1961

A method of estimating groundwater influx into a vertical mine shaft

Morris T. Worley

Recommended Citation

Worley, Morris T., "A method of estimating groundwater influx into a vertical mine shaft" (1961). *Masters Theses*. 4175.
https://scholarsmine.mst.edu/masters_theses/4175

A METHOD OF ESTIMATING GROUNDWATER INFLUX INTO A VERTICAL MINE SHAFT

BY

MORRIS T. WORLEY

A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE

IN

MINING ENGINEERING

Rolla, Missouri

1961

Approved by

G. E. Vaughn, Jr. (Advisor) Carl R Christiansen

James C. Maxwell Paul Dean Proctor

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table No. Page

ABSTRACT

Prediction of groundwater influx into mine openings is one of the more important pre-development problems encountered in mining. A satisfactory method of estimation would provide the information necessary for a mining company to dewater prior to shaft sinking, pre-grout the shaft area, or plan pumping schemes to handle the expected flow.

A standardized field method of estimating groundwater supply from pumping test data was developed by C. V. Theis and others. In the present research problem, the estimation procedure has been simplified by the use of nomograms. Certain modifications in the estimate must be made when a pumping well is replaced by a large diameter opening, such as a vertical mine shaft. Due to large surface area available for influx, a shaft diameter factor has been developed to account for the increased flow. During shaft sinking, influx is less than calculated by the Theis equations due to partial penetration of the water bearing strata; therefore, a correction factor for partial penetration is introduced. Finally, it is necessary to pump water from the shaft bottom at a rate equal to or greater than the rate of influx, in order that shaft sinking may proceed without interruption. An estimate is made of the amount of dewatering caused by pumping.

When pumping test data are analyzed and the results modified by correction factors, an estimate of influx is obtained which is close to that actually encountered during sinking.

STATEMENT OF THE PROBLEM

Excess influx of groundwater into mine shafts has long been one of the more important problems encountered in the development of a mining property. Much work has been done on methods of preventing such influx and on pumping schemes to control inflow if preventive measures fail. The fundamental aspects of the problem, on the other hand, seem to have been neglected.

If an economic evaluation of a property is to be made, consideration must be given to the possibility of excess water. An estimate of the quantity of water to be encountered is of value in planning grouting, pumping and other programs designed to control that influx.

The research described in this thesis is: 1) an attempt to evaluate the state of knowledge of the mining industry regarding estimation of the quantity of groundwater to be expected in shaft sinking, 2) to develop a rapid method of analyzing pumping test data in order to estimate influx into a mine shaft.

The economic importance of such a project can be shown by examining the following quotations from the column, "This Month in Mining," which appears in each issue of Engineering and Mining Journal.

From the October, 1958 issue:

> Rare Metals Corporation of America has developed more than one million tons of ore at its San Mateo mine in Ambrosia Lake (New Mexico).......Ore averages 0.26% U_3O_8 and is being reached at 1100 feet. Shaft is down to 880, where water was encountered. Sinking will continue when water is brought under control.

Based upon an AEC purchase price of $3.50 per lb. of U_3O_8 with a bonus of $ .75 per lb., if the ore contains more than 4 lb. per short ton, (1, p. 132)* this ore body has a potential value of approximately $19 million. Because of the water problem, production did not begin until November, 1959.

From the January, 1960 issue:

> Potash Company of America's new mine 15 miles east of Saskatoon (Saskatchewan) will be closed until March because of water seepage in the shaft.... The company will attempt to remedy the condition by pumping cement into the formation behind the walls of the 3300 ft. shaft.

From the February, 1960 issue:

> International Minerals and Chemicals Corporation is seeking the advice of additional consultants on procedures for lining the shaft walls to block off formation water, at its Esterhazy (Saskatchewan) potash development. Excavation of the shaft has been at a standstill since July, 1958, when the 1200 ft. level was reached. Water-impregnated Blairmore formation sands caused repeated floodings at that level....

The two properties mentioned above are located 150 miles apart in a 200 mile wide basin in southern Saskatchewan and the water problem mentioned is common to other firms operating in the area. The reserves of this basin are estimated to be 17,500 million short tons of K_2O, representing about 23% of the worlds reserves. (6, p. 672) The successful development of these vast reserves hinges upon the ability to overcome the water problem.

It should be emphasized that the method of analysis proposed in this thesis will not directly prevent the occurrence of such problems as are described above; rather it is a tool to be used in evaluating the problem before investing the capital necessary to begin development.

---

*Numbers in parentheses indicate references in bibliography.

ACKNOWLEDGEMENTS

The writer wishes to acknowledge the assistance of the following persons: Mr. G. B. Griswold, Mining Engineer, New Mexico Bureau of Mines, who first suggested the problem; Professors C. R. Christiansen, R. D. Caudle, and G. E. Vaughn, of the Mining Engineering Department, Missouri School of Mines and Metallurgy, who offered valuable criticism of the manuscript.

The United States Bureau of Mines, through the Rolla Office of Mining Research, provided financial assistance for background study.

Homestake Mining Company supplied the hydrologic data used to check the method of analysis.

INTRODUCTION TO FLOW EQUATIONS

In order to effectively approach the problem of estimating influx into a mine shaft, a knowledge of the fundamentals of fluid flow through a porous medium is necessary.

Henry Darcy, in 1856, developed an empirical relationship to explain the flow of water through sand filters. (17, p. 44) His statement that the flow rate through porous media is directly proportional to the head loss and inversely proportional to the length of flow is expressed mathematically:

$$v \sim \frac{dh}{dl}.$$ (See Appendix A for nomenclature.)

The resulting equation is a verification of the experiments of Hagan and Poiseuille who proposed a fluid flow relation after studying flow in capillary tubes. (19, p. 3) Poiseuille's law governs laminar or viscous flow, so it follows that Darcy's law must also apply to laminar flow.

Much work has been done to determine the range of validity of Darcy's law. The dimensionless ratio of inertial to viscous forces, Reynold's number, has been used to establish the upper limit of laminar flow. (12, p. 67) The upper limit has been found by several investigators to be in the range of $N_R = 1$ to 10. Theoretically, there is no lower limit. Laboratory experiments have shown that Darcy's law is valid for gradients as low as 2 or 3 inches per mile. (11, p. 447) It can be assumed that Darcy's law is a valid equation for fluid flow within the limits of natural aquifers.

A mathematical analysis discloses that Darcy's law is a solution of the Laplace equation

$$\frac{\partial 2\phi}{\partial x^2} + \frac{\partial 2\phi}{\partial y^2} + \frac{\partial 2\phi}{\partial z^2} = 0$$

when steady state flow is considered. Thus Darcy's law, Ohm's law, and Fourier's law are mathematically identical, (12, p. 140) a fact which is important in the derivation of an equation for non-steady or transient flow.

In 1863, Dupuit obtained a solution of Darcy's law for steady unidirectional flow. (17, p. 82) The solution

$$Q = \frac{2\pi K_e b(h_e - h_w)}{\ln(r_e / r_w)}$$

represents radial flow through a homogeneous, isotropic medium, when a state of equilibrium exists. Its value in the analysis of water influx into a mine shaft is to establish a relationship between flow into a drill hole and corresponding flow into a shaft. It can also be used to determine the pump capacity necessary to maintain a constant water level during mining operations.

In 1935, Theis developed a formula for determining the non-steady or transient flow through a homogeneous, isotropic medium. (16, p. 520) The formula was derived by recourse to the analogous relation between viscous fluid flow and the flow of heat by conduction. The resulting equation

$$Q = \frac{4\pi T\ (h_e - h_w)}{\int_u^{\infty} \frac{e^{-u}}{u}\, du} \qquad \text{where } u = \frac{r^2 S}{4Tt}$$

was also derived by Jacob in 1940 without recourse to the analogy. (7, pp. 575-81) The Theis equation is based on the assumptions that:

1. the medium through which the fluid flows is infinite in areal extent, homogeneous, and isotropic;
2. the well into which the fluid discharges completely penetrates the medium;
3. the characteristics of the medium remain constant at all times;
4. the initial pressure surface is horizontal;
5. the confining media are impervious and horizontal;
6. fluid is removed from storage instantaneously by a decline in pressure;
7. the diameter of the discharge well is infinitesimal with respect to the drainage radius of the medium.

Some of these assumptions are not justified by field conditions. The effect of deviations from assumed conditions on flow rate will be discussed in a later chapter.

Since in mine development, removal of water from the shaft in excess of inflow into the formation is desired, the aquifer is not in equilibrium and the transient equation must be used. This is true of any unwatering process whether it be through shaft development or pumping from boreholes.

Variables in the Equations

At this point, the variables which appear in steady and transient flow equations should be examined.

Permeability

Permeability is a measure of the ability of a porous material to transmit a fluid under pressure. It is defined by Muskat and others as the volume of a fluid of unit viscosity passing through a unit cross section of a porous medium in unit time under the action of a unit pressure gradient. (12, p. 71) Two types of permeability must be considered. The first has been called by Muskat, "absolute" permeability. It is derived from Darcy's equation

$$V = \frac{K_A\, dh}{\mu\, dl}.$$

Dimensional analysis shows K_A to have units of area (L^2). The fundamental unit is the darcy (12, p. 76)

$$\left(1 \text{ darcy} = \frac{1 \text{cm}^3/\text{sec} \times 1 \text{cp}}{1 \text{cm}^2 (1 \text{atm}/\text{cm})}\right).$$

In flow studies where water is the only fluid present, the pressure gradient in Darcy's law may be replaced by the hydraulic gradient. The resulting expression

$$K_e = \frac{K_A}{\mu} = \frac{v}{dh/dx}$$

is the "effective" permeability of the flow system. (12, p. 72) Dimensional analysis shows K_e to have units of velocity (L/T). The fundamental unit is the meinzer or U.S.G.S. unit (19, p. 9)

$$\left(1 \text{ meinzer} = \frac{1 \text{ gal at } 60^\circ \text{ F}}{1 \text{ day} \times 1 \text{ ft.}^2 \times 1 \text{ ft. } H_2O/\text{ft.}}\right)$$

The two permeabilities are related by the following expressions:

1 darcy = 18.24 meinzers at 68° F.

1 darcy = 20.50 meinzers at 60° F.

where $1 cm^3 = 0.26417 \times 10^{-3}$ gal.

1 atm = 1034.2 cm. water at 60° F.

1 atm = 1035.1 cm. water at 68° F.

1 ft. = 30.48 cm.

1 day = 86,400 sec.

are used to make the conversion.

Coefficients of effective permeability as low as 2×10^{-4} meinzers and as high as 9×10^{4} meinzers have been recorded. Table 1 shows the relation of absolute and effective permeability for a number of soil types.

Effective permeability decreases when the porous material is not completely saturated with water, but where undissolved gases occupy a portion of the pore space. This is an occurrence not uncommon in rocks favorable to ore deposition.

Hydraulic Gradient

The hydraulic gradient, $\frac{dh}{dl}$, is defined as the change in water pressure, or head, per unit length of flow path. It represents the driving force responsible for flow through a porous medium. The surface on which the hydraulic gradient is measured is known as the piezometric surface or water table depending upon the pressure characteristics of the aquifer. If the only driving pressure in the formation is the weight of the water, this surface is the water table and the aquifer is said to be unconfined. If, however, an additional pressure component is present in the form of confining formations of an impervious nature, the reference surface may rise above the upper boundary of the

K_A, darcys	10^5 10^4	10^3 10^2 10	1 10^{-1} 10^{-2} 10^{-3}	10^{-4} 10^{-5}
Soil Class	Clean Gravel	Clean Sands; Mixtures of Clean Sands & Gravels	Very Fine Sands; Silts; Mixtures of Sand, Silt, & Clay; Glacial Till; Stratified Clays; Etc.	Unweathered Clays
Flow Character	Good Aquifers		Poor Aquifers	Impervious
K_E, gal./day/ft.^{2}	10^6 10^5	10^4 10^3 10^2	10 1 10^{-1} 10^{-2}	10^{-3} 10^{-4}

Table 1. Magnitude of Absolute and Effective Permeability for Different Soil Classes (After Todd, 1959)

aquifer and is referred to as the piezometric surface. The aquifer is then said to be confined or artesian. Under natural conditions, the hydraulic gradient is very low, on the order of ten feet per mile. The hydraulic gradient in an isotropic, homogeneous medium should be constant prior to development by a well. When a well is drilled and water is removed from the aquifer by pumping, the hydraulic gradient near the well is constantly changing. At a point distant from the well, the original hydraulic gradient prevails. As the distance from the well decreases, the gradient, and likewise the slope of the pressure surface, increases until at the well facing, the gradient is theoretically infinite. The piezometric surface resembles an inverted cone with its apex at the well.

Coefficient of Transmissibility

The coefficient of transmissibility is defined as the product of the coefficient of "effective" permeability and the saturated thickness of the porous medium. (19, p. 11) Units used are gallons per day per foot.* It is a measure of the volume rate of flow through a strip of the medium one foot in width and equal in height to the saturated thickness of the medium. The "effective" permeability of the medium is a constant while the coefficient of transmissibility varies with the saturated thickness of the aquifer. This point is important in evaluating the quantity of flow into a well or shaft when the unwatering process is in its final stage. The coefficient of transmissibility is

---

*under a unit hydraulic gradient

commonly determined from pumping test data and is taken as an average value over the area under investigation.

Coefficient of Storage

The coefficient of storage is the volume of water in cubic feet discharged from a vertical column of a porous medium with a base one foot square as the water level drops one foot. (19, p. 87) It is a dimensionless quantity and a measure of the capability of a formation to allow removal of water from storage. When a formation is unwatered, some of the water must be removed from storage by compression of the water bearing formation, since water is generally considered to be incompressible.

Drawdown

The drawdown in a discharging (pumping) well is defined as the difference between the water level in the well before pumping and after pumping has reached a constant rate. It is a measure of the decline in pressure within the porous medium. In shaft development work, where pumps are installed at the bottom of the shaft to keep it dry, the drawdown is equal to the depth of the shaft below the water table or piezometric surface.

Drainage Radius

The drainage radius of an aquifer surrounding a discharging well or shaft is that distance to a point at which no water flows toward the well or shaft. It is also termed by some investigators the groundwater divide. Theoretically, the radius is infinite but in practice a maximum value of 750 to 1,000 feet is generally used. (12, p. 95, 156)

Well Diameter

An important consideration in mine water problems is the effect on an estimate of influx from data obtained in drill holes of increasing the hole diameter to the dimensions of a mine shaft. As will be shown in a later chapter, when the influx is great, the effect of increasing well diameter may be an important consideration.

Viscosity

Viscosity of a fluid is defined as the ratio of shear stress to transverse velocity gradient. (5, p. 167) Dimensional analysis shows viscosity to have dimensions $\left(\frac{M}{LT}\right)$. Metric system unit is grams per centimeter-seconds or poise. Under field conditions, variations in viscosity are usually due to temperature variations. Since the coefficient of "effective" permeability is defined at 60° F., it may be necessary to correct field measurements by determining the variation of viscosity with temperature. Fig. 1 shows the relationship between temperature and viscosity and the correction factor necessary to convert field values of "effective" permeability to standard temperature.

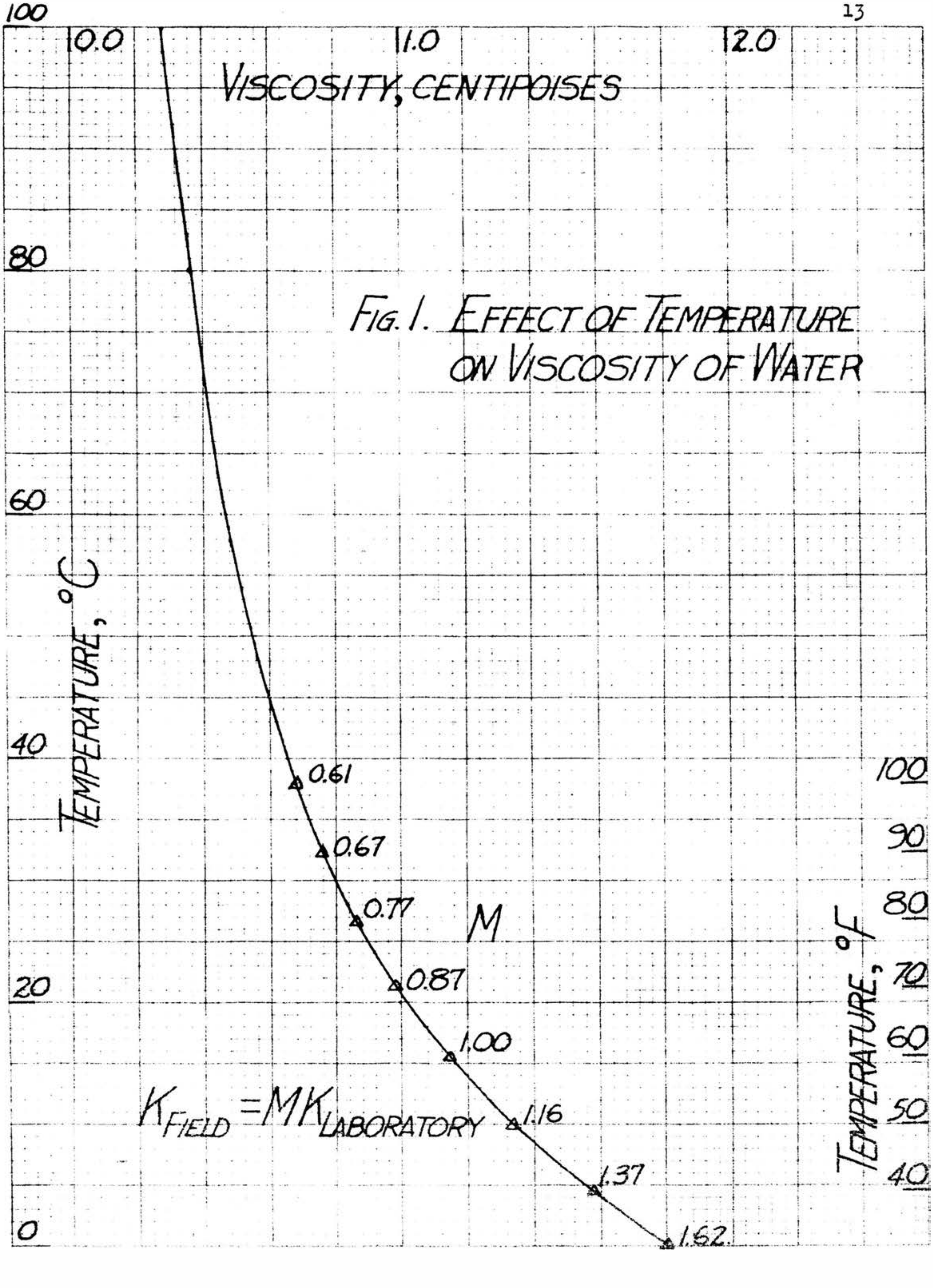


FIG. 1. EFFECT OF TEMPERATURE ON VISCOSITY OF WATER

$K_{FIELD} = M K_{LABORATORY}$

PREVIOUS WORK ON WATER SUPPLY ESTIMATES

In order to evaluate the state of knowledge regarding quantitative estimates of the flow of groundwater, the available literature was reviewed to determine what methods had been used and which, if any, were applicable to the problem under investigation.

Methods of estimating groundwater supplies may be divided into four categories:

1) hydrologic methods
2) mathematical methods
3) model studies
4) pumping tests

Of the four methods, estimates based on hydrologic studies have been most widely used. Strictly mathematical methods have met little success. Model studies give both quantitative and qualitative results. Pumping tests give good results for limited areas and are probably the best suited for mine water investigations.

Hydrologic Methods

The transmission and storage of groundwater constitutes a portion of the hydrologic cycle. This cycle is shown diagramatically in Fig. 2. That portion of water which enters water-bearing formations is called recharge. That portion of water which emerges from water-bearing formations is discharge. Storage of groundwater within

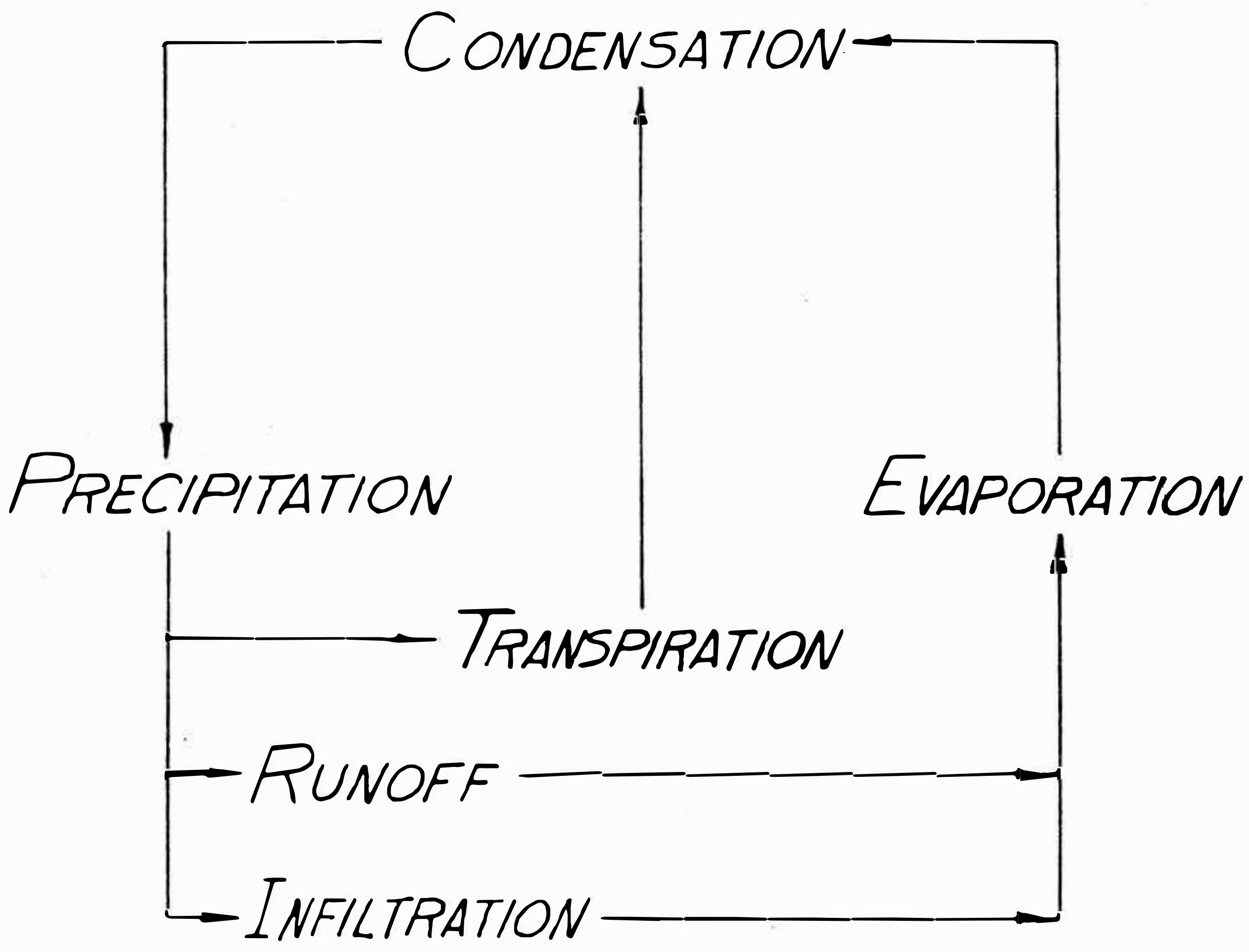


FIG. 2. THE HYDROLOGIC CYCLE

the earth may be expressed: storage = recharge - discharge. Hydrologic methods of estimating groundwater supply involve the quantitative determination of recharge and discharge.

Natural recharge may originate as precipitation or as flow from bodies of surface water. Artificial recharge may result from excess irrigation, seepage from dams, or from water applied purposely to supplement existing groundwater supplies. Natural discharge may occur as flow into streams, lakes or oceans. Artificial discharge is accomplished primarily by pumping from wells.

Recharge and discharge may be estimated in several ways. Perhaps the simplest and surely the least accurate is to measure stream flow. At various points along a stream, periodic measurements of the flow velocity are made. By multiplying the average velocity at a point by the cross-sectional area of the stream at that point, the quantity of flow is determined. Long term difference in flow between points is taken as the storage over that area. Accurate measurements of stream flow can be made; but water losses, such as evaporation, cannot be evaluated nor are other sources of recharge considered. Such estimates have value only by showing the general condition of groundwater reservoirs.

One of the earliest attempts to evaluate a groundwater supply by direct measurement was an investigation by Mariotte in 1686. (10, p. 103) He attempted to determine the groundwater supply of the Seine Basin by measuring the precipitation over the basin and correlating this with the river discharge.

This crude attempt suggested to others that by measuring rainfall and accounting for various losses, a fairly accurate estimate of groundwater supply could be made. However, many of the losses which occur between the time water falls as rain or snow and the time it enters a groundwater reservoir are difficult to evaluate. The rate of evaporation of soil moisture and surface water still remains impossible to determine with any degree of accuracy.

Much progress has been made in studies of water loss through transpiration of plants. Agricultural experts have determined transpiration rates for many species. In certain arid regions it is possible to accurately determine the amount of water lost through this process.

Likewise progress has been made in soil moisture determinations. It has been shown that each soil class has a definite moisture capacity, known as the field capacity. Until this amount of water is stored in the soil, none will percolate downward to the main groundwater body. Moisture content can be measured by electronic instruments.

When these factors can be ascertained, a rough estimate of groundwater supply can be made. However, no estimate of quantity of flow can be made.

Mathematical Methods

Mathematical methods used in groundwater studies include such methods of numerical analysis as iteration and relaxation. A short discussion of the possibilities of the analog computer is given as well as a description of the flow net or curvilinear squares method.

Numerical Analysis

When a flow problem is complex, even approximate analytic solutions are difficult. In such instances, graphical, empirical, or numerical procedures are used. In numerical analysis of steady state flow, partial differentials are replaced by their finite difference equivalents. The problem then reduces to one of solving a large number of simultaneous algebraic equations. It should be pointed out that the solution thus obtained is not generally valid, but is an explict solution for given conditions.

Numerical methods of analysis involve either iterative processes or relaxation techniques. Of the iterative processes, the linear rosette method is most commonly used. The four point influence formula,

$$F_r h_r + F_l h_l + F_u h_u + F_d h_d = F_o h_o \quad \text{where } F_r = \frac{Z_u - Z_d}{2} \cdot \frac{r_{or}}{r_r - r_o},$$

$$F_l = \frac{Z_u - Z_d}{2} \cdot \frac{r_{ol}}{r_o - r_l}, \qquad F_u = (r_{or} - r_{ol}) \cdot \frac{r_o}{Z_u - Z_o},$$

$$F_d = (r_{or} - r_{ol}) \cdot \frac{r_o}{Z_o - Z_d}, \qquad F_o = \sum F = F_r + F_l + F_u + F_d$$

is used.

Fig. 3 shows a typical network.

Initial values of the piezometric head are assigned each node of the network. Then the assigned values are improved from a knowledge of the boundary conditions. The successive improvement of assigned values is continued until the desired degree of accuracy is obtained. As shown in Fig. 3, the pressure distribution throughout the aquifer can be found.

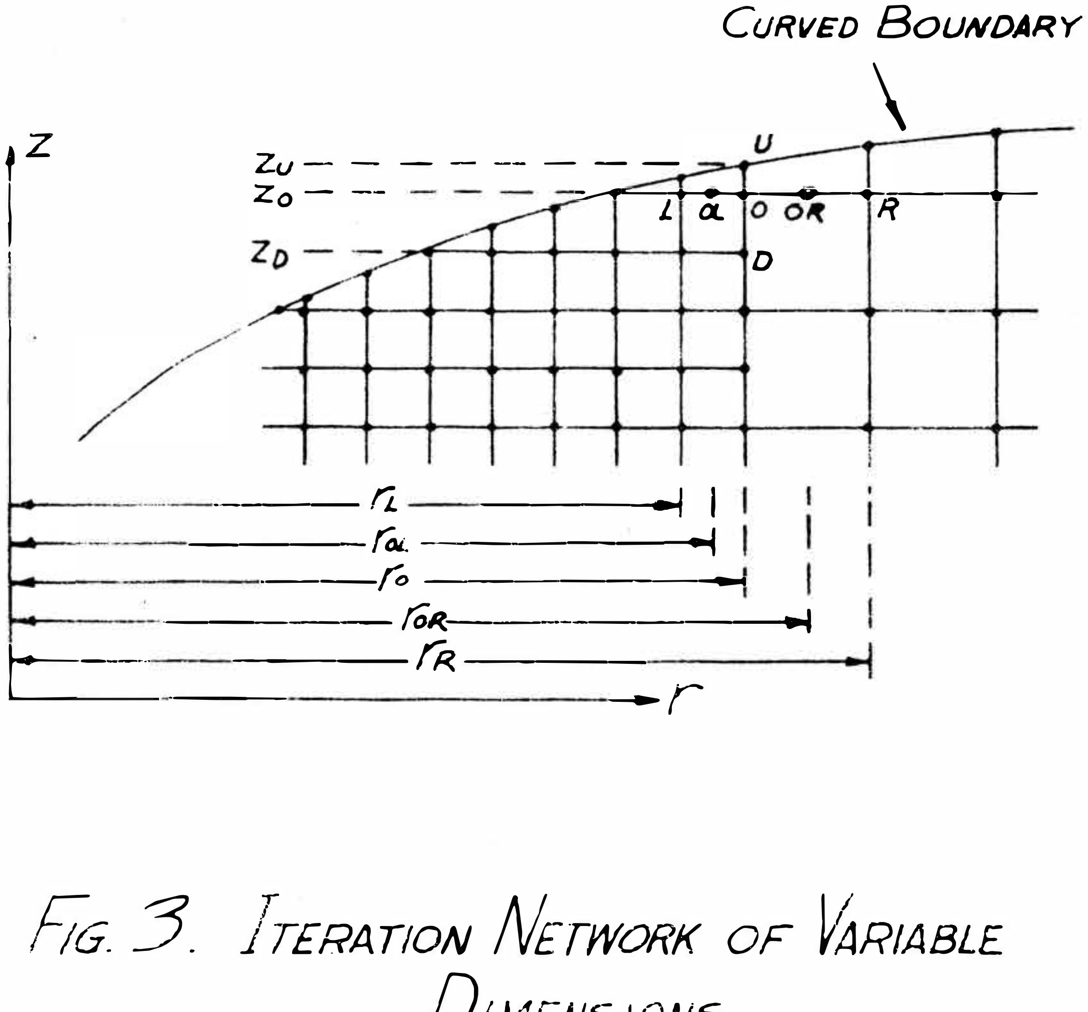


FIG. 3. ITERATION NETWORK OF VARIABLE DIMENSIONS

The relaxation method of numerical analysis was developed by Southwell. (8, p. 37) If, as in iterative procedures, the four point influence equation is used, it becomes $h_1 + h_2 + h_3 + h_4 - 4h_0 = R$. R is called the residual and may be considered as the summation of the errors in values of h. As the correct values of h are reached, the residual vanishes.

In this method of analysis, an initial value is assigned to each point in the network. All of the residuals are then calculated. To relax a point it is necessary to change h_0 in order to eliminate the residual at that point. However, this change in h_0 will increase or decrease the residuals at points 1, 2, 3, and 4. Successive relaxations will improve the values of h until the desired accuracy is obtained.

For a more detailed discussion of numerical methods applied to water supply problems, the reader is referred to Reference 8 of the Bibliography.

Analog Computer

It has been suggested that the differential analyzer type of analog computer might be utilized in the study of groundwater flow problems. Analog computers are of great value in studying time dependency of variables. Such a computer can solve linear differential equations of the type encountered in a groundwater investigation. The Theis equation expressed in terms of polar coordinates is

$$\frac{\partial h}{\partial t} = \frac{T}{S} \left[\frac{1}{r}\left(\frac{\partial h}{\partial r}\right) + \frac{\partial^2 h}{\partial r^2}\right].$$

The volume of flow into a well is then:

$$Q = 2\pi r_w T \left(\frac{\partial h}{\partial r}\right) + \int_{r_w}^{r_e} S \left(\frac{\partial h}{\partial t}\right) 2\pi r dr$$

The partial differential equations could be replaced by 2n ordinary differential equations, which are functions of t, by setting up finite differences for $\frac{\partial h}{\partial r}$ and $\frac{\partial^2 h}{\partial r^2}$ in terms of h and n increments of equal length extending radially from the well. (R. D. Caudle, personal communication)

A study of flow problems using the computer would enable one to investigate many of the effects of aquifer inhomogeneity on flow rate.

Flow Nets

Flow nets are constructed by plotting on suitable paper, lines of equal pressure (equipotential lines) and lines of flow (i.e. those lines to which the macroscopic velocity vector is always tangent). (17, p. 64) These lines are perpendicular to one another. Consider the flow net shown in Fig. 4. The quantity of flow through each curvilinear square is $dq = K \frac{dh}{ds} dm$ for a unit thickness. The quantity of flow through the net then is

$Q = \frac{kmh}{n}$ where n = no. of squares in net,
m = no. of flow paths

A trial and error procedure is usually followed in constructing such a flow net. The complementary lines are so constructed as to yield equal squares. When the geometry is established, the total quantity of flow can be computed directly.

Model Studies

The use of models for the study of the flow of groundwater is possible because of the analogous relations between Darcy's law, Ohm's

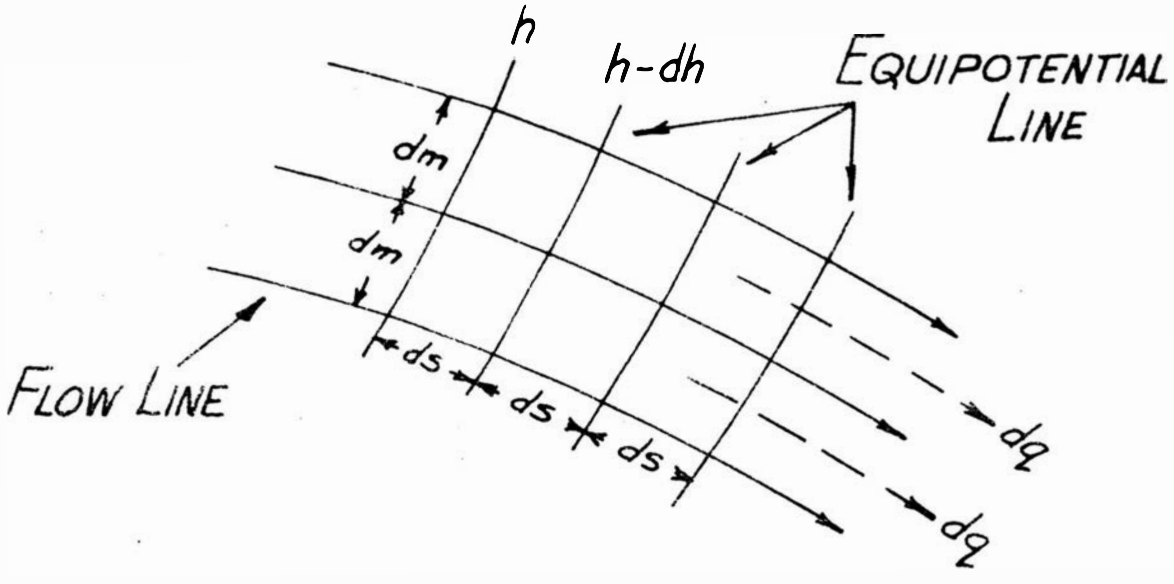


FIG. 4. PORTION OF AN ORTHOGONAL FLOW NET

law, and Fourier's law. Various types of models which may be used are sand, electrical, viscous fluid, and membrane. Of these only the sand model truly represents flow through porous media. The others must be related to the problem by analogy.

Sand Model

The sand model is a scaled down replica of the aquifer with the absolute value of permeability modified. (17, p. 307) In this type of model, linear dimensions are scaled directly, but the permeabilities in the model and prototype must be related by trial and error since it is impossible to scale y. If an inhomogeneous sand is used in the model, it is almost impossible to obtain consistent values for permeability. Because of this, sand models have little value in terms of quantitative results.

The construction of a sand model is relatively simple. In the case of models constructed for investigating flow, storage tanks must be provided. Since it is hard to accurately determine the position of the water surface by visual inspection, piezometer tubes are commonly inserted at intervals in order to measure the water pressure. When visual observation is required, a dye may be added to the water. Sodium fluorscein is commonly used.

Electrical Models

Electrical models are based on the fact that Ohm's law, $I = \sigma_0 \frac{dE}{dx}$ is a solution of the Laplace equation just as is Darcy's law. The analogy between fluid flow and electric current flow is then apparent. σ_0 is the specific conductivity of the material through which current passes and $\frac{dE}{dx}$ is the potential gradient.

Such models are restricted to steady state flow problems, but the usual assumptions of the homogeneity and isotropic character of the aquifer are unnecessary. Confined aquifers are usually studied, since there is no electrical analogy to gravitational forces. However, water table problems can be solved if the position of the free surface is determined by trial and error. (17, p. 310;12, p. 319) It is proposed that the elevation of the free surface in an electrical model is proportional to the potential drop along that surface.

Qualitative results are usually obtained. Equipotential lines are constructed and flow patterns are studied. If quantitative values of influx are desired, a flow net solution must be employed.

A great variety of electrical models have been used. Solid, liquid, or gelatin models are most common. Investigations utilizing such models range from studies of advancing fluid fronts in secondary recovery of petroleum to investigation of flow patterns of wells that partially penetrate an aquifer.

Viscous Fluid Models

The flow of a viscous fluid such as oil or glycerin, between closely spaced parallel plates is analogous to two dimensional groundwater flow. If the Dupuit assumptions are applied to Darcy's law, the mean velocity of flow in the model is given by $V_m = \frac{b^2 \rho_m g}{3 \mu_m} \frac{dh}{dx}$. (17, p. 315)

By proper choice of the fluid and the spacing of the plates, the desired permeability can be simulated. An important advantage of this type of model is the ability to study transient flow with irregular boundary conditions. Different geologic conditions can be modeled and their effects on influx studied.

Membrane Models

A thin rubber membrane can afford another analogy to the flow of groundwater. The expression for the deflection of the membrane is a solution of the Laplace equation. This type of model is useful in studying the shape of the piezometric surface. It is used to study interference effects of multiple well systems. When a single well is being studied, the model has little or no value.

Pumping Tests

Pumping tests have been widely used in the investigation of groundwater supplies, because the data obtained from such tests is obtained from the actual formation under study. (3, p. 849) Thus analogous relations are unnecessary.

Both equilibrium and non-equilibrium methods have been developed. In the case of mine development, where it is desired to remove or drain all of the water possible, a non-equilibrium method is applicable.

The most widely used method is that proposed by Theis (16). The procedure for the method follows. For the pumping test, three wells in line with one another are utilized. One of the end wells is pumped, the other two serve as observation wells. Since the method assumes an original water surface which is horizontal it does not matter which of the two possible pumping sites is chosen. The pumping test begins by measuring static water level in both observation wells. As the test begins, the pumping well discharges at a constant rate Q. At regular intervals of time, drawdown of the water level in the observation wells is recorded. The test should run at least 48 hours and preferably longer.

After the test is completed, the data are interpreted graphically. A graph is constructed by plotting log W (u) vs. log u. Values for the functions may be obtained from several sources. (19, p. 88; 17, p. 91) This graph is known as the type form and is shown in Fig. 15, Appendix C. Next a graph is constructed by plotting logΔh vs. log $\left(\frac{r^2}{t}\right)$ using the same scale as the type form graph. The two graphs are laid one upon the other and the data curve is fitted to the type form. During the curve fitting, the coordinate axes of both graphs must remain parallel. When the two curves are matched, corresponding points on each graph are selected for computation.

In the Jacob modification of the Theis method, values of drawdown are plotted against log t. The governing equations are $T = \frac{264Q}{\Delta h}$ and $S = \frac{0.3Tto}{r^2}$, where Δ h is the drawdown per log cycle of time and t_o is the initial time. A solution of this type is shown in Fig. 17, Appendix C.

The weak points of pumping test solutions are those inherent in the equations used; namely, the seven simplifying assumptions made by Theis.

There have been two articles written on the quantitative evaluation of mine water problems (14, 18). Both evaluations relied upon pumping test data, results of which were obtained by the Theis type form solution, checked by the Jacob modification.

PRESENT RESEARCH WORK

Construction of Nomographs for Determining Quantity of Flow from Pumping Test Data

After a review of the literature on methods of estimating groundwater flow, it was decided that pumping tests provided the most reliable data for an analysis of a water problem. It was further decided that if a system of analysis were outlined, it should provide a simple and straightforward approach to the problem. It should be rapid and yield reasonably accurate results.

A graphical method of analysis seems to best fulfil the requirements. By the use of graphs a simple and rapid procedure can be developed which will give results within the desired limits of accuracy.

Graphical expressions of complicated mathematical equations can be easily shown by the type of nomograph known as the alignment diagram. (13, p. 512) In this type of nomograph, the functions of the variables are scaled on a number of parallel lines. A solution of the equation is obtained by connecting the variables systematically by straight lines. Any number of variables can be treated by such a diagram.

In this investigation, the two equations developed in the Theis non-equilibrium method were prepared as alignment diagrams. The diagrams are shown in Fig. 5 and 6. The details of their construction are given in Appendix B.

The data needed for obtaining a solution for Q are:

1. S, the storage coefficient
2. T, the coefficient of transmissibility
3. r, the drainage radius
4. H, the drawdown
5. t, the time for which Q is desired.

Of these data, a pumping test supplies values for S and T. They are obtained by the type form solution of the Theis equations and should be checked by the Jacob modification. The drainage radius r must be estimated. A maximum practical limit is 1000 ft. (12, p. 156; 4, p. 134) The drawdown is estimated from a knowledge of the conditions at the shaft or well site.

Effect of Increased Hole Diameter

When the influx into a mine shaft is under investigation, the effect of increased hole diameter on quantity of flow must certainly be considered. It is apparent that the same amount of water will not flow into openings which have differing surface areas available to flow. This effect was studied from two aspects. An investigation of the derivation of the equations used to estimate flow was first made. Jacob's derivation was utilized, since it is based upon hydrologic considerations and does not rely upon the analogy to heat conduction.

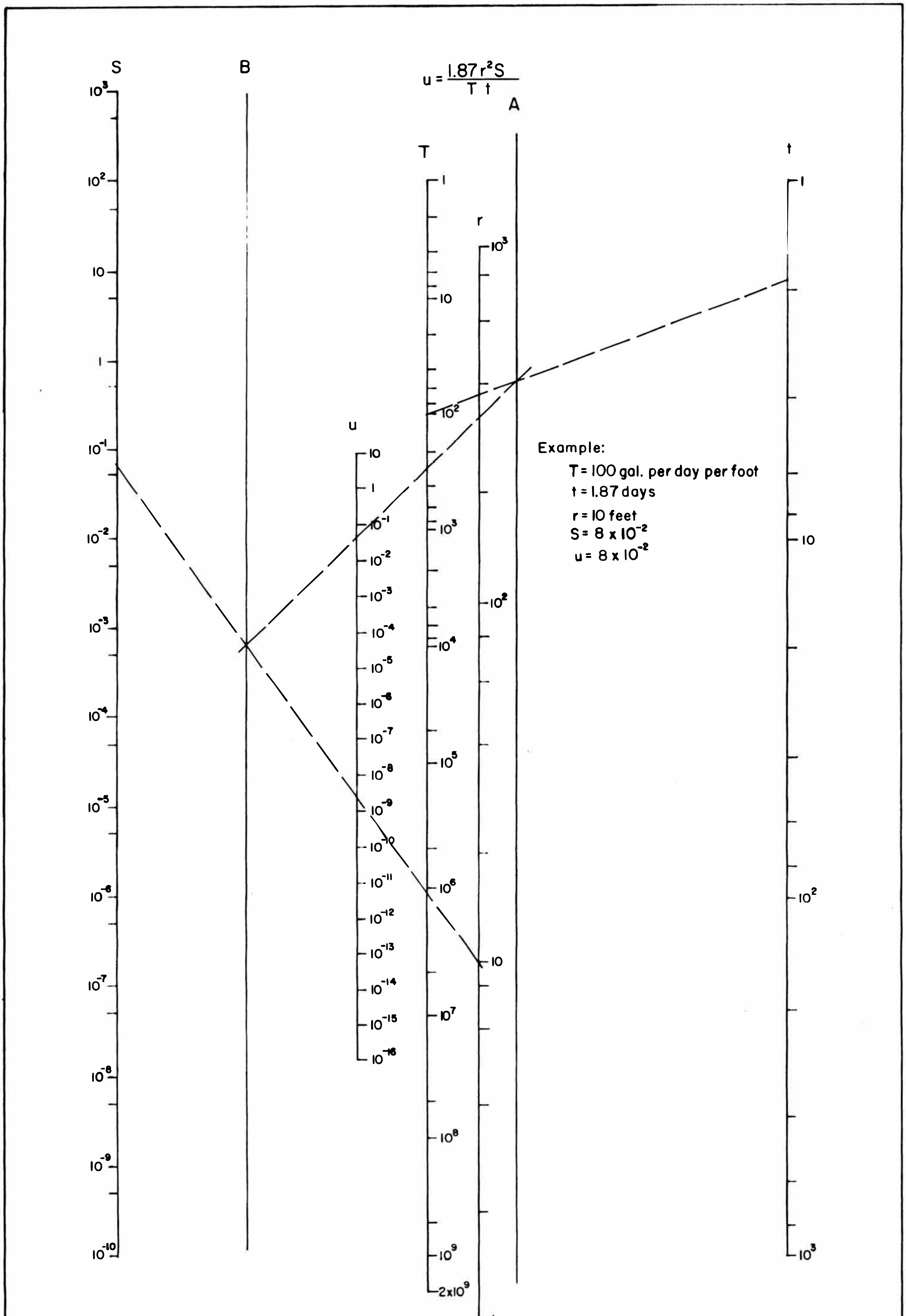
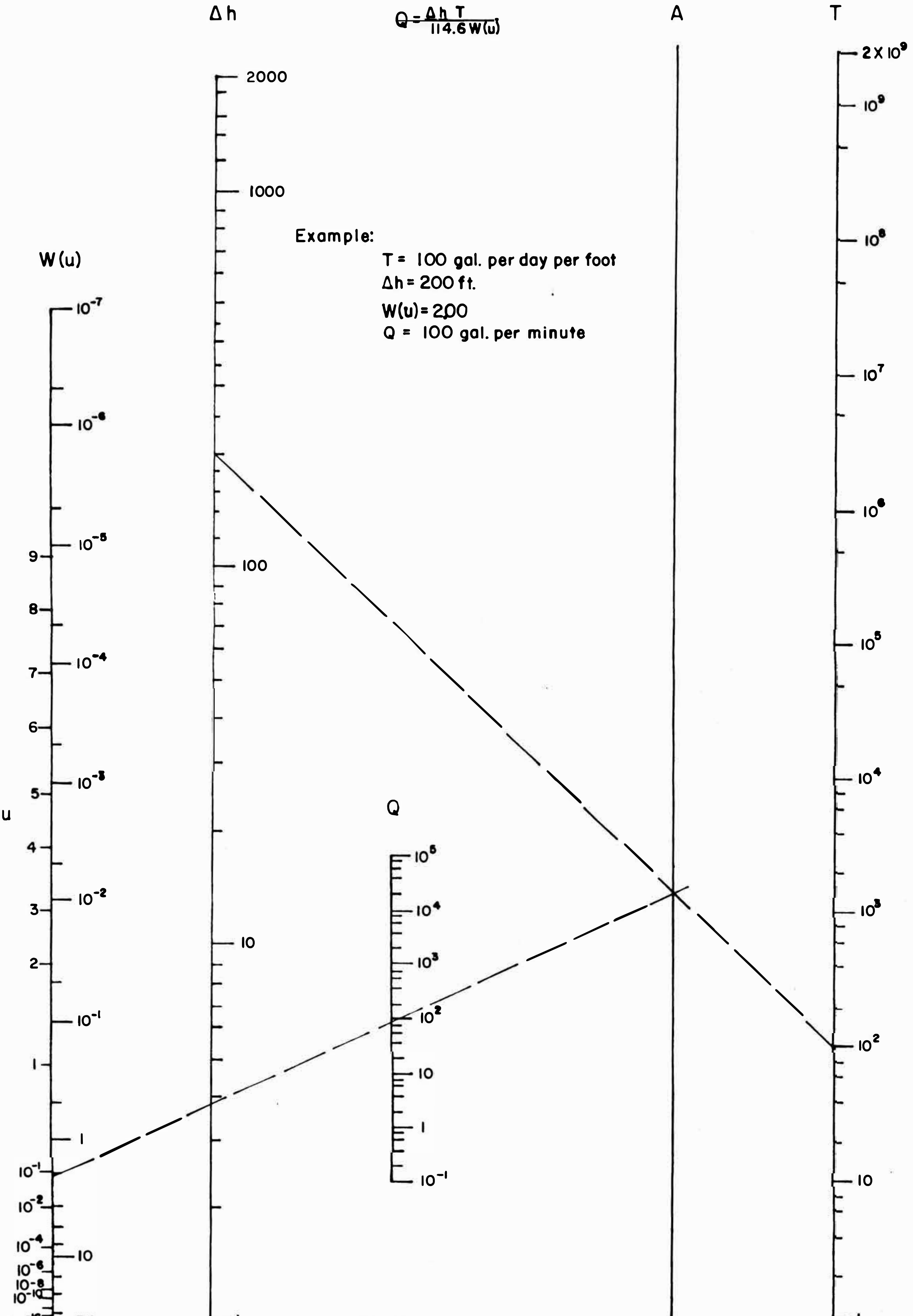


Fig. 5 Nomograph of the Equation $u = \frac{1.87 r^2 S}{T t}$



Example:
T = 100 gal. per day per foot
Δh = 200 ft.
W(u) = 200
Q = 100 gal. per minute

Fig. 6 Nomograph of the Equation $Q = \frac{\Delta h\, T}{114.6\, W(u)}$

Jacob states that the discharge of a well is equal to the sum of the flow through a cylinder of variable radius r and the increase in rate of flow caused by compression of the aquifer.

$$Q = -2\pi rm\,K\,\frac{\partial h}{\partial r} + \int_{0}^{r_e} S\left(\frac{\partial h}{\partial t}\right) 2\pi r\,dr \quad (7,\ p.\ 579)$$

The equation assumes r_w to be infinitesimal compared with r_e, the lower limit being zero.

$$\frac{\partial h}{\partial r} = \left(\frac{-2c}{r}\right) e^{\frac{-r^2S}{4Tt}}; \qquad \frac{\partial h}{\partial t} = \left(\frac{c}{t}\right) e^{\frac{-r^2S}{4Tt}} \qquad (7,\ p.\ 579)$$

If the lower limit of r is given a finite value r_w and the expressions for $\frac{\partial h}{\partial r}$ and $\frac{\partial h}{\partial t}$ are inserted into the flow equation, it becomes

$$Q = (4\pi Tc)\ e^{\frac{-r^2S}{4Tt}} + \left(\frac{2\pi Sc}{t}\right) \int_{r_w}^{r_e} e^{\frac{-r^2S}{4Tt}}\ r\,dr$$

Let $r^2 = u$, then $2rdr = du$. The resulting equation may be integrated to yield:

$$Q = 4\pi Tc\left[e^{\frac{-r^2S}{4Tt}} + e^{\frac{-r_w^{\,2}S}{4Tt}} - e^{\frac{-r_e^{\,2}S}{4Tt}}\right]$$

When r, the radius of the point under investigation approaches the value of the drainage radius, the exponential term involving r_w controls the flow rate. Solving the equation for c, it is seen that as r_w increases, c rapidly becomes very large. In Jacob's derivation, c was found to be constant and equal to $\frac{Q}{4\pi T}$.

If the value of c is not constant, but instead changes very rapidly, it is clear that the flow equation is not a valid expression of influx into mine openings.

It was thought that the effect of increased hole diameter might be evaluated in another and perhaps more practical way. The Dupuit equation $Q = \frac{2\pi T \Delta h}{\ln(r_e/r_w)}$ was used. This is the equation governing steady state flow into a well. It is assumed that at any time, the aquifer is in instantaneous equilibrium and the equation is valid. The effect of r_w is evaluated by solving the equation for Q while holding all other variables constant. The ratio of influx into a borehole to that into a mine shaft is called the "shaft diameter factor." Values obtained for various diameters of drillholes and shafts are tabulated in Table 2 and shown graphically in Fig. 7. Bosazza, (2 , p. 44) using data obtained by Morley-Parker, has plotted increased yield vs. well diameter. He states that for a six-inch diameter well, the yield will be 1.02 units, while for a six-foot diameter well, the yield will be 1.46 units and the increase in yield $\left(\frac{1.46}{1.02}\right)$ x yield from a six-inch well. The ratio equals 1.43, the same value as the "shaft diameter factor" determined in this investigation for the same ratio drillhole to mine shaft.

It should be noted that when a rectangular shaft is contemplated, a conversion to an equivalent circular section is necessary. The well surface available to influx is 2 x length of shaft x width of shaft or π x shaft diameter. The relation between surface areas is plotted in Fig. 8.

Table 2.

Shaft Diameter Factors

$\underline{r_{w_1}}$

$\underline{r_{w_2}}$	3"	4"	5"	6"	7"	8"
3'	1.43	1.38	1.34	1.31	1.28	1.26
4'	1.50	1.45	1.41	1.38	1.35	1.32
5'	1.56	1.51	1.47	1.43	1.41	1.38
6'	1.62	1.56	1.52	1.48	1.46	1.42
7'	1.67	1.61	1.57	1.53	1.50	1.47
8'	1.72	1.66	1.61	1.57	1.54	1.51
9'	1.76	1.70	1.65	1.61	1.58	1.55
10'	1.80	1.74	1.69	1.65	1.62	1.59
11'	1.84	1.77	1.72	1.68	1.65	1.62
12'	1.88	1.81	1.76	1.72	1.68	1.65
13'	1.91	1.84	1.79	1.75	1.71	1.68
14'	1.94	1.87	1.82	1.78	1.74	1.71
15'	1.97	1.90	1.85	1.81	1.77	1.74

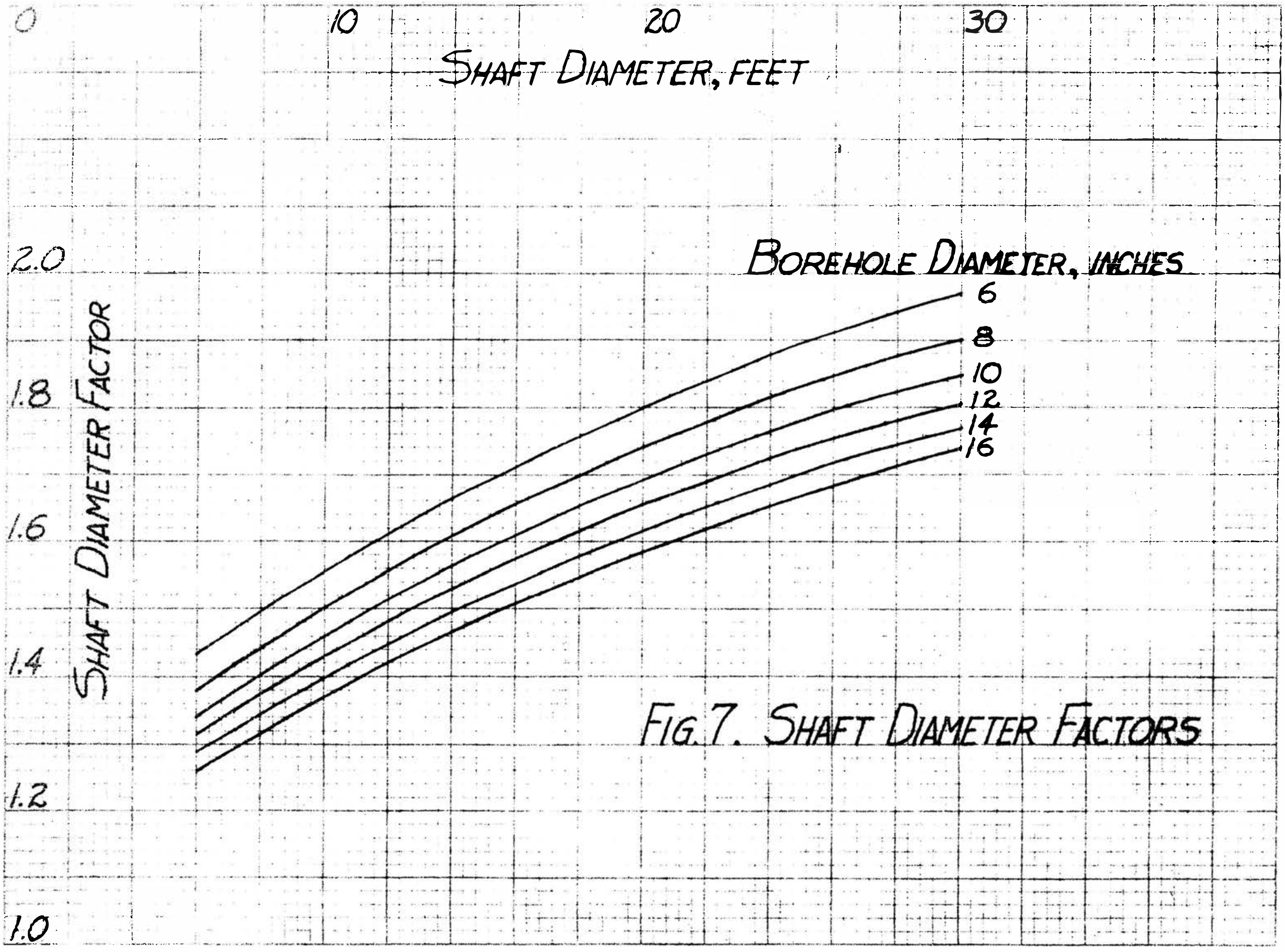


FIG. 7. SHAFT DIAMETER FACTORS

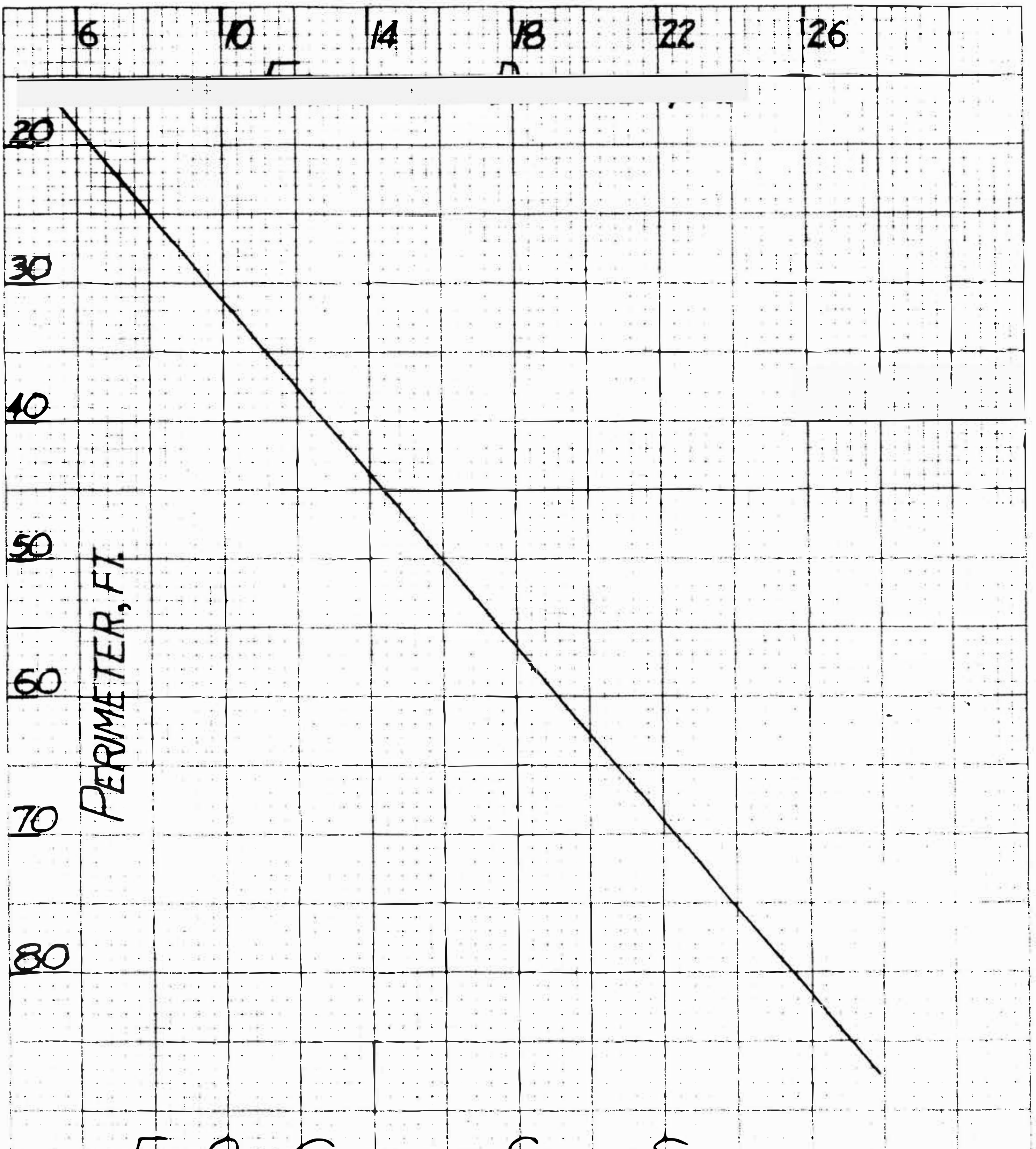


FIG. 8. CIRCULAR SHAFT SECTION EQUIVALENT TO A GIVEN RECTANGULAR SECTION

Effect of Invalid Assumptions

The Theis equations, used in the analysis presented herein, are based on several simplifying assumptions. (See p. 6) It is desirable to study what effect there is on the quantity of flow when these assumed conditions are not met in the field. A detailed analysis of the effect of one such assumption has just been presented. A discussion of possible effects caused by the invalidity of some of the other assumptions follows.

Theis assumed that the water bearing medium is infinite in areal extent, homogeneous, and isotropic. The heterogeneity of mine rocks is generally recognized. It is also realized that because of the complex geologic structures usually associated with mineral deposits, a formation is often restricted in area, and is seldom isotropic. Two very practical problems arise to complicate Theis' simplified situation.

First, because formations are not infinite in areal extent, the effect of groundwater boundaries on flow becomes important. LeGrand classifies such boundaries as positive or negative. (9 , p. 3) If the mine is in a permeable zone which abuts against an impermeable one, the boundary is a negative one. Here unwatering can proceed without much difficulty. However, if the mine rocks abut against more permeable ones or if the cone of depression reaches a stream or other body of surface water, the boundary is considered positive. In such a case, the difficulty of unwatering is considerable if not impossible. Fig. 9 and 10 illustrate the effect of such boundaries. The factor in

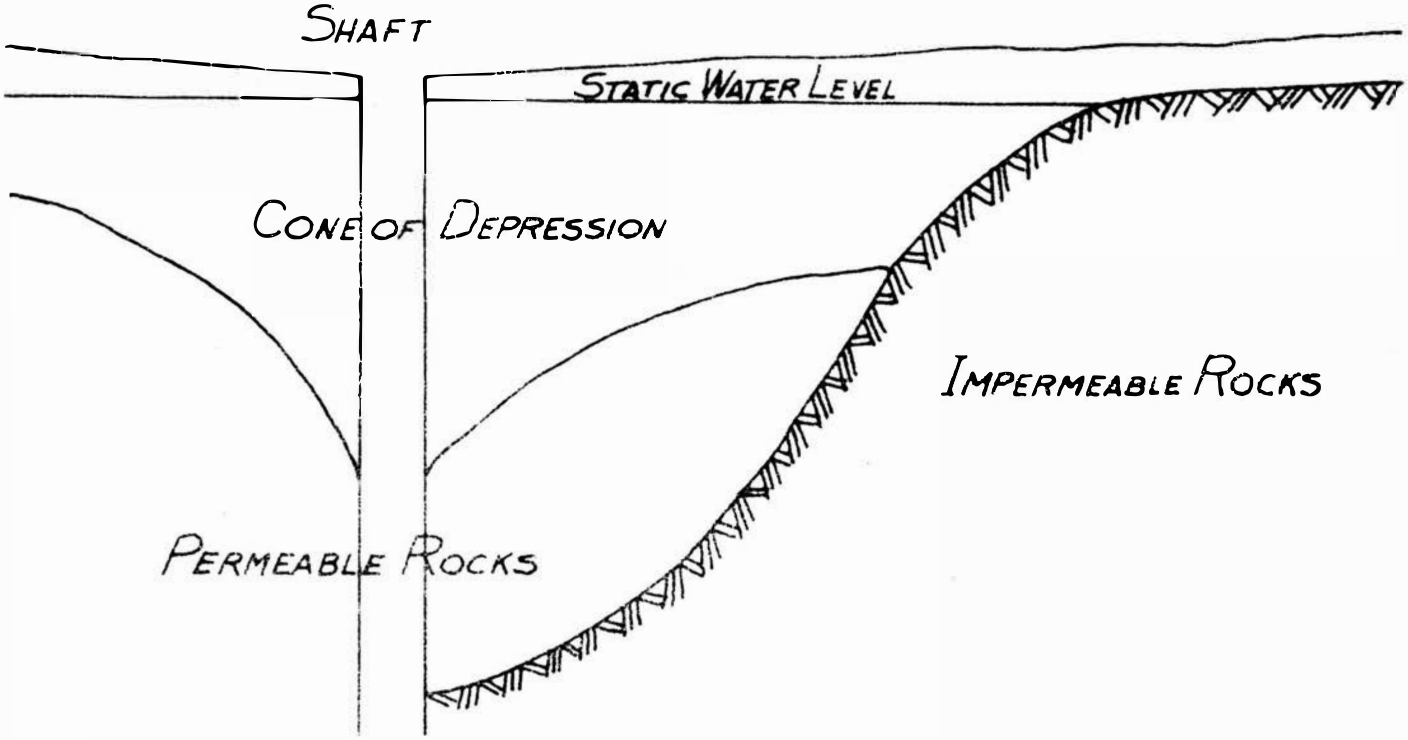


FIG. 9. A NEGATIVE AQUIFER BOUNDARY
(AFTER LEGRAND, 1958)

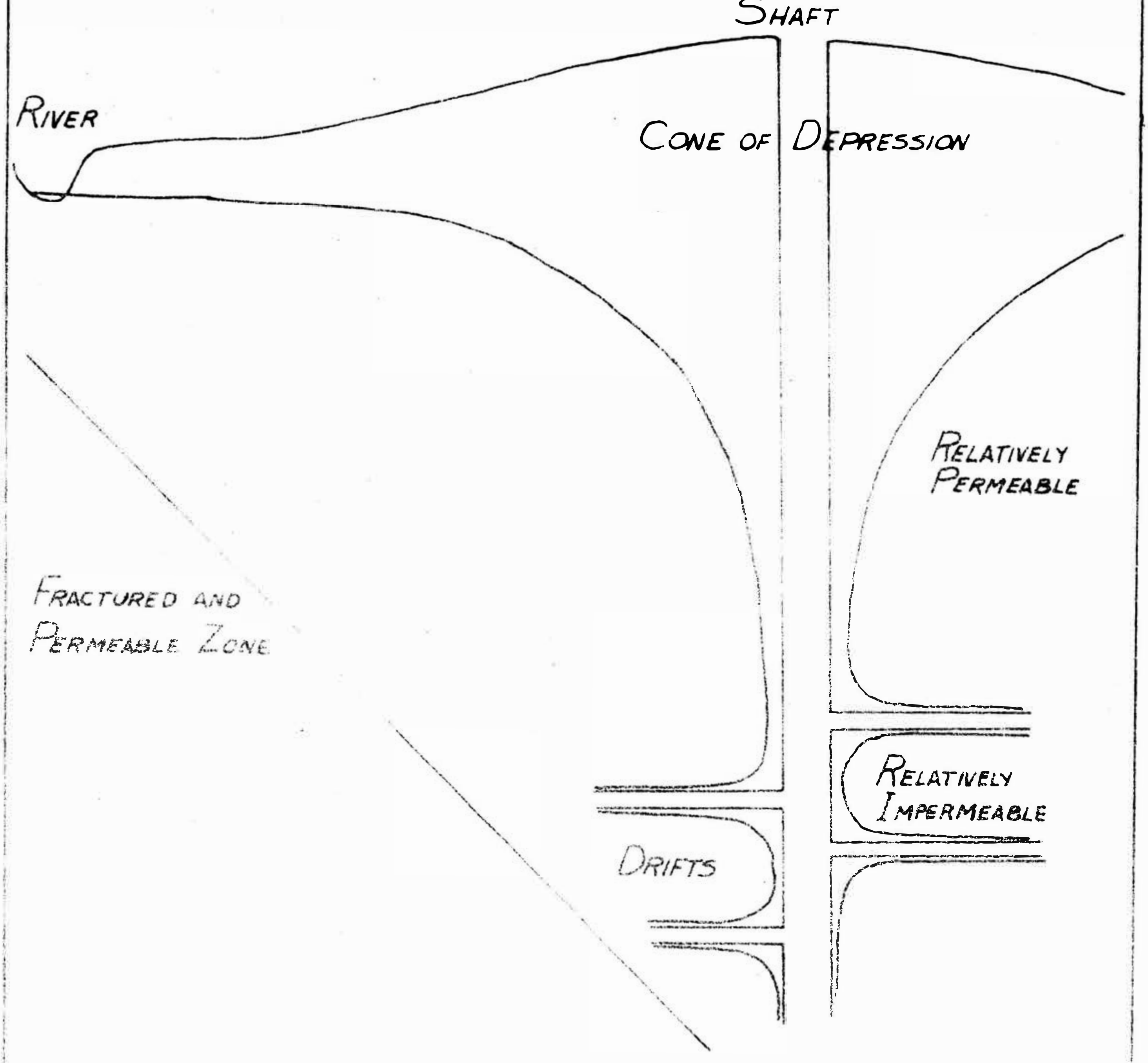


FIG. 10. TWO TYPES OF POSITIVE AQUIFER BOUNDARIES (AFTER LE GRAND, 1958)

the Theis equations which is affected is r, the drainage radius. If a boundary can be anticipated, as at Eureka, (14, p. 148) the value given the drainage radius can be modified to suit local conditions.

A second problem arises when fissure water is to be dealt with. Theis assumes that the aquifer is isotropic, that is, that water is transmitted equally in all directions. When water is circulated through fractures and fissures, as it is in most mines, this assumption is incorrect. If a large fissure zone is present, the formation constants determined by a pumping test will be approximately average values and the analysis outlined in this investigation can be used. If, however, the water comes from several major fissures, while the rest of the formation is relatively less permeable, a pumping test is apt to give erroneous values of S and T. In such a case, the analysis can serve only as a guide.

The homogeneity of the formations is never achieved. This factor has been the main reason advanced for incorrect predictions of influx in the Ambrosia Lake area. (V. L. Mattson, personal communication; L. W. Swent, personal communication) Here intercalated clay beds plus petroliferous residue in the formation have caused estimates to be high by a factor of 10.

Theis assumed that the opening for which influx is calculated completely penetrates the water bearing formation. This assumed condition is not encountered during shaft sinking operations, for the sinking must proceed through the formation. Because this often takes a long period of time, the effect of partial penetration must be studied.

As long as a shaft partially penetrates a water bearing stratum, some of the influx must percolate upward from material situated below the shaft bottom. This upward moving water must have moved a greater distance to the shaft than if it had moved horizontally. Thus a greater head loss is realized. The area immediately surrounding the shaft is affected by this increased head loss, the radial distance affected is in general inversely proportional to the depth of penetration. (19, p. 109) The loss in head results in a smaller amount of influx than predicted. Muskat has presented a correction factor to be applied:

$$C = \frac{Q}{Q_o}$$

where $\frac{Q}{Q_o} = \frac{(\text{quantity of flow into partially penetrating well})}{(\text{quantity of flow into completely penetrating well})}$.

Graphical presentation is shown in Fig. 11.

Theis assumed that the formation coefficients remained constant. The coefficient of transmissibility is defined as the product of the field coefficient of permeability and the saturated thickness of the aquifer. If unwatering is accomplished, the saturated thickness must diminish, causing in turn a negative change in the transmission constant. This is an important consideration in the latter stages of unwatering. If an estimate is made using the method of analysis proposed, the influx predicted for the latter stages of pumping will usually be high.

Theis also assumed that the initial piezometric surface is horizontal, that is, no movement of groundwater occurs before pumping begins. If this were the case, the cone of depression created would have

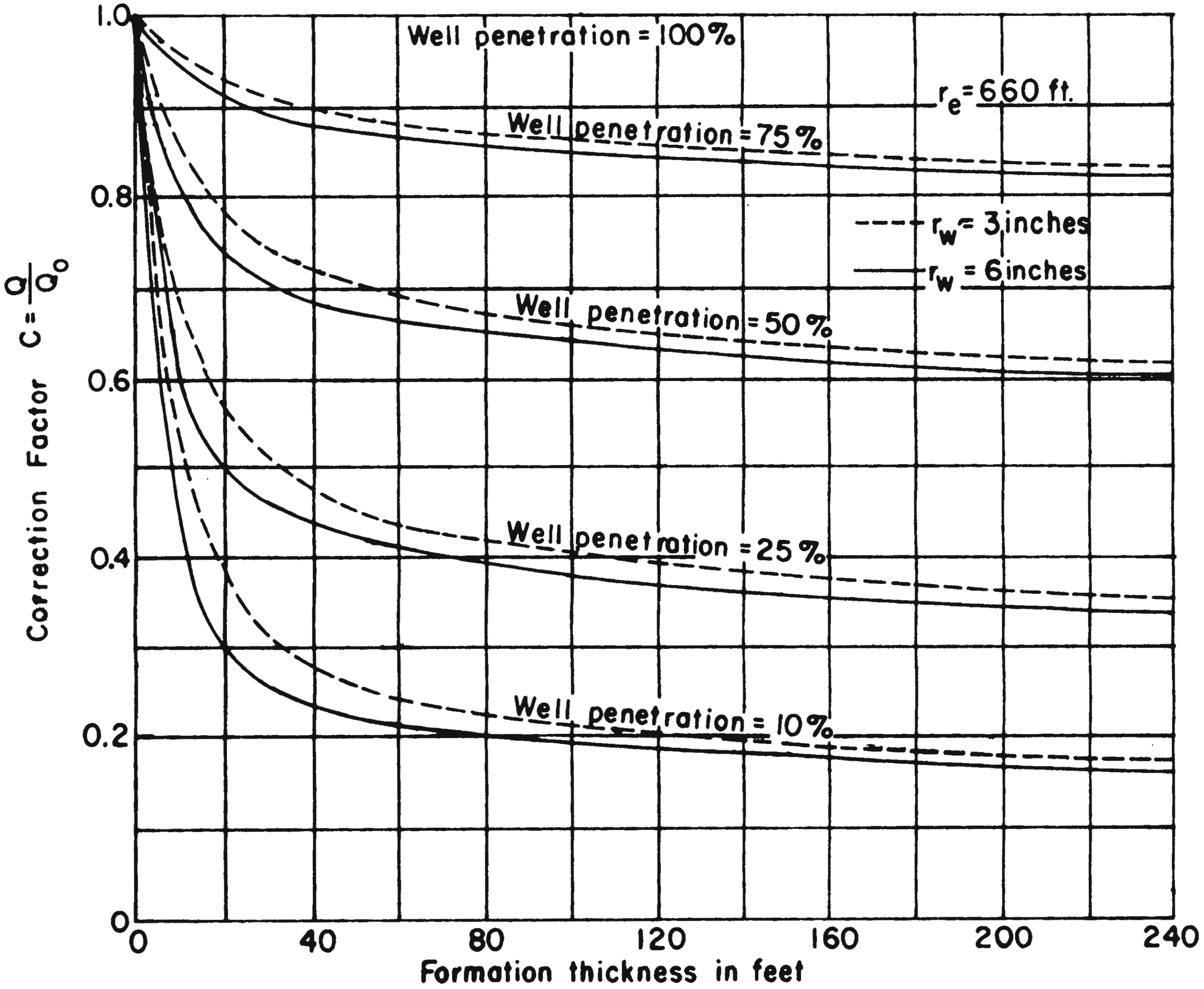


Fig. 11 Correction Factor for Partial Penetration

After Muskat (1949)

the shape of concentric circles when viewed in plan. In general, a sloping water table will be encountered. In this case, the cone of depression would have an elliptical horizontal projection. Theis has given a method for determining the distance to the "groundwater divide" or the drainage radius downstream from an artesian well. (15, p. 318) Wenzel (19, p. 104) has shown that the slope of the initial water surface greatly affects computed permeability values obtained from observation wells up stream and downstream from a pumping well. Drawdowns are greater downstream. He therefore suggests that drawdowns in wells on either side of the pumped well be averaged before computation of formation constants. Jacob states in his derivation of the Theis equations, that it is not necessary to assume the aquifer to be horizontal. (7, p. 576)

Theis assumed that the piezometric surface of the aquifer is never lowered below the top of the water bearing formation. In other words, no unwatering can occur. When dealing with mine water problems, it is seen that if no unwatering can occur, the problem of excess influx cannot be overcome. It is a fact that constant pumping at a rate exceeding that of recharge will unwater a formation. Therefore, some means of estimating the amount of unwatering due to pumping must be included in an analysis of a mine drainage problem. If drawdown vs. log time is plotted on semi-log paper a straight line relationship results for any given pumping rate. (See Fig. 12) Stuart (14, p. 152) states that since drawdown is proportional to rate of withdrawal, a simple proportion can be used to determine the drawdown of a point at any pumping rate.

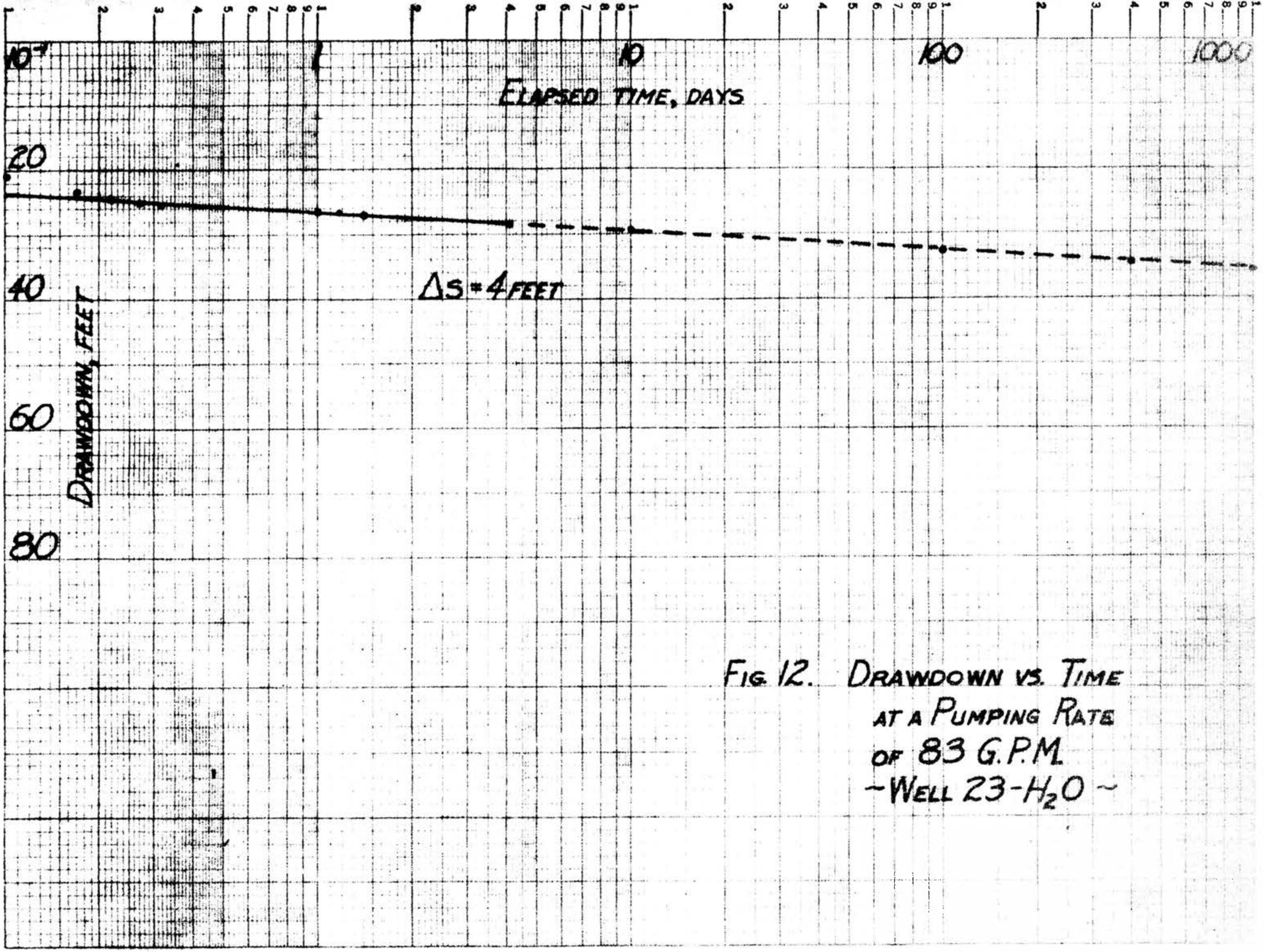


FIG. 12. DRAWDOWN VS. TIME AT A PUMPING RATE OF 83 G.P.M. ~WELL 23-H_2O~

To estimate the amount of unwatering accomplished by pumping, such a plot as previously mentioned should be used. Values should not be used for times of less than one day if possible. This will eliminate small variations in drawdown due to initial unwatering of the cone of depression. The drawdown per cycle of time can be estimated and a corresponding drawdown calculated for any desired pumping rate.

A discussion of effect of field conditions on the estimates of influx obtained by the graphical analysis presented in this thesis indicates that there are variations between real and assumed conditions. These variations necessarily affect the validity of the equations used and the usefulness of the results obtained.

It is clearly recognized that the present analysis is not a complete solution and estimates must be tempered accordingly. However, the value of such an analysis is still great, for it now provides a guide where previously there was none.

Suggested Procedure for Analysis

The procedure to be followed in estimating water influx into a proposed mine shaft follows.

1. Conduct a long term pumping test. From the data acquired, use the type form solution to obtain average values for S and T. (See p. 25).
2. Estimate the drainage radius of the proposed shaft. This value may be taken as 1000 feet if desired.
3. Select a time t, for which Q is desired. Remember that t_0 is the time at which the water bearing formation is first encountered.

4. Estimate the drawdown in the shaft. The maximum value which can be used is equal to the difference between the static water level and the shaft bottom. In the case of unconfined aquifers, this will be the thickness of the water bearing strata.
5. Insert the variables into the two nomograms in proper order to obtain a value for Q.
6. If shaft has not completely penetrated the aquifer, determine the partial penetration and apply the appropriate correction factor from Fig. 11.
7. The value obtained in Step 5 has not considered the effect of shaft diameter. Therefore select a "shaft diameter" factor from Table 2 to adjust the quantity of flow.
8. Consider the unwatering effect of pumping. Plot on semi-log paper drawdown vs. log time at pumping rate used in the field test. Determine drawdown at pumping rate necessary to keep shaft dry. Correct drawdown at new time, (t), by amount of unwatering.
9. Repeat the procedure for every desired time, t.

Correlation of Estimates with Ambrosia Lake Predictions

In order to test the correctness of the graphical analysis proposed, an analysis of pumping test data from Ambrosia Lake, New Mexico, was made, and an estimate of influx was checked against a previous estimate.

Ambrosia Lake is the center of uranium mining and milling in the United States. Approximately 57% of the country's uranium reserves are located here.

The ore is generally found within the Westwater Canyon member of the Morrison Formation. It is upper Jurassic in age, "...consists of a series of white sandstones (composed of rounded medium to coarse grains of quartz cemented by calcium carbonate and arranged in lenticular, irregular beds 1 to 30 feet thick) interbedded with red earthy soft fine-grained sandy shales or mudstones...." (20, p. 2313) It has a local thickness of 150 to 200 feet. Intercalated clay beds and petroliferous residue cause local variations in permeability.

Almost all groundwater occurs in the Westwater. Because of this, much consideration was given to the problem of excessive influx into development openings.

One company in the area, Homestake Mining Company, engaged an eminent groundwater hydrologist who conducted a series of pumping tests and estimated the influx to be expected in the mine shaft and in lateral headings. The data used and results obtained are tabulated in Appendix C. Using the same data and the nomographs previously constructed, the following correlation was made.

Table 3

Estimated Influx into Mine Shaft

t (days after completion)	Homestake Est.	Nomographs
1	640 gpm	600 gpm
10	420	500
100	320	350
400	280	280
1000	260	250

The drainage radius was assumed to be 1000 feet and the drawdown equal to the difference in elevation between static water level and the shaft bottom or 275 feet. It was stated in the report that shaft sinking would progress at a rate of 5 feet per day. The water bearing formation is approximately 200 feet thick, so forty days would be required for sinking through the aquifer. t_0 is the time at which the water level is static, or in other words, is the time at which the water is first encountered. The initial value for t in the calculations then is actually 41 days. The values for formation constants S and T as found by the Theis type form solutions are 10.7×10^{-5} and 1608 gpd per foot respectively. (See Appendix C) These values were inserted into the nomographs and values of Q were obtained.

The values obtained by using nomographs were considered to be in general agreement with the Homestake estimates.

A complete analysis of the data using the method proposed in this thesis was then undertaken.

The analysis begins when shaft sinking first encounters the water bearing strata. At this time the water level rises approximately 75 feet above the shaft bottom. After one day, five feet of shaft will have been sunk and the drawdown will then be eighty feet. These data are inserted into the nomographs and Q is found to be 1700 gpm. This, however, assumes that the shaft completely penetrates the formation. Since it does not, the partial penetration correction factor is applied. The partial penetration is 2.5% and from Fig. 11, the correction factor is 0.05. Thus Q is 85 gpm. This influx does not consider the effect of shaft diameter.

The shaft has clear dimensions of 11 feet, 4 inches by 14 feet, 4 inches. This yields a surface area per foot of depth of 51 1/3 square feet. From Fig. 8, a 16 1/2 foot diameter circular shaft has an equivalent surface area. The pumped well was 6-inches in diameter. From Fig. 7, the "shaft diameter" factor is 1.72.

The influx into the shaft is then 85 x 1.72 or 144 gpm.

Consideration must be given to the effect of unwatering the formation on the drawdown at any time t. This can be accomplished by plotting on semi-log paper drawdown vs. log time. (See Fig. 12) It is seen that the drawdown per cycle of time is approximately 4 feet at a pumping rate of 83 gpm.

In order to keep the shaft dry, it is assumed that water will be pumped initially at a rate of 144 gpm. After ten days of pumping, the static water level has been lowered 7 feet, while shaft sinking has advanced 50 feet. Thus 43 feet of added drawdown must be considered at the end of ten days.

The assumption that the shaft will be pumped at the influx rate determined for a time t, until a new rate of influx is calculated is not strictly true. In order to keep the shaft dry, the rate of pumping will continually increase with the result that the water level will be drawn down further than is indicated for the shaft sinking period. This probably accounts for the relatively high influx estimated for the first few days after completion of the shaft.

The estimated influx for various times during and after sinking is tabulated in Table 4.

Table 4

Calculated Influx into Mine Shaft

t (days after aquifer is first encountered)	1	10	20	30	40	41*	51	141	441	1041
Drawdown (feet)	80	123	155	175	182	164	117	68	42	22
Q (full penetration)	1700	750	620	610	600	570	400	160	100	44
Q (partial penetration)	85	225	372	500	—	—	—	—	—	—
Q (shaft)	144	383	632	850	1020	970	680	272	170	75

*1 day after shaft completion

It was stated in the Homestake report that the estimates reported were thought to be high in the latter stages of unwatering. This is true, the estimates being high because the Theis equations assume that the

The assumption that the shaft will be pumped at the influx rate determined for a time t, until a new rate of influx is calculated is not strictly true. In order to keep the shaft dry, the rate of pumping will continually increase with the result that the water level will be drawn down further than is indicated for the shaft sinking period. This probably accounts for the relatively high influx estimated for the first few days after completion of the shaft.

The estimated influx for various times during and after sinking is tabulated in Table 4.

Table 4

Calculated Influx into Mine Shaft

t (days after aquifer is first encountered)	1	10	20	30	40	41*	51	141	441	1041
		-	---	---	[illegible]	[illegible]	117	68	42	22

113	142	170	186	189	170	120	70	37	20	[illegible]	100	44
6	51	105	156	—	—	—	—	—	—	—	—	—
10	88	181	268	325	292	206	120	64	34	2	170	75

*1 day after shaft completion

It was stated in the Homestake report that the estimates reported were thought to be high in the latter stages of unwatering. This is true, the estimates being high because the Theis equations assume that the piezometric surface never falls below the upper boundary of the water bearing formation. When the concept of unwatering is injected into the analysis, much lower values of influx are obtained. This is in line with reports of actual inflow when this particular mine was developed. (L. W. Swent, personal communication)

RECOMMENDATIONS FOR FURTHER STUDY

During the course of this investigation, a number of questions have been raised concerning extension of the results presented. Some of these questions should serve to indicate areas where further study is warranted. For example:

1. How does the piezometric head vary with time under transient flow conditions? A rough approximation has been made in this investigation, but a more thorough understanding of the behavior of the piezometric surface is needed. Perhaps the use of the analog computer, as mentioned previously, would be useful.
2. How do geologic inhomogeneities affect the quantity of influx? Throughout this study, the water bearing formation has been considered infinite in areal extent, homogeneous and isotropic in character. The effect of lateral and vertical changes in permeability, as well as the influence of various geologic structures, such as dikes, faults, folds, etc. are not well known. It is suggested that model studies might yield the necessary qualitative information needed.
3. How can the formation constants be evaluated when the groundwater flow is through fissures? Here, perhaps, is

the most challenging question posed. One thought along this line is to attempt a correlation between laboratory tests of permeability and field tests.

4. When a water problem is recognized, how can it best be dealt with? This is the logical extension of the work presented in this thesis. One such approach would be the design of pumping patterns for effective unwatering. Such studies could be made using membrane models.

The answer to each of the questions posed above will enable future estimates of groundwater influx to be more realistic and certainly more accurate.

SUMMARY AND CONCLUSIONS

This investigation was conducted

1. to evaluate the state of knowledge of the mining industry concerning estimation of groundwater influx during shaft sinking,
2. to present a method for estimating such flows.

A literature search revealed that abundant information on the flow of groundwater could be obtained from the fields of hydrology and civil engineering. Little work however, had been done in mining.

The various methods of estimating quantity of flow were studied. Pumping tests appeared to give the needed information under actual field conditions. A method of analysis was developed utilizing data obtained from such tests.

The method of analysis presented in this thesis is based upon the Theis non-equilibrium equations. The initial development of these equations was accomplished by making a number of simplifying assumptions. These assumed conditions are not generally found in the field; therefore, the analysis is not entirely correct.

The effect of these assumptions on groundwater influx has been discussed, and the analysis has included some correction factors.

From this study it can be concluded that the knowledge of the mining industry on the subject of groundwater estimates is meager.

No satisfactory method of analyzing shaft water problems has yet been outlined. Much information can be gathered as shafts are sunk into water bearing strata. From this information, it should not be difficult to make a reasonable estimate of influx. At the present time, a guide is needed to outline information needed and methods of obtaining such information. It is hoped that the method of analysis herein presented will fulfil that function.

Specific conclusions reached regarding the method of analysis are:

1. Solution of the Theis equations by the use of nomographs is rapid and the same degree of accuracy is obtained as with computations.
2. When a large vertical opening is considered, the Theis equations are not valid; but, by using a shaft diameter factor found by solving the Dupuit equation, a satisfactory correction factor can be applied.
3. Muskat's correction factors for partial penetration can be used in analyzing influx during shaft sinking through the water zone.
4. An approximation of the effect of unwatering can be found by plotting drawdown vs. log time at any given pumping rate, then by simple proportion, drawdown for the pumping rate necessary to keep the shaft dry can be obtained.
5. The resulting estimate is reasonably close to the amount of actual influx encountered in the mine shaft for which data were available.

APPENDICES

A. Nomenclature

B. Construction of Nomographs

C. Pumping Test Data, Ambrosia Lake, New Mexico

A. Nomenclature

1. A = cross-sectional area through which flow occurs, ft.^{2}
2. b = saturated thickness of porous medium, ft.
3. h_e = head, in aquifer ft.
4. h_w = head in well, ft.
5. K_A = absolute permeability, darcys
6. K_e = effective permeability, meinzers
7. l = length of flow, ft.
8. N_R = Reynold's number
9. $\phi = -Kh$ = velocity potential
10. p = pressure, psi
11. Q = quantity of flow
12. r_e = drainage radius of porous medium, ft.
13. r_w = well radius, ft.
14. S = coefficient of storage
15. T = coefficient of transmissibility, gal. per day per ft.
16. t = time, days
17. $u = \frac{r^2S}{4Tt}$
18. μ = viscosity, centipoises
19. v = macroscopic velocity of fluid, ft./min.
20. $W(u)$ = well function of $u = \int_u^\infty \left(\frac{e^{-u}}{u}\right) du$
21. x = distance parallel to X axis
22. y = distance parallel to Y axis
23. z = distance parallel to Z axis

B. Construction of Nomographs

The limit of the variables were selected arbitrarily from a knowledge of the range of such variables. The nomographs can be modified to suit any conditions by varying the limits accordingly.

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

The type form is $f_1(u) + f_2(v) + f_3(w) + \dots = f_n(q)$.

The equation then takes the form:

$$\log u + \log T + \log t = \log 1.87 + 2 \log r + \log S$$

It is separated into three parts:

1. $\log T + \log t = A$
2. $\log 1.87 + 2 \log r + \log S = B$
3. $\log u + A = B$

$X_T = m_T \log T$ T varies from 1 to 2×10^9 gpd/ft.

Let $X_T = 12$ then $m_T = \frac{12}{9.301} = 1.3$

$$\therefore X_T = 1.3 \log T$$

T	1	10	10^2	10^3	10^4	10^5	10^6	10^7	10^8	10^9	2×10^9
$\log T$	0	1	2	3	4	5	6	7	8	9	9.30
X_T	0.00	1.30	2.60	3.90	5.20	6.50	7.80	9.10	10.40	11.70	12.10

$X_t = m_t \log t$ t varies from 1 to 1000 days

Let $X_t = 12$ then $m_t = \frac{12}{3} = 4$

$$\therefore X_t = 4 \log t$$

t	1	10	100	1000
$\log t$	0	1	2	3
X_t	0.00	4.00	8.00	12.00

In order to locate the A scale, let the T and t scales be placed four inches apart.

$$\frac{a}{b} = \frac{m_T}{m_t}$$

a = distance from T scale to A scale

b = distance from t scale to A scale

$a = 1.00$ inches

$b = 3.00$ inches

The scale modulus $m_A = \frac{m_T m_t}{m_T + m_t} = .98$

$X_r = m_r (\log 1.87 + 2 \log r)$ r varies from 1 to 1000 ft.

Let $X_r = 12$ then $m_r = \frac{12}{6} = 2$

$$\underline{\therefore X_r = 4 \log r}$$

r	1	10	100	1000
$\log r$	0	1	2	3
X_r	0	4.00	8.00	12.00

$X_s = m_s \log S$ S varies from 10^{-10} to 10^2

Let $X_s = 12$ then $m_s = \frac{12}{12} = 1$

$$\underline{\therefore X_s = \log S + 10}$$

S	10^{-10}	10^{-8}	10^{-6}	10^{-4}	10^{-2}	10^{-1}	1
log S	-10	-8	-6	-4	-2	-1	0
X_s	0	2.00	4.00	6.00	8.00	9.00	10.00

In order to locate the B scale, let the r and S scales be placed four inches apart.

$$\frac{a}{b} = \frac{m_r}{m_s}$$

a = 2.57 inches

b = 1.43 inches

The scale modulus $m_B = \frac{m_r m_s}{m_r + m_s} = .67$

$X_u = m_u \log u$ u varies from 10^{-16} to 10

$$m_u = \frac{m_A m_B}{m_A + m_B} = .40$$

$$\therefore \underline{X_u = .40 \log u}$$

u	10^{-16}	10^{-10}	10^{-5}	10^{-1}	1	10
log u	-16	-10	-5	-1	0	1
X_u	-6.40	-4.00	-2.00	-0.40	0	0.40

In order to locate the u scale:

$\frac{a}{b} = \frac{m_u}{m_A}$ a' = distance from u scale to B scale

b' = distance from B scale to A scale

a' = 0.87 inches

b' = 2.13 inches

2. $Q = \frac{\Delta h\ T}{114.6\ W(u)}$

The type form is $f_1(u) + f_2(v) + f_3(w) + \ldots = f_n(q)$

The equation then takes the form:

$$\log Q + \log 114.6 + \log W(u) = \log \Delta h + \log T$$

It is separated into two parts:

1. $\log \Delta h + \log T = C$
2. $\log Q + \log 114.6 + \log W(u) = C$

$X_h = m_h \log \Delta h$ Δh varies from 1 to 2000 ft.

Let $X_h = 12$ then $m_h = \frac{12}{3.301} \cong 3.65$

$$\therefore X_h = 3.65 \log \Delta h$$

Δh	1	10	100	1000	2000
$\log \Delta h$	0	1	2	3	3.30
X_h	0	3.65	7.30	10.95	12.05

$X_T = m_T \log T$ T varies from 1 to 2×10^9 gpd/ft.

Let $X_T = 12$ then $m_T = \frac{12}{9.301} \cong 1.3$

$$\therefore X_T = 1.3 \log T$$

T	1	10	10^2	10^3	10^4	10^5	10^6	10^7	10^8	10^9	2×10^9
log T	0	1	2	3	4	5	6	7	8	9	9.30
X_T	0.00	1.30	2.60	3.90	5.20	6.50	7.80	9.10	10.40	11.70	12.10

In order to locate the C scale, let the Δ h and T scales be placed six inches apart.

$$\frac{a}{b} = \frac{m_h}{m_T}$$

a = 4.45 inches

b = 1.55 inches

The scale modulus $m_c = \frac{m_H m_T}{m_H + m_T} = .96$

$X_{W(u)} = m_{W(u)} \left[\log 114.6 + \log W(u)\right]$ W(u) varies from 10^{-7} to 34.

Let $X_{W(u)} = 10$ then $m_{W(u)} = \frac{10}{8.53} \cong 1.15$

$$\underline{\therefore X_{W(u)} = 1.15 \left[\log W(u)\right]}$$

$W(u)$	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10	34
$[\text{Log } W(u)]$	-7	-6	-5	-4	-3	-2	-1	0	1	1.53
$X_{W}(u)$	-8.05	-6.90	-5.75	-4.60	-3.45	-2.30	-1.15	0	1.15	1.76

$X_Q = m_Q \log Q$ Q varies from 1 to 10^5 gpm.

$$m_Q = \frac{m_{W(u)}\, m_c}{m_{W(u)} + m_c} \cong 0.52$$

$$\underline{\therefore X_Q = 0.52 \log Q}$$

Q	1	10	10^2	10^3	10^4	10^5
log Q	0	1	2	3	4	5
X_Q	0	0.52	1.04	1.56	2.08	2.60

In order to locate the Q scale, let the W(u) and C scales be placed six inches apart.

$$\frac{a}{b} = \frac{m_Q}{m_{W(u)}}$$

$a = 3.28$ inches

$b = 2.72$ inches

C. Pumping Test Data, Ambrosia Lake, New Mexico

The data presented have been abstracted from a private report to Homestake Mining Company, April, 1957.

The pumping test data were collected from 1013 hours, 5 April, 1957 to 1903 hours, 7 April, 1957. One well was pumped and two others used as observation wells. The well locations, as well as the proposed shaft site are shown in Fig. 13.

The ore bearing horizon is the Westwater Canyon member of the Morrison formation, a 175 ft. sequence of interbedded sandstones and clay. It is overlain by the Brushy Basin member and underlain by the Recapture. The Westwater was assumed to be homogeneous, although this assumption later proved to be incorrect. (L. W. Swent, personal communication) Generalized drill logs of the three wells used in the test are shown in Fig. 14.

A 33-stage, 5 1/2 inch Reda pump, type Y-180 was used for the test. (18, p. 4)

Data taken from the two observation wells during the test are tabulated in Tables 5 and 6.

Formation constants were determined using the Theis type form solution and the Jacob modification. The graphical solutions are shown in Fig. 15, 16, and 17. From the type curve solution, the following values for S and T were found: $S = 13.0 \times 10^{-5}$ and $T = 1399$ gpd/ft. for 23-OB-1. $S = 8.4 \times 10^{-5}$ and $T = 1816$ gpd/ft.* for 23-OB-2. The average values by this method are $S = 10.7 \times 10^{-5}$, $T = 1608$ gpd/ft.

---

*under a unit hydraulic gradient

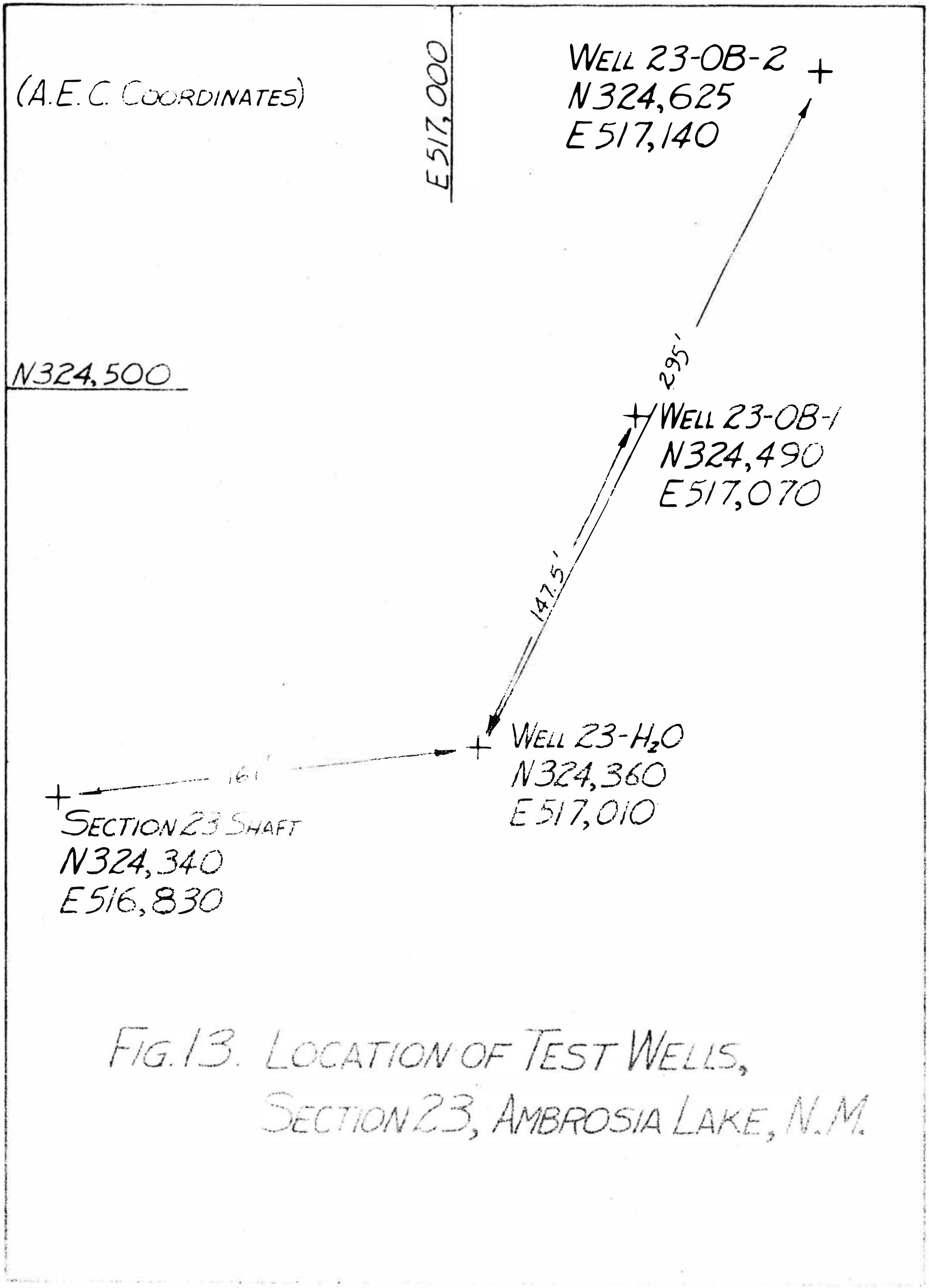


FIG. 13. LOCATION OF TEST WELLS, SECTION 23, AMBROSIA LAKE, N.M.

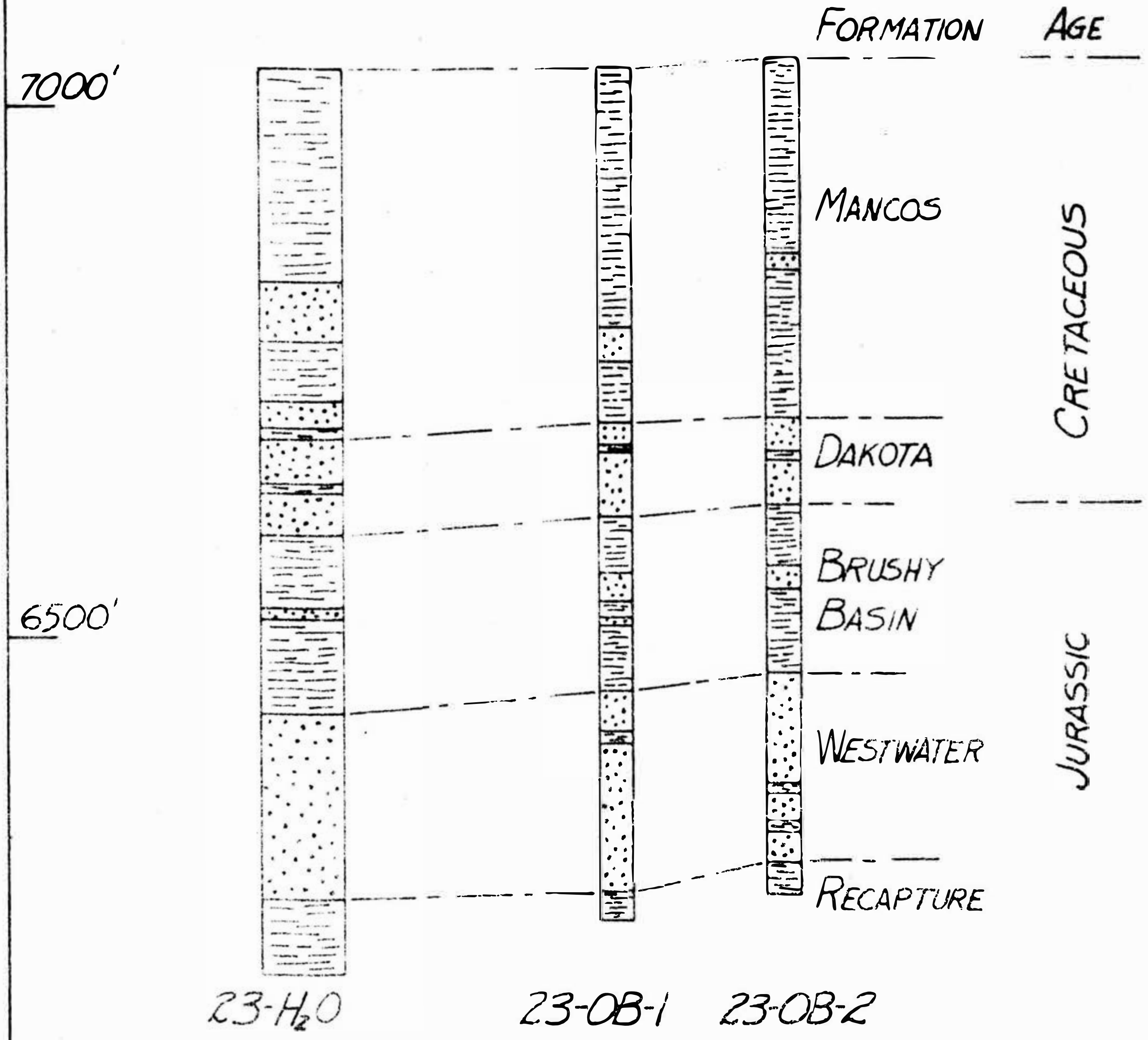


FIG. 14. GENERALIZED DRILL LOGS, TEST WELLS IN SECTION 23, AMBROSIA LAKE, N.M.

Table 5

Drawdown Test Data for Observation Wells 23-OB-1 and 23-OB-2

(Used for plot to be superposed on Theis type curve)

Date April, 1957	Hour	Elapsed Time		$\frac{t}{r^2}$	Drawdown s ft.	Water Level ft.
		Min.	t days			
Well 23-OB-1 (r = 147.5')						
5	1013	0	0	0	0	6555.2
	1054	41	0.0285	1.31×10^{-6}	10.6	44.6
	1120	67	0.0465	2.14×10^{-6}	14.0	41.2
	1157	104	0.0722	3.32×10^{-6}	16.8	38.4
	1257	164	0.1139	5.24×10^{-6}	19.4	35.8
	1407	234	0.1626	7.47×10^{-6}	21.2	34.0
	1459	286	0.1986	9.13×10^{-6}	22.1	33.1
	1702	409	0.2840	1.31×10^{-5}	23.4	31.8
	1902	529	0.3674	1.69×10^{-5}	24.3	30.9
	2100	647	0.4493	2.07×10^{-5}	24.9	30.3
Well 23-OB-2 (r = 295')						
5	1013	0	0	0	0	6555.8
	1055	42	0.0292	3.36×10^{-7}	4.4	51.4
	1121	68	0.0472	5.42×10^{-7}	7.0	48.8
	1158	105	0.0729	8.38×10^{-7}	9.3	46.5
	1258	165	0.1146	1.32×10^{-6}	11.6	44.2
	1408	235	0.1632	1.88×10^{-6}	13.2	42.6
	1500	287	0.1993	2.29×10^{-6}	14.0	41.8
	1705	412	0.2861	3.29×10^{-6}	15.1	40.7
	1904	531	0.3688	4.24×10^{-6}	15.9	39.9
	2102	649	0.4507	5.18×10^{-6}	16.5	39.3
6	0108	895	0.6215	7.14×10^{-6}	17.1	38.7
	0313	1020	0.7083	8.14×10^{-6}	17.3	38.5

Table 6

Drawdown Data for Observation Wells 23-OB-1 and 23-OB-2

(Used for application of the Jacob modification of Theis method)

Date April, 1957	Hour	Elapsed Min.	Drawdown ft.	Water Level
Well 23-OB-1 (r = 147.5')				
5	1013	0	0	6555.2
	1120	67	14.0	41.2
	1157	104	16.8	38.4
	1257	164	19.4	35.8
	1407	234	21.2	34.0
	1702	409	23.4	31.8
	1902	529	24.3	30.9
	2100	647	24.9	30.3
	2310	777	25.3	29.9
6	0104	891	25.6	29.6
	0310	1017	25.8	29.4
	0904	1371	26.3	28.9
	1454	1721	26.6	28.6
	2105	2092	26.6	28.6
7	0303	2450	26.6	28.6
	0900	2807	26.9	28.3
	1254	3041	27.1	28.1
	1903	3410	27.2	28.0
Well 23-OB-2 (r = 295')				
5	1013	0	0	6555.8
	1121	68	7.0	48.8
	1158	105	9.3	46.5
	1258	165	11.6	44.2
	1408	235	13.2	42.6
	1705	412	15.1	40.7
	1904	531	15.9	39.9
	2102	649	16.5	39.3
	2312	779	16.9	38.9
6	0108	895	17.1	38.7
	0313	1020	17.3	38.5
	0906	1373	17.6	38.2
	1456	1723	17.9	37.9
	1907	1974	18.0	37.8
7	0110	2337	18.0	37.8
	0710	2697	18.0	37.8
	1440	3147	18.6	37.2
	1710	3297	18.8	37.0

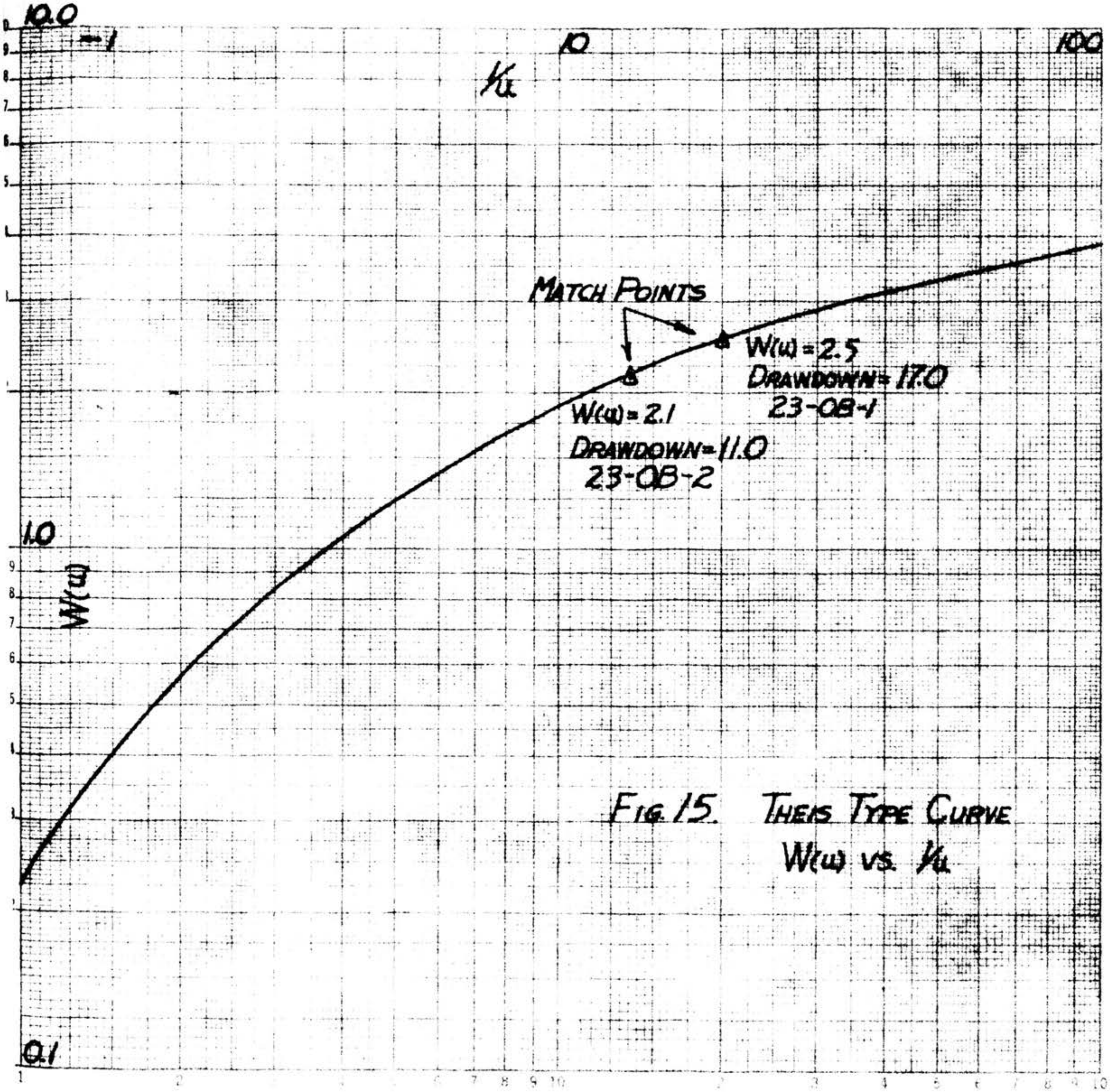


FIG. 15. THEIS TYPE CURVE
W(u) vs. 1/u

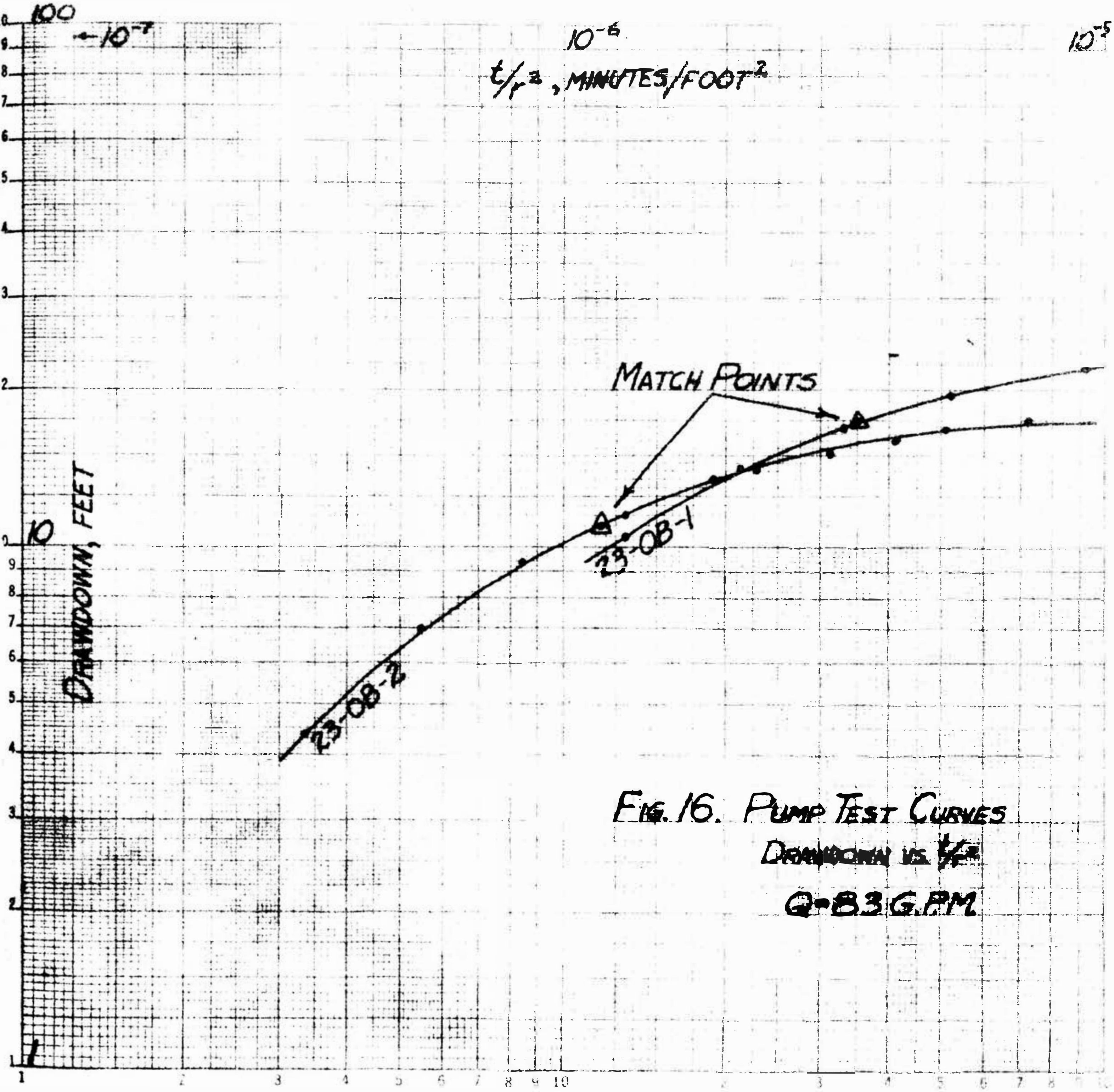


FIG. 16. PUMP TEST CURVES
DRAWDOWN vs t/r²
Q=83 G.P.M.

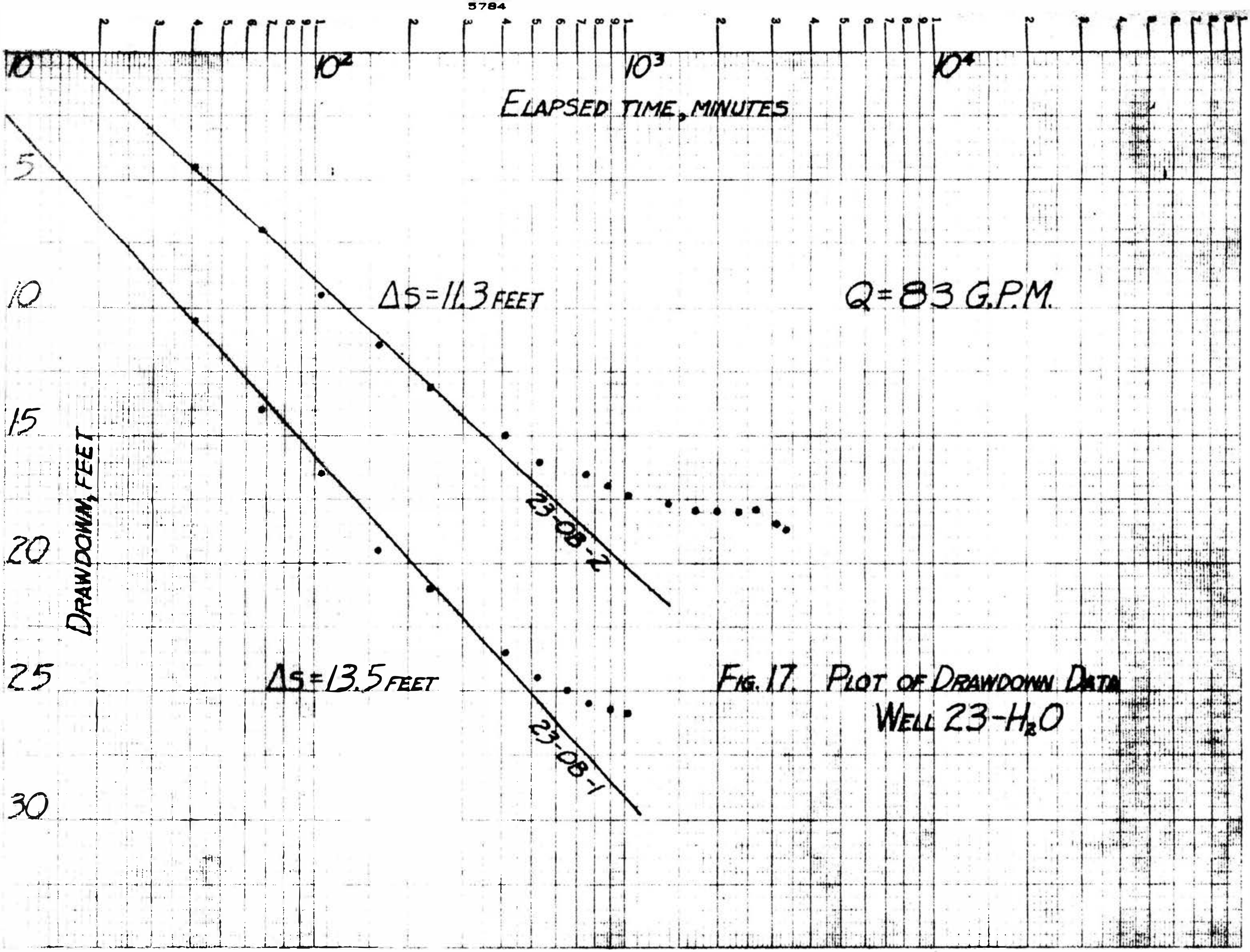


FIG. 17. PLOT OF DRAWDOWN DATA
WELL 23-H_2O

When the Jacob modification was used, the following values were obtained: $S = 10 \times 10^{-5}$ and $T = 1623$ gpd/ft.* for 23-OB-1. $S = 7.4 \times 10^{-5}$ and $T = 1939$ gpd/ft.* for 23-OB-2. The average values by this method are $S = 8.7 \times 10^{-5}$ and $T = 1777$ gpd/ft.*

From this data, the estimate of influx into the shaft was made. (18, p. 21)

Days after shaft is completed	Estimated Discharge gpm
1	640
10	420
100	320
400	280
1000	260

---

*under a unit hydraulic gradient

BIBLIOGRAPHY

1. Atomic Energy Commission and United States Geological Survey, Prospecting for Uranium, U. S. Government Printing Office, Washington 25, D. C., 217 pp., 1957.

2. Bosazza, V. L., "On the Storage of Water in Rocks in Situ," Transactions, American Geophysical Union, vol. 33, pp. 42-48, 1953.

3. Brown, Russell H., "Selected Procedures for Analyzing Aquifer Test Data," Journal, American Water Works Association, vol. 45, no. 8, pp. 844-866, 1953.

4. Butler, Stanley S., Engineering Hydrology, Prentice Hall, Inc., Englewood Cliffs, New Jersey, 355 pp., 1957.

5. Dodge, R. A. and Thompson, M. J., Fluid Mechanics, McGraw-Hill Book Company, Inc., New York, New York, 495 pp., 1937.

6. Gillson, J. L., ed., Industrial Minerals and Rocks, AIME, New York, New York, 934 pp., 1960.

7. Jacob, C. E., "On the Flow of Water in an Elastic Artesian Aquifer," Transactions, American Geophysical Union, vol. 21, pp. 574-586, 1940.

8. Kashef, Abdel-Aziz I., Toulouklan, Y. S. and Fadum, R. E., "Numerical Solutions of Steady-State and Transient Flow Problems--Artesian and Water Table Wells," Purdue Engineering Experiment Station, Research Series No. 117, 116 pp., 1952.

9. LeGrand, H. E., "Some Notes on the Principles of Mine Hydrology," AIME, Preprint No. 5817A20, 8 pp., 1958.

10. Meinzer, O. E., "Outline of Methods for Estimating Groundwater Supplies," USGS Water Supply Paper 638C, pp. 99-144, 1932.

11. ______________, ed., Hydrology, Dover Publications, Inc., New York, New York, 712 pp., 1942.

12. Muskat, M., The Flow of Homogeneous Fluids through Porous Media, McGraw-Hill Book Company, Inc., New York, New York, 763 pp., 1937.

13. Remson, Irwin, and van Hylckama, T. E. A., "Nomographs for the Rapid Analysis of Aquifer Tests," Journal, American Water Works Association, vol. 48, pp. 511-516, 1956.

14. Stuart, Wilbur T., "Pumping Test Evaluates Water Problem at Eureka, Nevada," Transactions, AIME, vol. 202, pp. 148-156, 1955.

15. Theis, C. V., "Equation for Lines of Flow in Vicinity of Discharging Artesian Well," Transactions, American Geophysical Union, vol. 13, pp. 317-320, 1932.

16. __________, "The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Groundwater Storage," Transactions, American Geophysical Union, vol. 16, pp. 519-524, 1935.

17. Todd, D. K., Groundwater Hydrology, John Wiley and Sons, Inc., New York, New York, 336 pp., 1959.

18. Utah Construction Company, "Report on Water Well Tests, Sections 23, 25, and 36, Ambrosia Lake Area near Grants, New Mexico," private report to Homestake Mining Company, 1957.

19. Wenzel, L. K., "Methods for Determining Permeability of Water-Bearing Materials, with Special Reference to Discharging-Well Methods," USGS Water Supply Paper 887, U. S. Government Printing Office, Washington, D. C., 192 pp., 1942.

20. Wilmarth, M. Grace, "Lexicon of Geologic Names of the United States (Including Alaska)," USGS Bulletin 896, 2396 pp., 1938.

VITA

Morris Thrane Worley was born October 16, 1936, at Snyder, Texas. He attended public schools in Carlsbad, New Mexico, and in 1958, was granted the degree Bachelor of Science in Mining Engineering (with honors) from New Mexico Institute of Mining and Technology, Socorro.

He was appointed Instructor in Mining Engineering at Missouri School of Mines and Metallurgy in September, 1958.

His practical experience includes summer employment with United States Borax and Chemical Corporation, The Anaconda Company, New Mexico Bureau of Mines and Mineral Resources, and the United States Bureau of Mines.