0.39

A BATTERY OF WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

TABLE 4.82

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DISCHARGES

Case II: Radius of the battery circle remains constant

Data: ... $H = 20$ ft, $hw = 0$, $rw = 0.25$ ft, $HB = 0.107\ ft^2/sec.$

Note: ... Refer to equation 4.86

Q_o refers to discharge of a single well in identical conditions.

Results plotted in Fig. 4.82.

n	R = 5000 ft						R = 2000 ft					
	r=50 ft		r=100 ft		r=200 ft		r=50 ft		r=100 ft		r=200 ft	
	Q (cfs)	Q/Q_o	Q (cfs)	Q/Q_o	Q (cfs)	Q/Q_o	Q (cfs)	Q/Q_o	Q (Cfs)	Q/Q_o	Q (cfs)	Q/Q_o
1	1.36	1.00	1.36	1.00	1.36	1.00	1.50	1.00	1.50	1.00	1.50	1.00
2	0.98	0.72	1.03	0.76	1.09	0.83	1.13	0.75	1.20	0.80	1.28	0.86
3	0.71	0.52	0.81	0.60	0.89	0.66	0.89	0.59	0.97	0.65	1.08	0.72
4	0.59	0.43	0.67	0.49	0.75	0.55	0.73	0.49	0.81	0.54	0.93	0.62
5	0.51	0.38	0.57	0.42	0.64	0.47	0.61	0.41	0.70	0.47	0.82	0.55
6	0.44	0.32	0.49	0.36	0.56	0.41	0.53	0.35	0.61	0.41	0.72	0.48
7	0.38	0.28	0.43	0.32	0.50	0.37	0.46	0.31	0.54	0.36	0.65	0.43
8	0.34	0.25	0.38	0.28	0.45	0.33	0.41	0.27	0.48	0.32	0.59	0.39
9	0.31	0.23	0.35	0.26	0.41	0.30	0.37	0.25	0.44	0.29	0.54	0.36
10	0.28	0.21	0.32	0.24	0.38	0.28	0.34	0.23	0.40	0.27	0.49	0.33

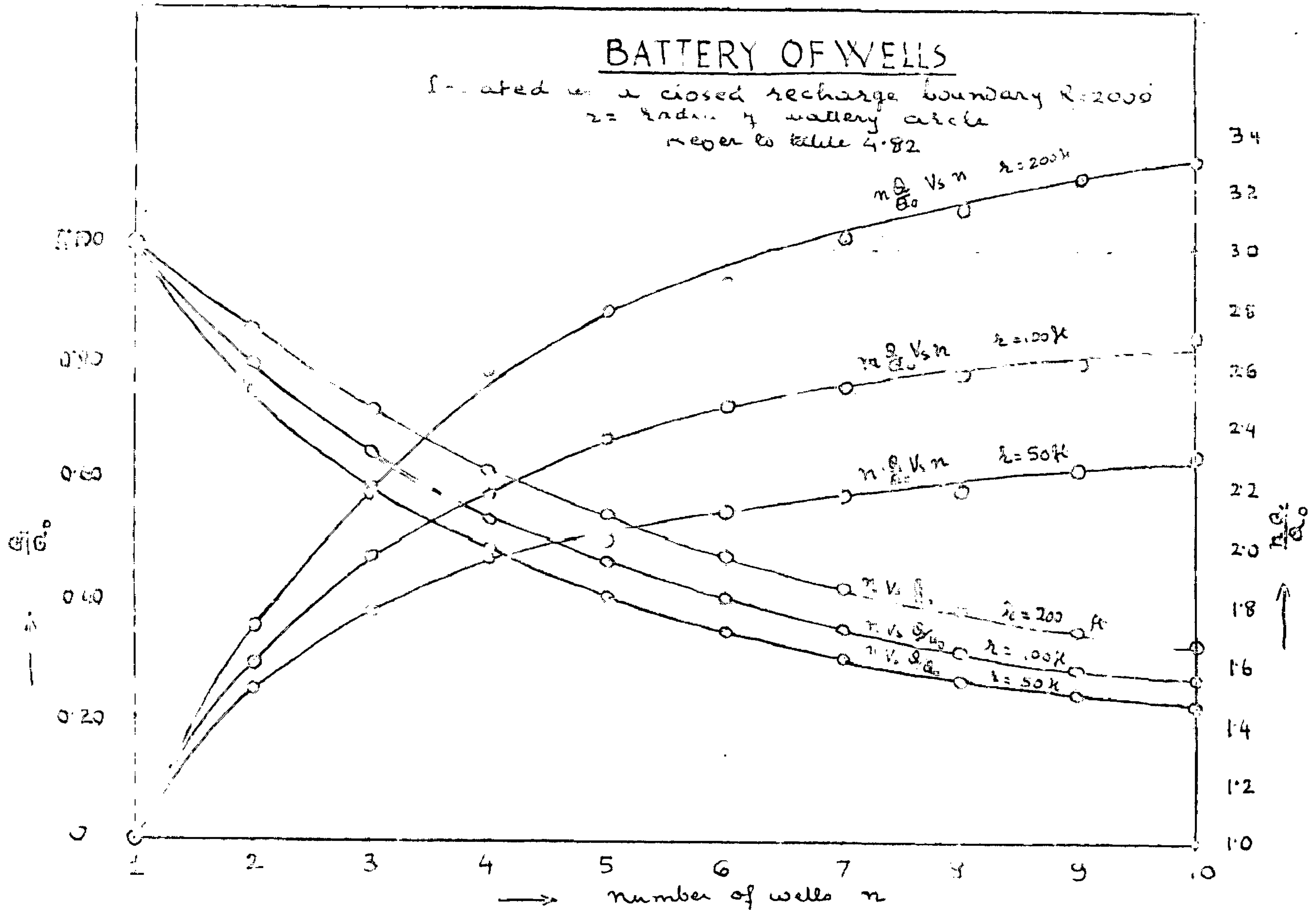


FIG 4·82 - Influence of number of wells and radius of battery circle on discharges

A BATTERY OF WELLS LOCATED IN A CLOSED RECHARGE BOUNDARY

TABLE 4.83

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DRAWDOWN CURVES

... H = 20 ft, hw = 0, rw = 0.25 ft

KB= 0.107 ft^2/sec.

... Refer to equation 4.87

Draw down curves have been plotted through a diameter passing through two circles.

n = number of wells in the battery.

x = distance in feet from centre.

n = 2 Q = 1.28 cfs h (feet)	n = 4 Q=0.93 cfs h (feet)	n=6 Q=0.72 cfs h (feet)	n=8 Q=0.59 cfs h (feet)	n=10 Q=0.49 cfs h (feet)
11.25	7.30	5.25	3.90	3.30
11.15	7.28	5.20	3.89	3.28
10.94	7.25	5.18	3.87	3.25
10.40	7.10	5.10	3.84	3.20
9.53	6.56	4.90	3.70	3.15
8.10	5.80	4.45	3.35	2.90
0	0	0	0	0

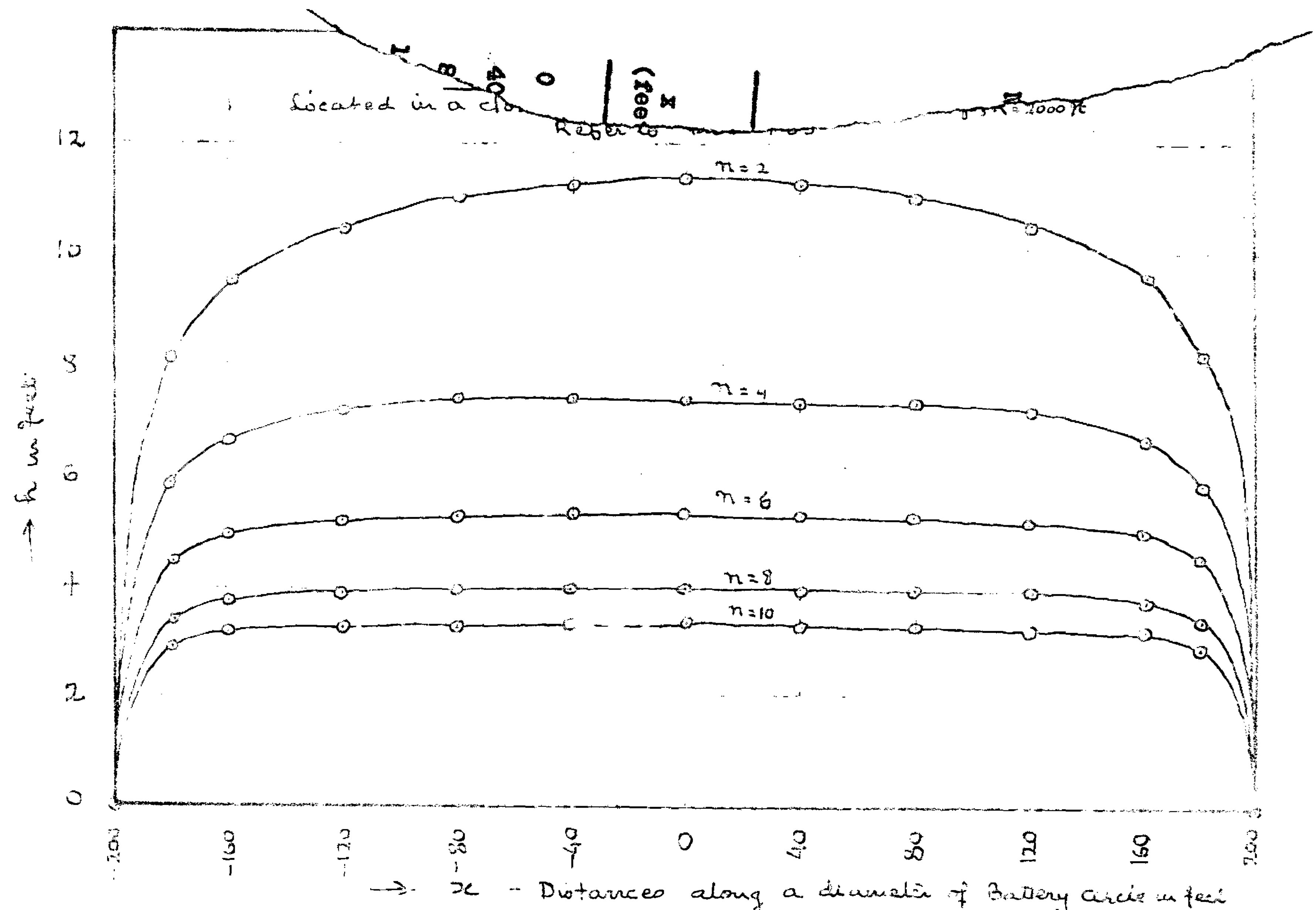


FIG. 4.93 - Effect of number of wells in a battery on drawdown curves.
Drawdown curve along a dia passing through any two wells in the battery

TWO WELLS PLACED AT RIGHT ANGLES TO AN INFINITE LINE DRIVE

TABLE 4.91

EFFECT OF INTERFERENCE OF WELLS ON DISCHARGE

Data: ... $H = 20$ ft, $hw = 0$, $rw = 0.25$ ft.

$KB = 0.107\ ft^2/sec.$

Note: ... Refer to equation 4.97

Drawdown is equal on faces of wells.

Q = average discharge = $\frac{Q_1 + Q_2}{2}$

Q_o = Discharge of a single well placed at a distance d_1 from line drive.

results plotted in Fig. 4.91.

$d_2 - d_1$ (feet)	d_1 = 500 ft, Q_o = 1.63 cfs				d_1 = 1000 ft, Q_o = 1.5 cfs			
	Q_1	Q_2	$\frac{Q_2}{Q_1}$	$\frac{Q}{Q_o}$	Q_1	Q_2	$\frac{Q_2}{Q_1}$	$\frac{Q}{Q_o}$
100	1.26	1.22	0.97	0.76	1.13	1.11	0.99	0.75
200	1.35	1.29	0.96	0.81	1.19	1.14	0.96	0.77
500	1.45	1.32	0.91	0.85	1.28	1.20	0.94	0.83
1000	1.51	1.34	0.88	0.87	1.34	1.23	0.92	0.86
2000	1.56	1.35	0.87	0.89	1.38	1.23	0.89	0.88
	d_1=2000 ft, Q_o=1.4 cfs				d_1=5000 ft, Q_o=1.28 cfs			
100	1.01	1.00	0.99	0.72	0.90	0.89	0.99	0.70
200	1.06	1.04	0.98	0.75	0.94	0.93	0.99	0.73
500	1.14	1.10	0.97	0.80	1.00	0.99	0.99	0.78
1000	1.19	1.14	0.96	0.85	1.04	1.02	0.98	0.80
2000	1.26	1.16	0.93	0.87	1.10	1.06	0.96	0.85

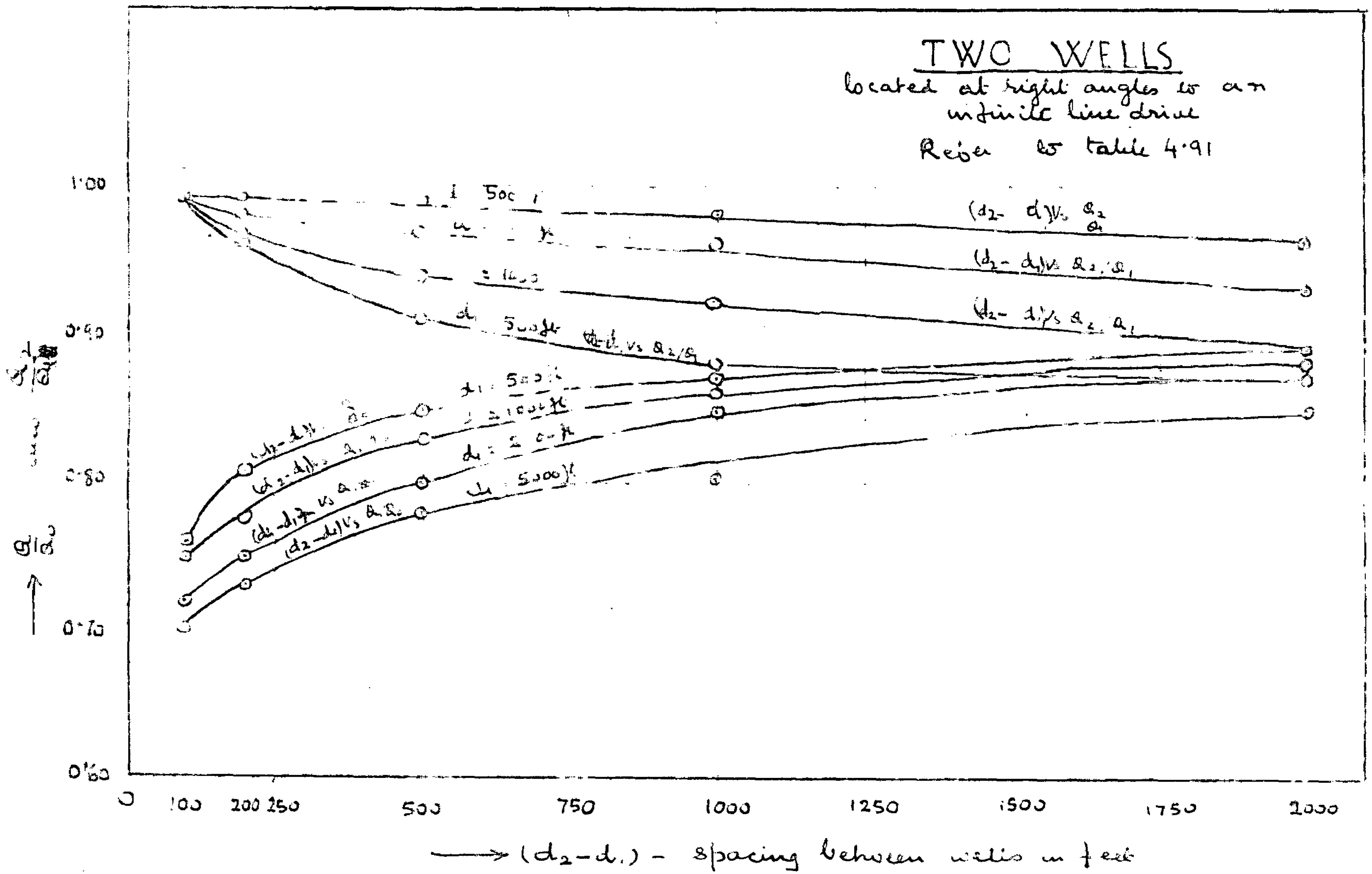


FIG. 4.91 - Influence of distance between wells on discharge

TWO WELLS PLACED PARALLEL TO A RECHARGE BOUNDARY OR AN INFINITE LINE DRIVE

TABLE 4.101

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DISCHARGES

Data: ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft

$KB = 0.107$ ft^2/sec.

Note: ... Refer to equation 4.104.

Drawdowns at the faces of wells are equal.

Q_o=discharge of a single well under identical conditions.

Results plotted in Fig. 4.101.

	d=500 ft Q_o=1.63 cfs		d=1000 ft Q_o=1.50 cfs		d=2000 ft Q_o=1.44 cfs		d=5000 ft Q_o=1.28 cfs	
a (feet)	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$
100	1.27	0.78	1.13	0.75	1.01	0.72	0.89	0.70
200	1.36	0.84	1.20	0.80	1.08	0.76	0.93	0.73
500	1.48	0.91	1.30	0.86	1.15	0.82	0.99	0.77
1000	1.56	0.96	1.38	0.92	1.21	0.86	1.05	0.82
2000	1.60	0.98	1.45	0.97	1.29	0.92	1.10	0.86

THREE WELLS PLACED PARALLEL TO A RECHARGE BOUNDARY OR INFINITE LINE DRIVE

TABLE 4.111

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DISCHARGES

Data: ... $H = 20$ ft, $hw = 0$, $rw = 0.25$

$K = 0.107\ ft^2/sec.$

Note: ... Refer to Equation 4.118

Q = Average discharge = $\frac{Q_1 + Q_2 + Q_3}{3}$

Q_o = Discharge of a single well under identical conditions

Results plotted in Fig. 4.111.

$\frac{d}{a}$	a = 200 ft, Q_o = 1.83 cfs				a = 500 ft, Q_o = 1.63 cfs			
	Q_1 (cfs)	Q_2 (cfs)	$\frac{Q_2}{Q_1}$	$\frac{Q}{Q_o}$	Q_1 (cfs)	Q_2 (cfs)	$\frac{Q_2}{Q_1}$	$\frac{Q}{Q_o}$
0.1	2.64	2.63	1.00	0.99	2.24	2.24	1.00	0.99
0.2	2.31	2.30	0.99	0.97	1.96	1.93	0.99	0.97
0.5	1.91	1.83	0.97	0.92	1.07	1.02	0.97	0.93
1.0	1.61	1.49	0.93	0.86	1.44	1.35	0.94	0.87
1.5	1.42	1.30	0.92	0.80	1.30	1.21	0.93	0.82
2.0	1.33	1.21	0.91	0.77	1.19	1.12	0.92	0.80
2.5	1.26	1.10	0.90	0.74	1.15	1.06	0.91	0.76
	a = 1000 ft, Q_o = 1.50 cfs				a = 2000 ft, Q_o = 1.40 cfs			
0.1	2.02	2.02	1.00	1.00	1.82	1.82	1.00	1.00
0.2	1.79	1.77	0.99	0.97	1.65	1.64	0.99	0.99
0.5	1.55	1.50	0.97	0.94	1.43	1.40	0.98	0.95
1.0	1.33	1.27	0.94	0.87	1.23	1.16	0.95	0.87
1.5	1.23	1.14	0.93	0.83	1.15	1.08	0.94	0.84

2.0	1.17	1.06	0.92	0.81	1.08	1.01	0.93	0.82
2.5	1.09	1.01	0.92	0.78	1.03	0.96	0.93	0.80

INFINITE ARRAY OF WELLS PARALLEL TO AN INFINITE LINE DRIVE - SINGLE ARRAY

TABLE 4.121

EFFECT OF MUTUAL INTERFERENCE OF WELLS ON DISCHARGES

Data: ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft

$KB = 0.107\ ft^2/sec.$

Note: ... Refer to equation 4.125

Q_o = Discharge of a single well for the same value of d.

d = distance from line drive.

a = spacing between wells.

Results plotted in Fig. 4.121

	d=500 ft Q_o=1.63 cfs		d=1000 ft Q_o=1.50 cfs		d=2000 ft Q_o=1.40 cfs		d=5000 ft Q_o=1.28 cfs.	
a (feet)	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$	Q (cfs)	$\frac{Q}{Q_o}$
100	0.38	0.24	0.20	0.13	0.10	0.07	0.04	0.03
200	0.66	0.41	0.38	0.25	0.20	0.15	0.08	0.06
500	1.12	0.69	0.74	0.49	0.44	0.31	0.20	0.16
1000	1.41	0.86	1.06	0.71	0.71	0.51	0.36	0.28
2000	1.56	0.96	1.31	0.87	1.00	0.71	0.59	0.46

TABLE 4.122

DRAWDOWN CURVE ALONG A LINE PASSING THROUGH THE CENTRES OF WELLS

~~Centres of~~ d = 100 ft, a = 500 ft, Q = 0.74 cfs
Refer to equation 4.116. (Fig. 4.122)

x (feet)	0.25	25	50	100	150	200	250
h (feet)	0	5.0	5.7	6.4	6.8	6.9	7.0

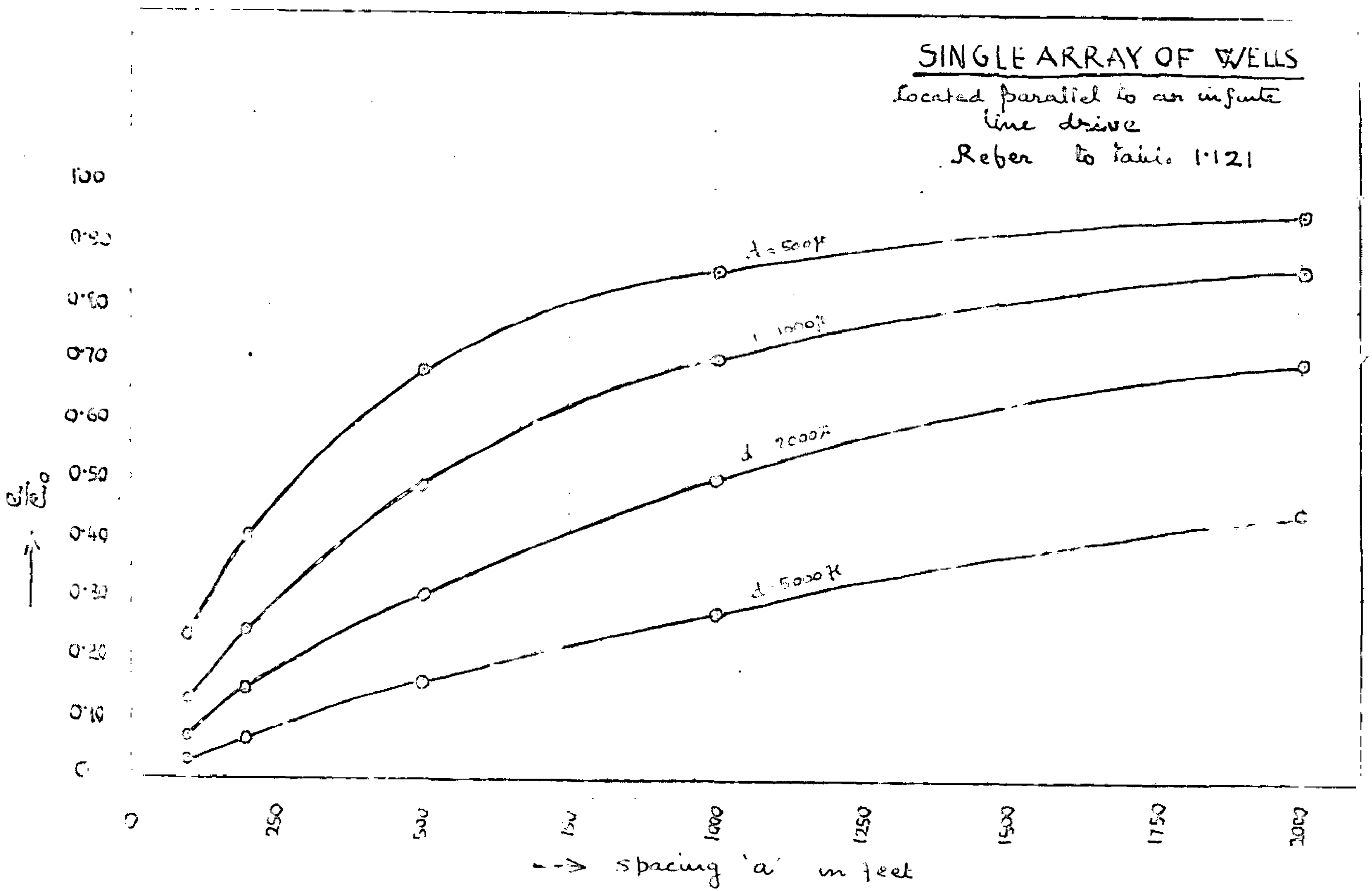


FIG - 4.121 - Influence of spacing of wells 'a' and distance from line drive, 'd' on discharges

INFINITE ARRAY OF WELLS PARALLEL TO A LINE DRIVE-SINGLE ARRAY [illegible]

TABLE 4.123

EFFECT OF MUTUAL INTERFERENCE ON DRAW DOWN

Data: ... $H = 20$ ft, $h_w = 0$, $r_w = 0.25$ ft,

$KB = 0.107$ ft^2/sec, $d = 1000$ ft, $a = 500$ ft,

$a = 500$ ft, $d = 1000$ ft, $Q = 0.74$ cfs.

Notes: ... Refer to equation 4.126

Drawdown along line at right angles to the line drive.

Case I - $x = 0$ Line passing through a well

Case II- $x = 250$ ft, water divide.

Results plotted in fig. 4.133.

Along a line passing through a well				Along the water divide, x=250ft			
y (feet)	h (feet)	y (feet)	h (feet)	y (feet)	h (feet)	y (feet)	h (feet)
0	20.00	1050	5.35	0	20.00	1050	6.70
250	16.55	1100	5.85	250	16.57	1100	6.50
500	13.10	1150	6.00	500	13.10	1150	6.36
750	9.65	1200	6.20	750	9.70	1200	6.32
800	8.90	1250	6.20	800	9.00	1250	6.30
850	8.10	1500	6.25	850	8.45	1500	6.30
900	7.20	2000	6.25	900	7.90	2000	6.30
950	6.20	5000	6.30	950	7.40	5000	6.30
1000	0	10000	6.30	1000	7.00	10000	6.30

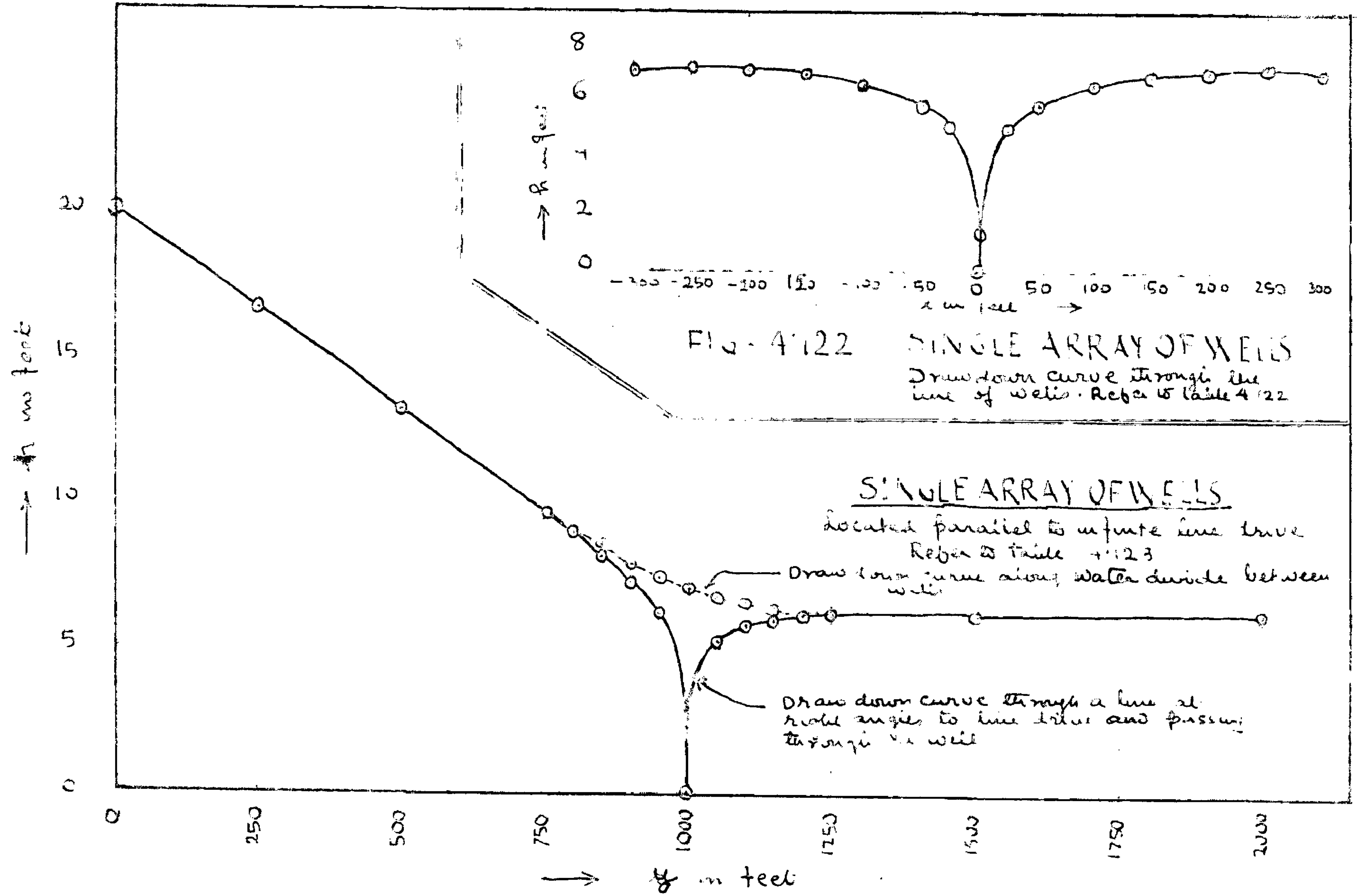


FIG - 4.122 SINGLE ARRAY OF WELLS
Drawdown curve through the line of wells. Refer to table 4.122

FIG - 4.123 Drawdown Curves - (a) along a line passing through a well and at right angles to line drive. (b) Along the water divide between wells

INFINITE ARRAY OF WELLS PARALLEL TO AN INFINITE LINE DRIVE DOUBLE ARRAY

TABLE 4.131

EFFECT OF MUTUAL INTERFERENCE ON DISCHARGES AND SHIELDING CHARACTERISTICS

Data ... $H = 20$ ft, $hw = 0$, $rw = 0.25$, $KB = 0.107$ ft^2/sec.

Note: ... Refer to equation 4.137

$a = d_2 - d_1$

S = Shielding effect = $\frac{Q_1}{Q_1+Q_2}$

Q_o = Discharge of a single well for $d = d_1$

Results plotted in Fig. 4.131 and 4.132

a (feet)	$\frac{d_1}{a}$	Q_1 (cfs)	Q_2 (cfs)	$\frac{Q_2}{Q_1}$	$\frac{Q_1}{Q_2+Q_1}$	$\frac{Q}{Q_o}$
1	2	3	4	5	6	7
100	0.1	2.89	1.09	0.364	0.733	0.66
	0.2	2.33	0.90	0.386	0.722	0.61
	0.5	1.57	0.62	0.396	0.716	0.49
	1.0	1.03	0.41	0.396	0.716	0.36
	1.5	0.78	0.31	0.396	0.716	0.29
	2.0	0.62	0.25	0.396	0.716	0.24
	2.5	0.52	0.21	0.396	0.716	0.21
200	0.1	2.50	1.01	0.404	0.712	0.67
	0.2	2.07	0.88	0.425	0.702	0.62
	0.5	1.45	0.63	0.435	0.699	0.[illegible]
	1.0	0.98	0.43	0.435	0.699	0.39
	1.5	0.74	0.32	0.435	0.699	0.31
	2.0	0.59	0.26	0.435	0.699	0.26
	2.5	0.50	0.22	0.435	0.699	0.22

1	2	3	4	5	6	7
500	0.1	2.13	0.96	0.450	0.690	0.69
	0.2	1.84	0.86	0.467	0.682	0.63
	0.5	1.32	0.63	0.467	0.678	0.55
	1.0	0.91	0.43	0.467	0.678	0.41
	1.5	0.69	0.33	0.467	0.678	0.33
	2.0	0.56	0.27	0.467	0.678	0.28
	2.5	0.47	0.22	0.467	0.678	0.24
1000	0.1	1.92	0.92	0.480	0.675	0.70
	0.2	1.65	0.82	0.490	0.667	0.65
	0.5	1.20	0.61	0.506	0.665	0.56
	1.0	0.85	0.43	0.506	0.665	0.43
	1.5	0.65	0.33	0.506	0.665	0.34
	2.0	0.55	0.28	0.506	0.665	0.31
	2.5	0.45	0.23	0.506	0.665	0.29
2000	0.1	1.73	0.88	0.506	0.650	0.71
	0.2	1.41	0.74	0.523	0.642	0.67
	0.5	1.13	0.60	0.532	0.639	0.58
	1.0	0.81	0.43	0.532	0.639	0.46
	1.5	0.63	0.34	0.532	0.639	0.37
	2.0	0.51	0.27	0.532	0.639	0.37
	2.5	0.43	0.23	0.532	0.639	0.26

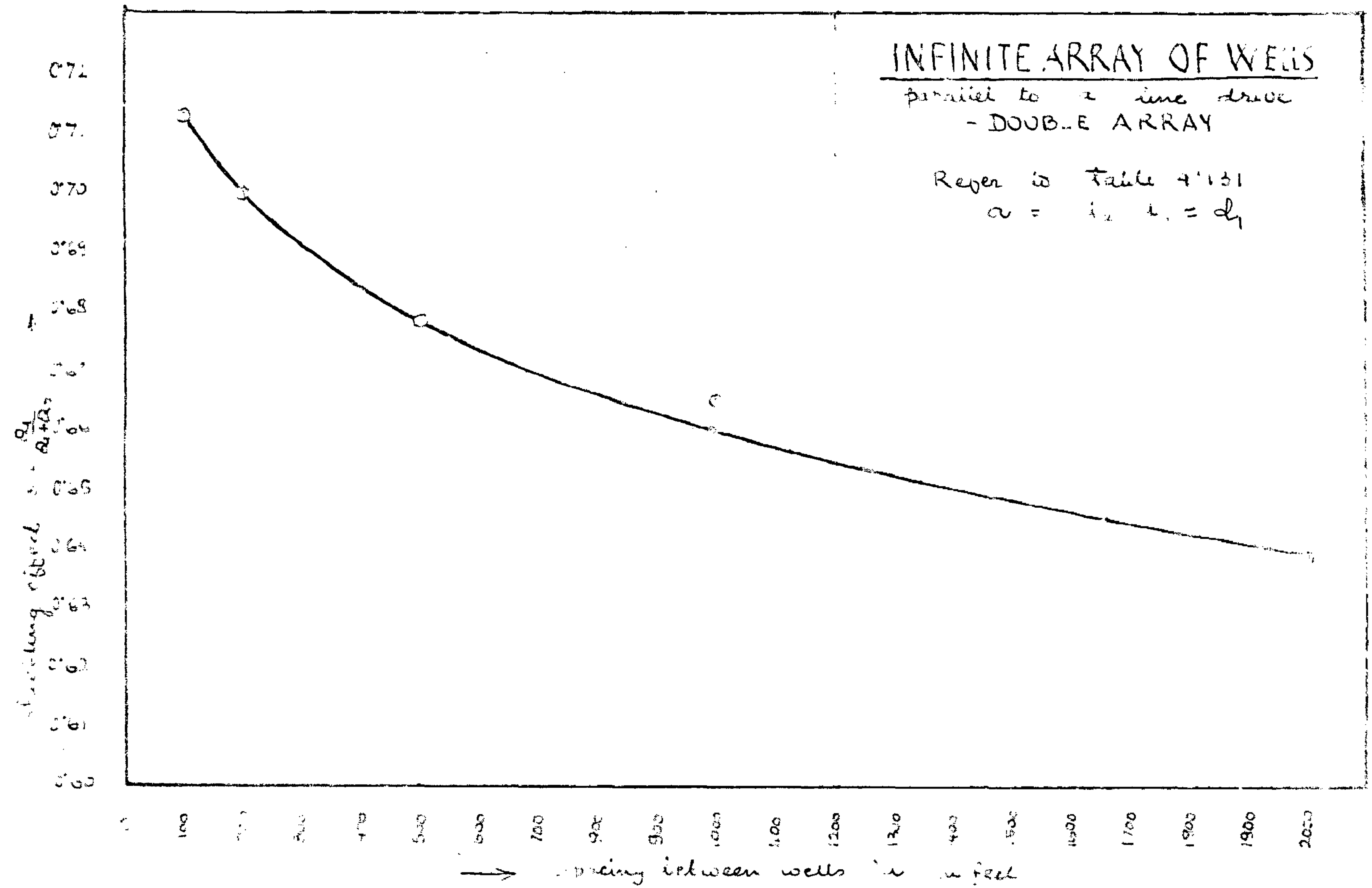


FIG 4·131 – Shielding characteristics of an array of wells

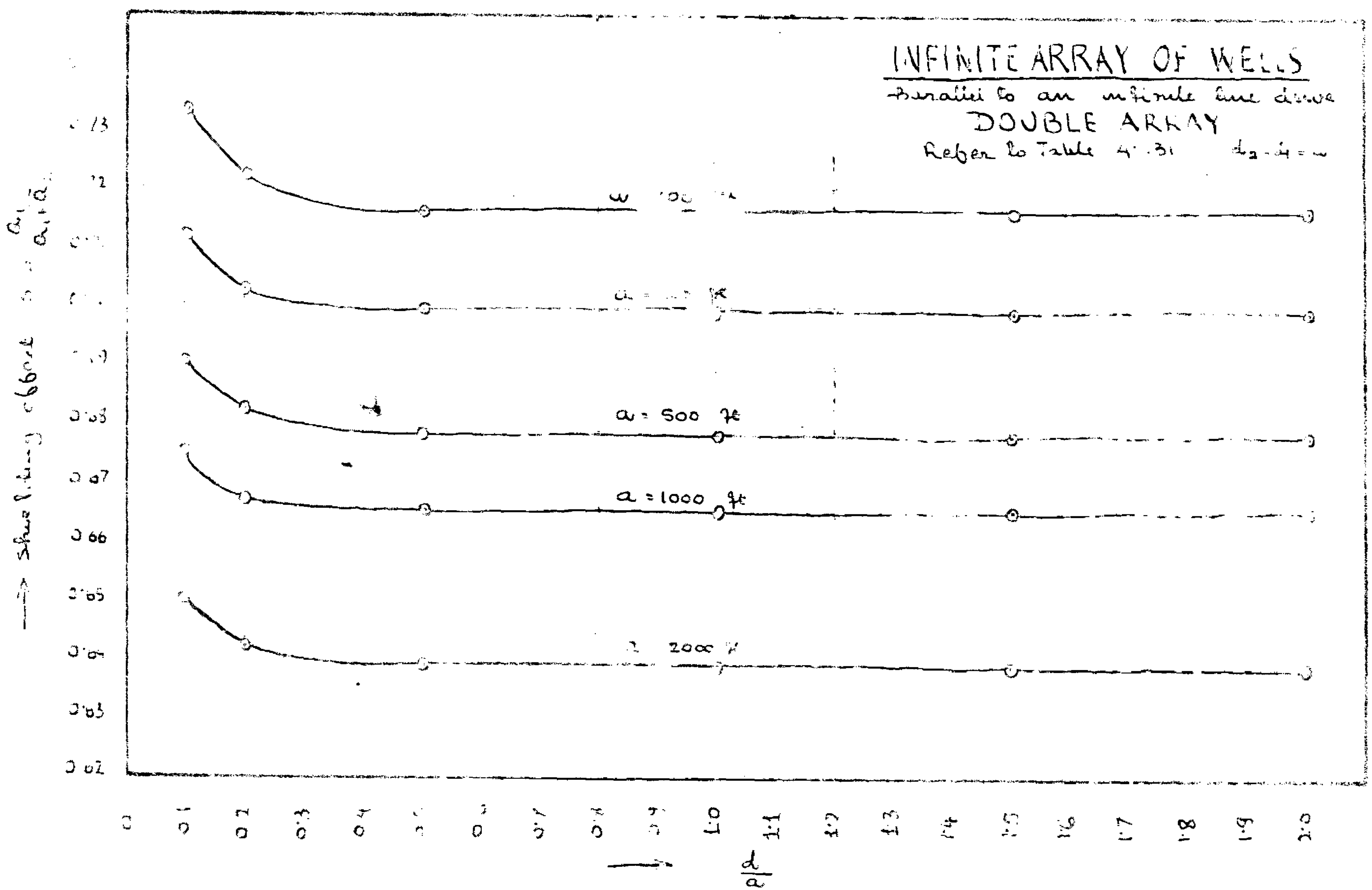


Fig 4.132 Shielding Characteristics of arrays of wells

TABLE 4.132

EFFECT OF INTERFERENCE ON SHIELDING CHARACTERISTICS DOUBLE ~~AWAY~~ array OF WELLS (Fig.4.133)

$\frac{d_2 - d_1}{a}$	$a = d_1 = 500$ ft		$a = d_1 = 1000$ ft	
	$\frac{Q_2}{Q_1}$	$\frac{Q_1}{Q_1+Q_2}$	$\frac{Q_2}{Q_1}$	$\frac{Q_1}{Q_1+Q_2}$
0.2	0.810	0.563	0.830	0.547
0.5	0.646	0.607	0.672	0.598
1.0	0.478	0.677	0.506	0.664
1.5	0.373	0.727	0.407	0.710
2.0	0.309	0.763	0.339	0.746
2.5	0.262	0.792	0.291	0.775

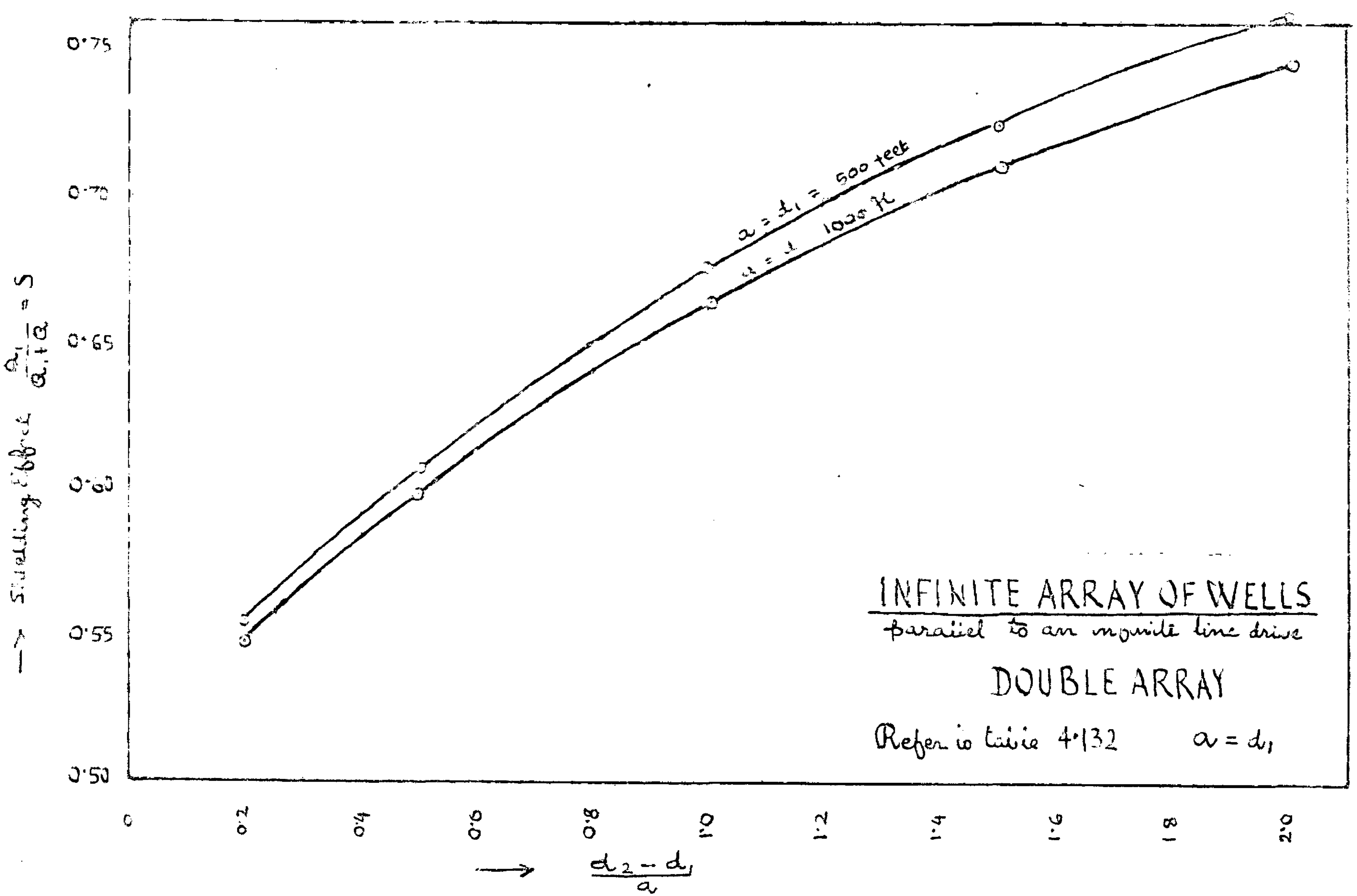


FIG- 4·133 – Shielding characteristics of arrays of wells.

INFINITE ARRAY OF WELLS PARALLEL TO AN INFINITE LINE DRIVE - DOUBLE ARRAY

TABLE 4.133

EFFECT OF MUTUAL INTERFERENCE ON DRAWDOWN

Data : ... H = 20 ft, hw = 0, rw = 0.25 ft

KB = 0.107 ft^2/ sec, d_1= 1000 ft, d_2=1500 ft,

a = 500 ft, Q_1 = 0.56 cfs, Q_2 = 0.27 cfs.

Note: ... Refer to Equation 4.138

Drawdown along lines at right angles to line drive.

Case I - x = 0 - Line through wells.

Case II- x = 250 ft - water divide.

Results plotted in Fig. 4.134 and 4.135

Line passing through wells-x=0				Water divide x = 250 ft			
y (feet)	h (feet)	y (feet)	h (feet)	y (feet)	h (feet)	y (feet)	h (feet)
0	20.00	1150	3.70	0	20.00	1150	3.92
250	16.13	1200	3.44	250	16.14	1200	3.59
500	12.25	1250	3.15	500	12.30	1250	3.33
750	8.37	1300	3.03	750	8.43	1300	3.10
800	7.58	1350	2.75	800	7.73	1350	2.85
850	6.74	1400	2.42	850	7.00	1400	2.66
900	5.79	1450	2.00	900	6.27	1450	2.48
950	4.85	1500	0	950	5.67	1500	2.34
1000	0	1550	1.75	1000	5.14	1550	2.22
1050	3.64	1600	1.92	1050	4.60	1600	2.15
1100	3.78	2000	2.05	1100	4.39	2000	2.05

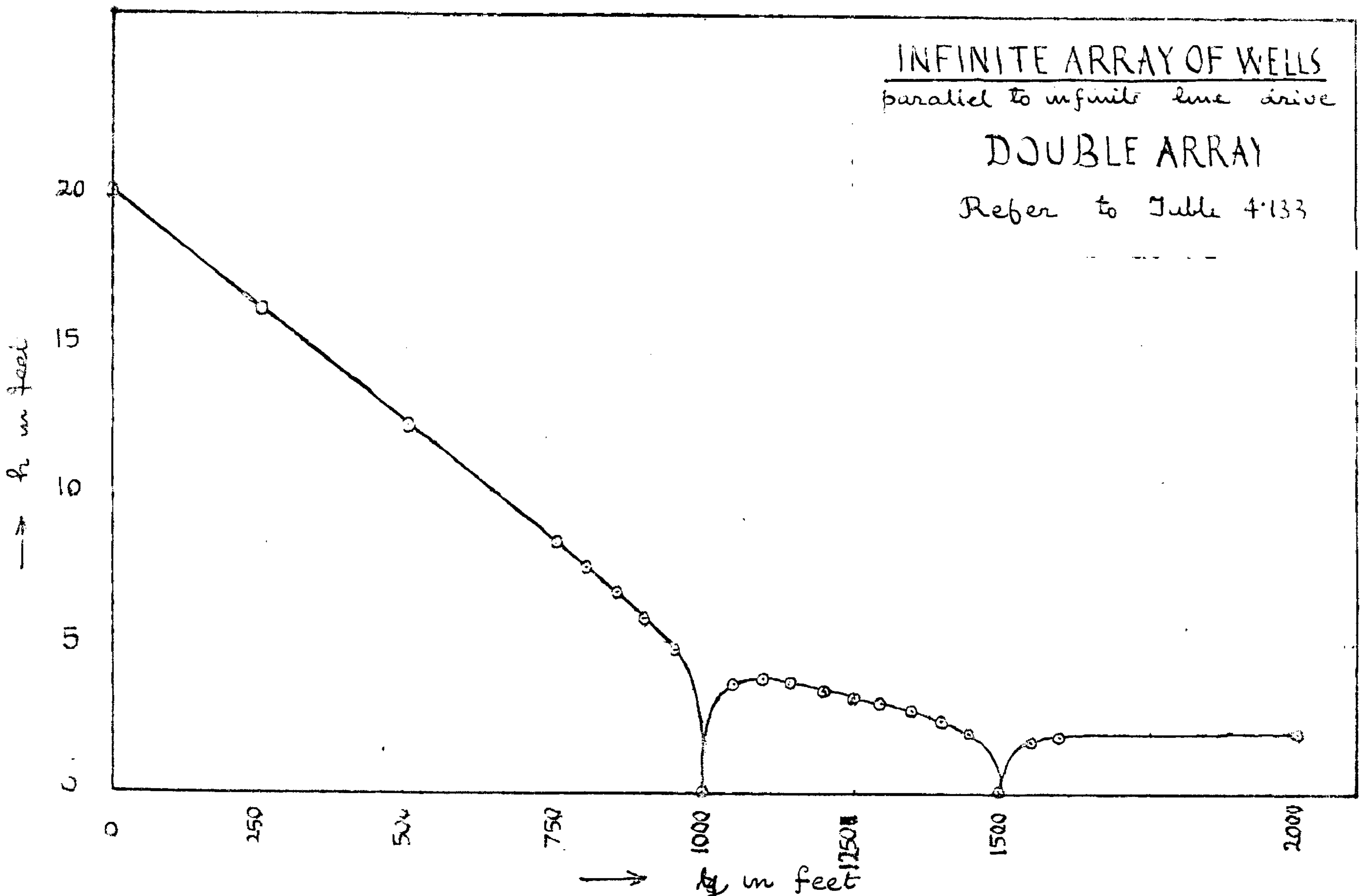


FIG 4·134 – Drawdown Curve along a line passing through wells and at right angles to line drive

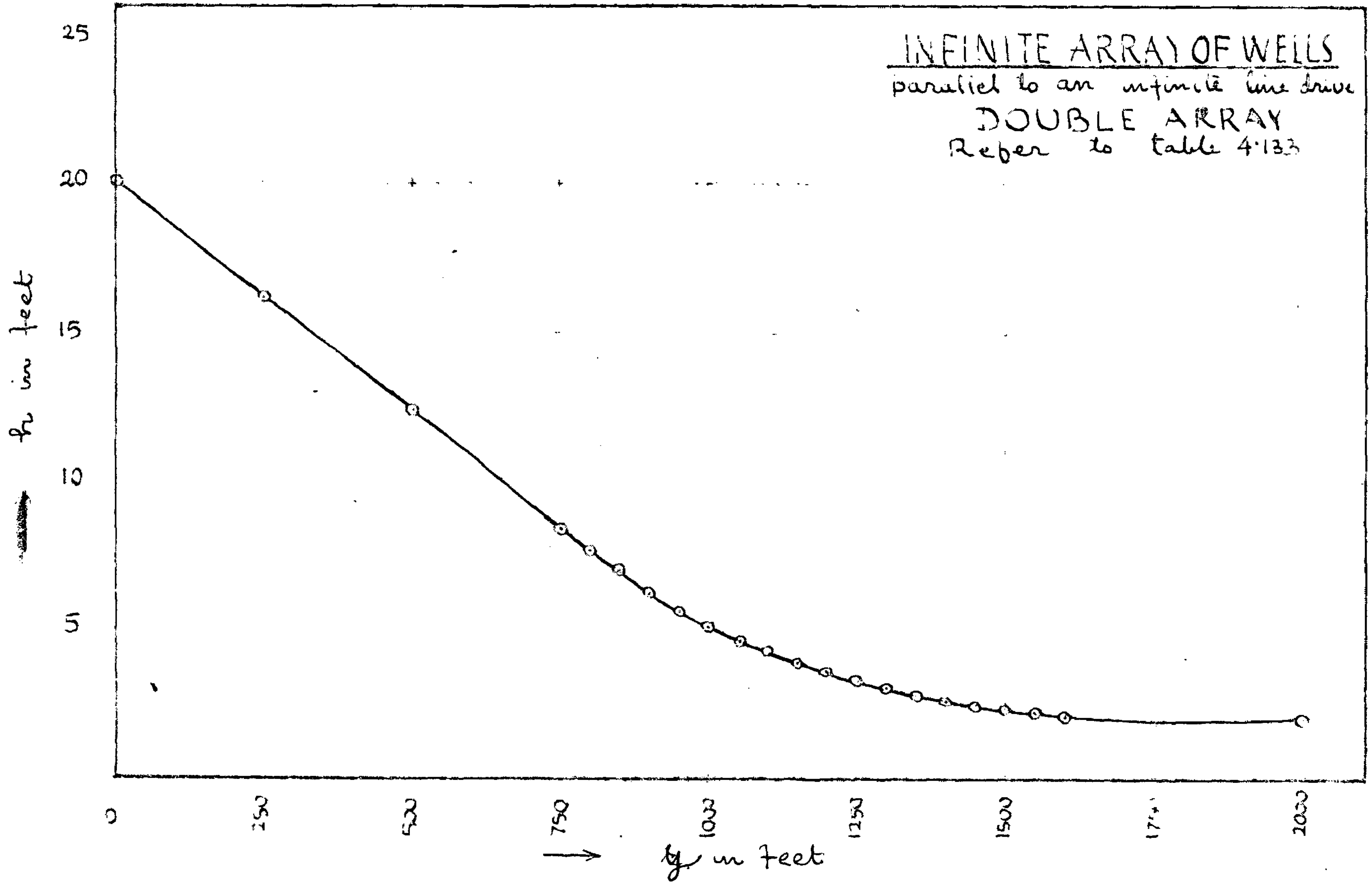


FIG - 3·135 Drawdown Curve along water divide between wells and at right angles to line drive

<u>Infinite array of wells parallel to an infinite line drive- Double array of wells in staggered setting:</u>

Table 4.141 - Shielding effect of first array for different values of (d_2-d_1)

<u>Data</u> - H = 20 ft, h_w = 0, r_w = 0.25 ft.

KB = 0.107 $ft.^2$/sec.

<u>Notes</u> - Refer to equation 4.144

a = spacing between wells

d_1= Distance of first array from recharge boundary

d_2-d_1 = spacing between the two arrays of wells.

Shielding effect = $\frac{Q_1}{Q_1+Q_2}$

$\frac{d_2-d_1}{a}$	a = 500 ft. d_1= 500 ft.			a = 1000 ft. d_1 = 1000 ft.		
	d_2	$\frac{Q_2}{Q_1}$	$\frac{Q_1}{Q_1+Q_2}$	d_2	$\frac{Q_2}{Q_1}$	$\frac{Q_1}{Q_1+Q_2}$
0.1	550	0.91	0.53	1100	0.92	0.52
0.2	600	0.82	0.55	1200	0.84	0.54
0.5	750	0.65	0.61	1500	0.67	0.60
1.0	1000	0.48	0.68	2000	0.51	0.66
1.5	1250	0.38	0.73	2500	0.40	0.72
2.0	1500	0.31	0.76	3000	0.34	0.75
2.5	1750	0.27	0.79	3500	0.29	0.77

Chap V – CONCLUSIONS AND PRACTICAL APPLICATIONS

Conclusions:

The analytical derivations, computations for a working range of variables and conclusions connected with the behaviour of a single well and groups of wells and the effects of mutual interference between wells have been discussed in detail in Chapters III and IV. The significant conclusions based on the present study are detailed below:

(a) Performance of a single well-

(i) Variation of discharge is to the extent of 9% ~~20%~~ for a variation of 150% in the value of R from 2000 ft. to 5000 ft.(Table 3.11, Fig.3.11). Any value of R of the above order is therefore good enough for analysis of field problems.

(ii) Increase in the discharge is 50% for a 20 fold increase in the radius of the well from 0.25 ft. to 5 ft. and 100% for 100 fold increase from 0.25 ft. to 25 ft.(Table 3.12, Fig.3,12) It is not economical to have large diameters of wells.

(iii) An eccentricity of 70% in the location of a well in a closed recharge boundary, increases the discharge by 10%(Table 3.21, Fig.3.21). The effect of eccentricity can therefore be ignored in analysis of field problems.

(iv) Iregular shape of a closed recharge boundary has nominal effect on discharge (Para 3.4)

(v) Presence of recharge boundary, impervious boundary and other geological discontinuities influence the behaviour of a well substantially. Individual cases should be analysed according to treatment given in para 3.4, 3.5 and 3.6.

(vi) Natural flow in an aquifer modifies the flow pattern. Low velocities upto 50 ft.100 ft/year, effect the region of influence nominally.(Para 3.7, Fig. 3.70). Higher velocities convert the region of influence into a narrow strip parallel to the direction of flow. In such cases, the wells can be placed close to each other(at right angles to the direction of flow) without causing interference.

(b) Performance of groups of wells in closed recharge boundaries, Fig.5.10 gives the effect of putting one to ten wells with equal spacing in a closed area. All comparisons have been made with respect to a single well in identical conditions. Specific points connected with cases under study are given below:

(i) Two wells:- For $\frac{a}{R}$ = 0.2 the discharge is reduced to 85%.(Table 4.11 Fig.4.11).

a = spacing between wells.

R = Radius of recharge boundary or radius of influence.

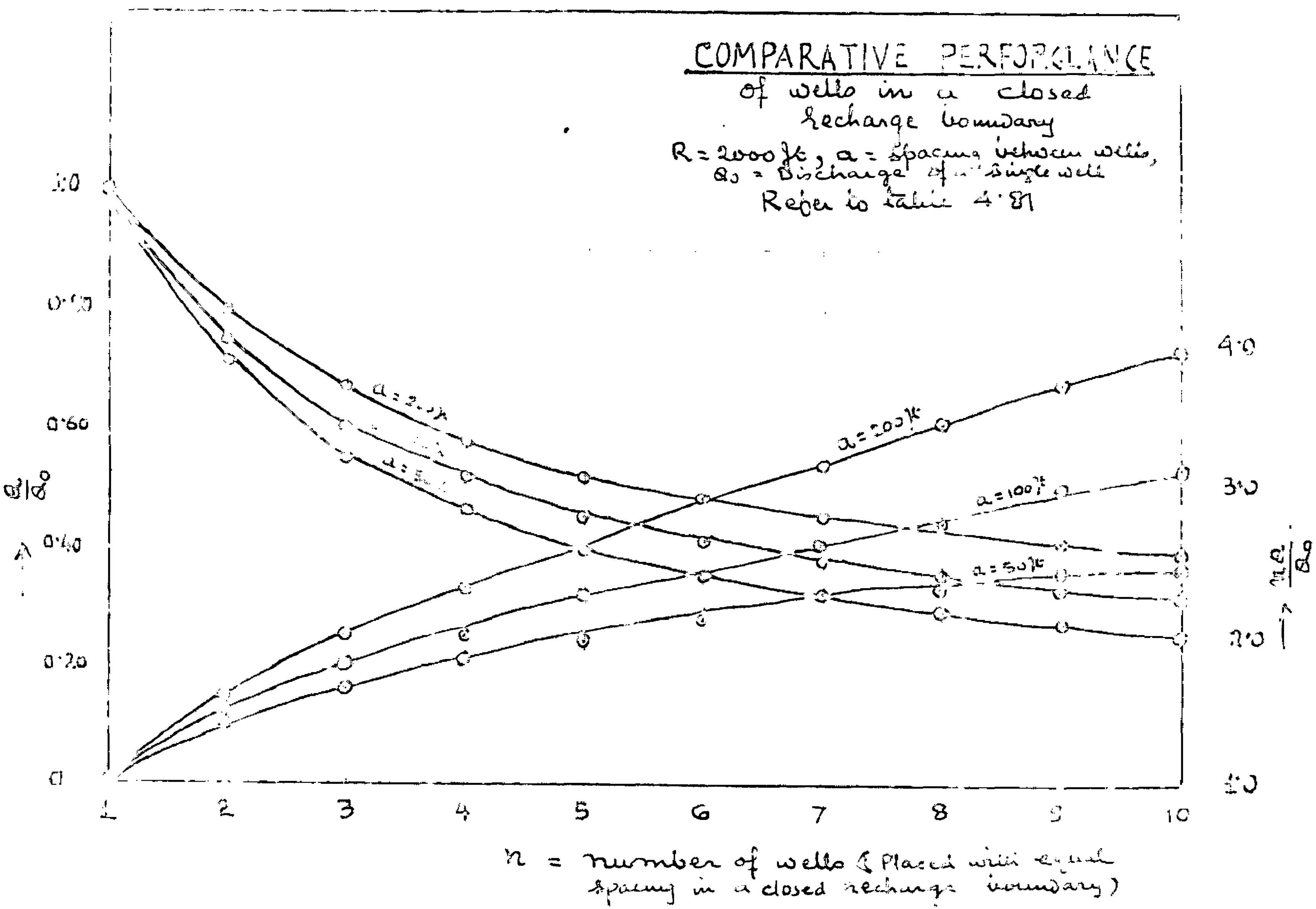


FIG - 5.10 Influence of number of wells on discharge.

(ii) Three wells in a straight line- equal drawdown. For $\frac{a}{R}$ = 0.2 the average discharge of three wells is 77%. Ratio of discharges of end wells to that of central wells is of the order of 90%(Table 4.21, Fig.4.21).

(iii) Three wells in a straight line-equal discharge from all wells. The average discharge for $\frac{a}{R}$ =0.2 is 74%. The end wells register 11% lesser drawdown than the central well(Table 4.32 Fig.4.32).

(iv) ~~From~~ Four wells placed in a square pattern. Average discharge for $\frac{a}{R}$ =0.2 is 66.7%(Table 4.51).

(v) Battery of wells arranged along the circumference of a circle- For $\frac{r}{R}$ =0.1 the discharge drops from 86% in the case of two wells, to 55%, for ~~In~~ five wells ~~end~~ and to 33% for ten wells where r is the radius of the battery circle.(Table 4.82, Fig.4.82). As compared to a drawdown of 20 ft at the face of the wells the drawdown at the centre of the battery circle is 8.75 ft for two wells, 14.15 ft for six wells and 16.7 ft for ~~In~~ ten wells. For ~~form~~ four wells and ~~more~~ above 75% of the enclosed zone has more or less uniform drawdown.(Table 4.83, Fig.4.83). ~~One to Fig.5.10 gives the effect of putting one to ten equally spaced wells in an~~ .

(c) Performance of wells located on one are side of a line drive. Fig.5.20 gives a camparison of the performance of different arrangements parallel to a line drive. All comparisons have been made with respect to performance of a single well in identical conditions. Significant points of actual cases under study are given below:

(i) Two wells placed at right angles to the line drive - the average discharge is of order of 85% for when the ratio $\frac{d_2-d_1}{d_1}$ ranges ~~for~~ from 0.5 to 1.0.(Table 4.91 Fig.4.91). d_1 = distance of first well from line drive. d_2 = distance of second well from line drive.

(ii) Two wells parallel to a line drive- The discharge for a ratio of ~~a = p~~ $\frac{a}{d} = 1$ is 92%(Table 4.101). d = distance from line drive. a = spacing between well

(iii) Three wells parallel to a line drive. The discharge for a ratio of $\frac{a}{d}$ = 1, is 87% (Table 4.111).

(iv) Infinite array of wells parallel to a line drive -single array- the discharge for a ratio of $\frac{a}{d}$ = 1, is 71% (Table 4.121) and Fig.4.121). For a = 500 ft and d = 1000 ft, the potential drops by 67.5% from 20 ft. at the line drive to 6.30% beyond the array of wells. The hydraulic gradient is uniform from line drive to a distance of $\frac{a}{2}$ from the well. The potential becomes almost constant after a distance of $\frac{a}{2}$ beyond the well(Table 4.123 and Fig.4.123).

(v) Infinite array of wells parallel to a line drive- double array -square setting. Average discharge is of the order of 40% for $a = d_1 = d_2-d_1$(Table

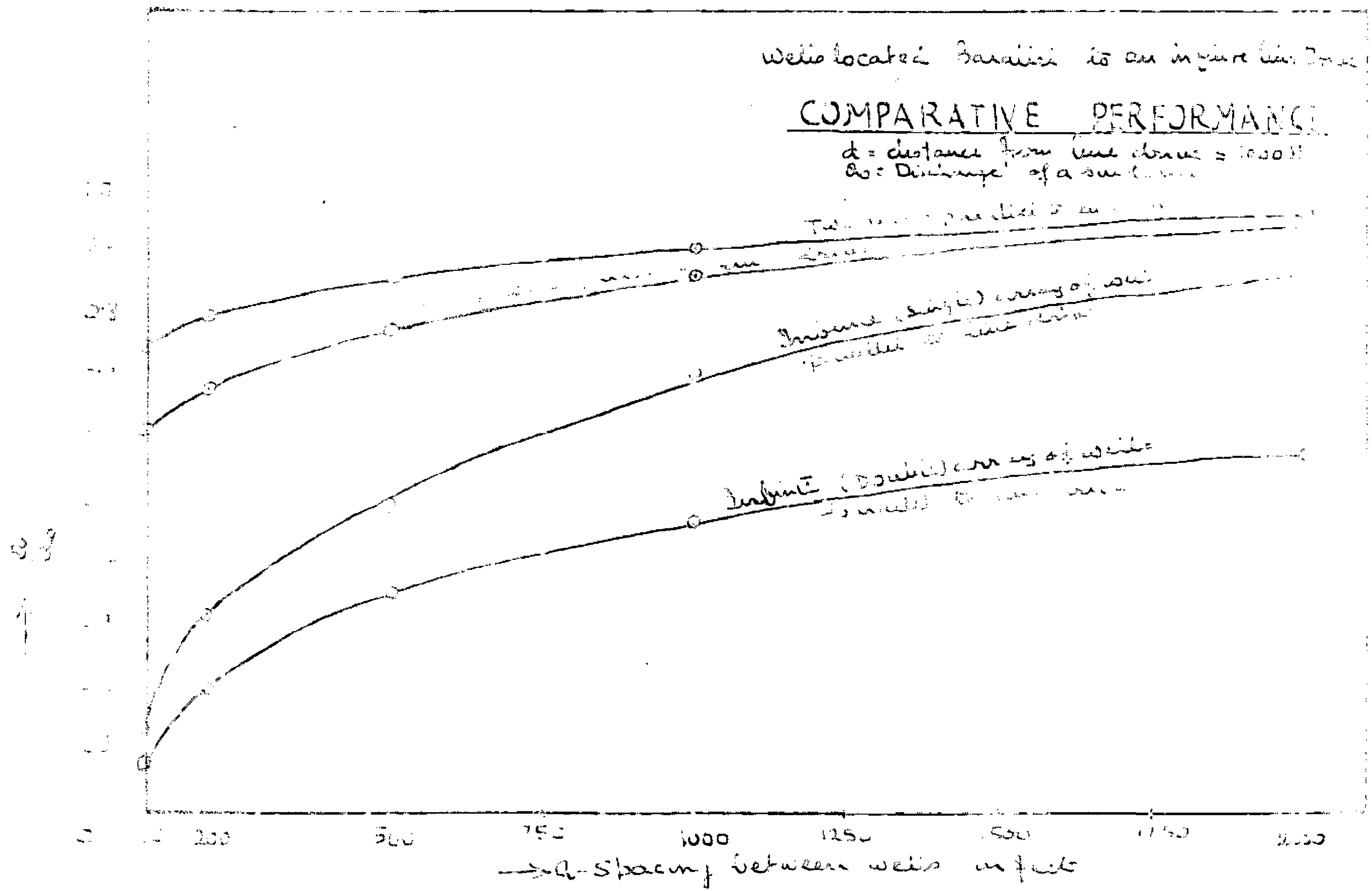


FIG-5.20 Influence of spacing between wells on discharges

4.131). Shielding effect of the first array of wells becomes constant at 65% to 70% for $\frac{d_1}{a}$ 0.5 and d_2-d_1 = a. For a = 500 ft. and $d_1 = d_2-d_1$ = 1000 ft, the potential register a drop of 90% from 20 ft at the line drive to 2.05 ft. beyond the second array of wells.

(vi) Infinite array of wells parallel to a line drive- double array-staggered setting there is no influence of ~~stagging an~~ staggering on shielding effect for values of $\frac{d_2-d_1}{a} > 0.5$. For lower values upto 0.1 the influnece is nominal.

<u>Practical Applications:</u>

(a) Planning a group of wells for irrigation. Main considerations are economy in installation and operation. The wells are generally spread out to cover large areas. Maximum allowable drawdown can be fixed from practical and economic considerations. If the recharge boundaries are defined, the treatment given in chapter IV can be utilised to determine alternative spacings and corresponding discharge for study of financial implications.

If the recharge boundary is not defined the value of R can be fixed from data available from pumping tests.

If additional wells are proposed to be installed in an area which is already ~~several~~ served by wells, the influence of additional wells an discharges of existing wells and drawdown in the area can be worked out.

(e) Drainage of water logged areas the problem is similar to that of irrigation wells. Desired drawdown is fixed from requirements of drainage. Discharge is not an important parameter. Alternative spacings and corresponding discharges can be worked out for most economical pumping.

(c) Planning wells for water supply- The problem is to have maximum water within a reasonable distance. Wells parallel to sources of recharge e.g., river, canal, lake or reservoirs are suitable for water supply. Discharge for different spacings of wells in a line or other patterns as required by topography can be worked out for study of financial implications.

(d) Dewatering operations:- The problem involves lowering the watertable to a desired level in a restricted area. If the area is closed, a battery of wells can be used in one or more circles to lower the watertable. Treatment of para 4.8 can be used for working out different spacing and discharges for study of financial implications.

If the area is open, i.e., large as compared to the width a single or double array of wells can be used. Well point system utilises this principle.

(e) Pressure relief wells down stream of earthen dams. The length of earthen dams is generally large. The pressure relief wells can therefore be treated as an infinite array of wells. The desired down stream potential is fixed from practical considerations at or a little below the river bed level. Usually discharge is not significant. As such spacing which will give a uniform lowering of potential under and downstream of the dam can be worked out.

Actual spacing will again depend on the level of collecting drain down stream of relief wells.

(f) Similarly, the present study can be utilised in preliminary studies connected with other practical problems. Although the treatment given in Chapter IV is restricted to steady state flow in confined aquifer it can also be adopted for problems in unconfined aquifer with change of constants. (Ref.Para 2.35).

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