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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1536-D

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By H. E. SKIBITZKE *and* J. A. da COSTA

GROUND-WATER HYDRAULICS

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A theoretical analysis of ground-water flow in a basalt aquifer

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By H. E. Skibitzke and J. A. da Costa

ABSTRACT

The principal ground-water reservoir in the Snake River Plain, Idaho, is the Snake River basalt. Neither the permeability nor the transmissibility of this aquifer is uniform throughout any large part of the plain. Since the development of the Minidoka irrigation project and the construction of the National Reactor Testing Station of the Atomic Energy Commission, it has become important to define the regional ground-water flow system, taking into consideration the effects of the predicted increases in water withdrawal and of future irrigation.

A piezometric map of the Snake River Plain, assumed to represent the natural hydrologic system before it was disturbed artificially, was used to construct an idealized flow net of the region. The flow net was used to obtain permeability data for the construction of a two-dimensional electric analog model of the ground-water reservoir.

Four different hypothetical problems are analyzed by means of the electric model. The first assumes pumping at the National Reactor Testing Station with recharge along the entire reach of the Snake River. The second assumes pumping at the testing station without recharge along the Snake River. The other two problems are similar to these, but with pumping at the Minidoka project instead of at the testing station. The resultant idealized flow patterns are shown on a map of the Snake River Plain.

The magnitude of pumping that may be developed on the plain cannot be predicted accurately because the variations in the amount of evapotranspiration and recharge to the ground-water system generally are not known. The magnitude of present ground-water recharge from sources other than the Snake River is another unknown. However, the amount of recharge does not enter into determinations of the lowering of water levels caused by pumping unless the amount of recharge were changed in the future.

Analysis of the piezometric maps of the Snake River Plain shows that much additional information on permeability variations in the aquifer would be needed for an adequate understanding of the hydrologic conditions.

INTRODUCTION

A necessity in ground-water investigations of an arid region such as the Snake River Plain is to predict long-term local and regional effects that will be imposed on the ground-water flow system by progressively increasing draft on ground water for irrigation, industry, and other uses. Prediction of the effects in terms of flow-system modification has special interest to the Atomic Energy Commission.

The immediate interest is in the effects that may be expected from a predicted increase in the amount of water pumped for service supply at the National Reactor Testing Station (hereafter called NRTS). More important, however, are the local and regional long-term effects that would follow a great increase in pumping for service use at the NRTS and for irrigation on the Minidoka irrigation project and other irrigation tracts, or for other use. Low-level radioactive wastes are discharged into the ground at the NRTS through wells, seepage pits, open-surface infiltration ponds, and other facilities. Some of this radioactive waste merges with ground water. Also, accidentally or otherwise, waste having higher concentrations of radioactivity may be added to the ground water. Thus, to determine where such wastes may go and how long will be required, it is necessary to determine the direction and rate of motion of water in the ground-water system of the Snake River Plain.

This report deals with the effects of pumping and the problems of ground-water movement. In part of the discussion, assumed or predicted increases in ground-water pumping are considered. It is assumed throughout, however, that the present pattern of reservoir storage and diversions of Snake River water will not change.

Principal factors and their relations that affect rates and direction of ground-water motion are as follows:

1. Hydrologic properties of the porous medium, such as porosity, shape and size of voids, extent to which voids are interconnected, and thickness of porous zones.
2. Degree of homogeneity of the porous medium.
3. Relation between the foregoing properties and such hydrologic variables as permeability and coefficient of storage.
4. Variations in permeability with distance and direction in the porous medium.
5. The quantities of water flowing into and out of the water-bearing material, and the places where inflow and outflow occur.

The purpose of this report is to illustrate how these and other factors, as they are known or assumed to exist, control the flow system in the Snake River Plain and to develop thereby a reasonably complete, though somewhat idealized picture, of that flow system. Such assumptions as that of no recharge over the plain, constant thickness of the zone of saturation, and isotropy of the porous medium were made primarily to facilitate the construction of an electric model and to simplify the analysis of the problem. However, even if these assumptions had not been made, it is likely that the overall results obtained would not have been significantly different.

When the authors first analyzed the problem described herein, with the aid of an electric model, they used only a few generalized geologic and hydrologic data on the Snake River Plain. If all the data available today had been used, a much more detailed model and analysis could have been made. Nevertheless, the real value of this report lies in the description of fundamental principles and analytical techniques which may be equally applicable to other problems of similar complexity.

PRINCIPLES AND FACTORS INVOLVED IN ANALYSIS OF A HYDROLOGIC SYSTEM

Hydrologic factors to be considered in an analysis of the hydrologic system of an arid region are the position and fluctuation of groundwater levels, regional geology, and natural inflow and outflow. Interrelations among these factors are illustrated in figure 12. The only constant factor in the whole scheme is the rock skeleton. Block *D* in figure 12 represents the overall permeability and porosity configuration of the aquifer. This rock skeleton encloses a dynamic liquid body, the ground water. The ground water is produced and affected by natural processes and forces (blocks *A* and *B*). It is modified by human activities (*E*). The interplay of the several forces depends importantly on the rock skeleton. Gravitational force moves the liquid. The frictional forces caused by motion of the liquid are pressure forces. Hydraulic head is the resultant of pressure and gravitational forces. Variations in head and other factors cause the changes represented in block *C* of the diagram.

The hydraulic head has far more significance than that of a mere hydraulic variable. It has economic significance also in the development of ground water. Differences in the hydraulic head or the hydraulic gradient along a line at a given time are determined by the permeability of the formation through which the water is moving and by the rate of movement. The head at any point in an aquifer represents an integration of the changes in water level downstream from that point along a streamline to the point of discharge. For a specific purpose, such as defining the path of a band of liquid waste to a discharge point, the streamline chosen at the discharge end must be one that extends back through the point where the liquid was introduced.

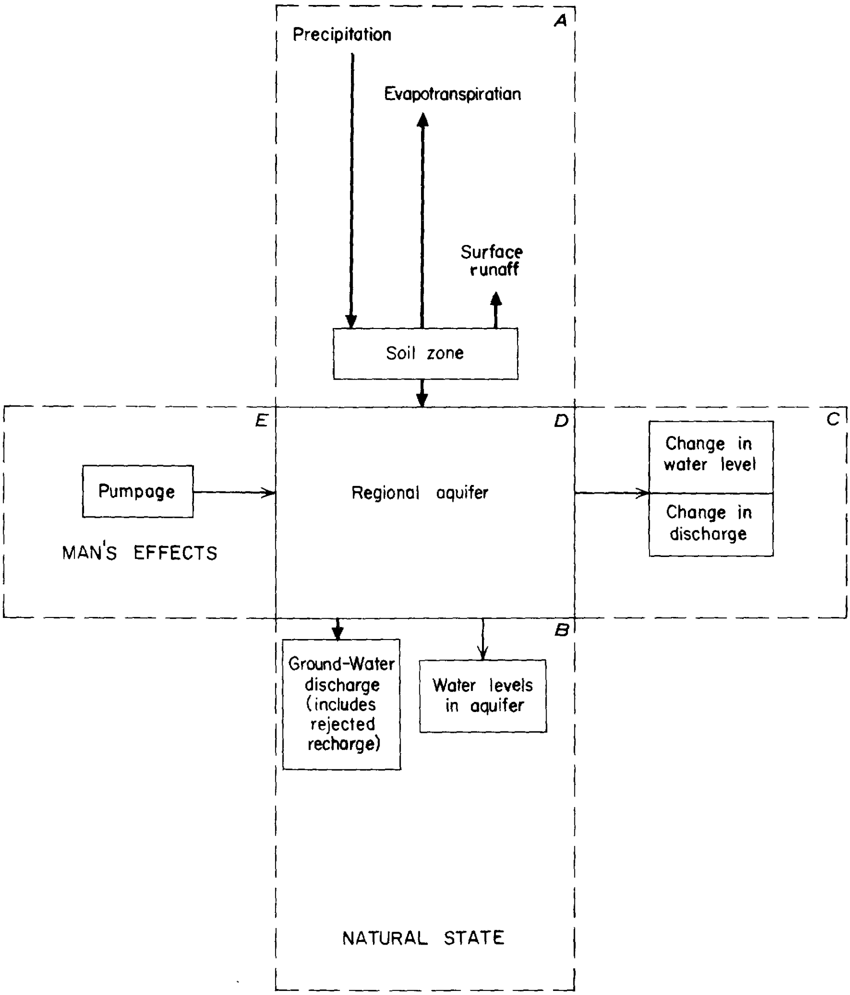

FIGURE 12.—Functional diagram of hydrologic parameters in an arid region.

These principles are obvious, but some of their implications are often overlooked. One important implication is that the streamlines and equipotential lines at any point are controlled by the hydrologic boundaries of the aquifier and by its hydrologic characteristics.

The basic problem in predicting effects of alterations in the dynamic state is that, in prediction, no direct measurements can be made. If the head, for example, is to be determined by indirect means, as it must be when future events of effects are predicted, the characteristics of the dynamic liquid-flow system and the spatial arrangement of hydrologic variables must be known to predict anything at all about water levels and their behavior. Moreover, the water levels must be known before the direction and quantity of flow can be determined.

Assume that the present dynamic state of liquid flow along the external boundary of a ground-water system is known. Then, future states can be predicted by (a) defining what is to be done to the system, and (b) adding or subtracting from the present state the effects of the things to be done. In simple homogeneous aquifers in which the flow at the boundaries is known, the internal flow system can be determined mathematically. The internal head distribution can be determined in a complex aquifer also, if the spatial factors of the problem are known. The problem for both types of aquifers is illustrated in figure 12, where artificial changes in the aquifer (hydrologic stresses caused by man) are represented by block *E*. Pumping of a well, for example, causes changes in water levels throughout the aquifer and in the discharge system. The configuration of change, by itself, has special significance in hydrology. The effects of the changes are controlled in the central block (*D*). The effects of the hydrologic stresses could be predicted only if much were known about the aquifer and the spatial arrangement of its hydrologic properties. Unfortunately, the converse is not true. The spatial arrangements cannot be determined from known dynamic factors unless the permeability is constant in magnitude and direction, and the medium is homogeneous. For this reason, homogeneity and isotropy are often assumed in the analysis of ground-water problems; some media are sufficiently homogeneous that such an analysis is acceptable. The Snake River basalt is neither isotropic nor homogeneous; but in this report it is assumed to be isotropic, and only the effects of nonhomogeneity will be discussed.

HYDROLOGIC PROPERTIES

The amount of information about subsurface geology that is needed to understand and describe a hydrologic system depends on the uniformity of the properties of the system. Even so-called uniform aquifers have local differences in their properties—although these differences are difficult or impractical to describe in detail—and in an aquifer of large areal extent they are of little significance. Commonly, therefore, field problems are idealized to reduce the variables to a number and form that can be resolved by the analytical methods available.

Many aquifers are treated as though they were uniform in permeability because the properties that control their permeability change but little with direction or distance. The regional hydrologic properties of such aquifers can be determined from observational data recorded at relatively few locations. The properties of many other aquifers, however, vary widely within short distances. Such aquifers need many observational data for control, and estimating areal variations in hydrologic properties requires judicious use of the data. For example, after geologic and hydrologic data are organized and assimilated, they must be correlated. That is, hydrologic variables must be related to geologic factors, or full use can be made of neither. Often this is difficult.

It is difficult, for example, to relate data on pore size, joints, and other voids directly to permeability, even where the data are detailed and quantitative. Even more difficult is the task of relating permeability to the qualitative descriptions of aquifer material that are commonly available. Fortunately, the translation of geologic data into hydrologic variables can be aided greatly by aquifer tests made to determine the permeabilities of significantly large parts of the aquifer.

AQUIFER TESTS AND THEIR SIGNIFICANCE

A common kind of aquifer test ("pumping test") uses a discharging well and observational data on the rate of pumping and its effects on water levels. Analysis of such a test is relatively simple, and the end product is a set of hydraulic coefficients. But these represent, at most, a measure of well performance and the approximate characteristics of the aquifer only in the vicinity of the pumped well. Yet regional coefficients and their effects on water movement are the parameters that are sought. To interpret test data in terms that express regional hydrologic variables is difficult, but each correct interpretation of a local aquifer test is an addition to the sum of knowledge of regional hydrologic properties.

Most methods for analyzing aquifer tests yield numerical values of hydrologic properties in the part of the flow system that is affected by the test. To find mathematical solutions, these methods require certain idealized assumptions concerning the natural state of the aquifer. Without idealization no solution can be reached. The usual idealizations are that the aquifer is isotropic and homogeneous. In this report, isotropy and nonhomogeneity refer to permeability. A porous medium is isotropic when its permeability is the same in all directions. Where permeability varies with direction, the medium is anisotropic. If the permeability is constant from point to point within the mass, the medium is homogeneous. Where the permeability varies from point to point within the mass, the medium is nonhomogeneous. If the changes are continuous within the mass, the medium is also nonheterogeneous. If the changes in permeability are discontinuous, the medium is heterogeneous. These idealization state, in effect, that mathematical computations are valid if no complicating geologic factors intrude—that is, if the geologic configuration is of the simplest type conceivable. In short, the problem of relating geologic to hydrologic variables can be solved only by assuming that no problem exists. Despite this paradox, experience shows that a large number of "point" determinations of hydrologic properties can be used to develop useful approximations of regional variations in transmissibility and permeability.

A "point" permeability must be evaluated in relation to the probable degree of anisotropy and nonhomogeneity of the medium. Anisotropy or nonhomogeneity may be controlling factors in the basalt aquifer of the Snake River Plain, but few or none of the quantitative methods now used by hydrologists measure those properties. This fact makes the interpretation of aquifer tests highly difficult, and the interpretation may be meaningless or even misleading if the shortcomings of available methods are ignored. For example, current methods for computing transmissibility from the results of a test on a pumped well ignore the vertical component of permeability in an anisotropic medium. This vertical component, however, may be dominant among the factors that control flow conditions. Some of these conditions are critical determinants in the movement of waste solutions in the zone of saturations.

Obviously, "point" determinations of aquifer parameters cannot be used to predict or analyze accurately the regional flow systems in certain types of aquifers. Regional methods of analysis, however, can be used to advantage. The method described below establishes the basis for a preliminary regional analysis of the Snake River Plain. This method includes dimensional analysis by means of an electric analog model. Before that method is developed, however, it seems advisable to explain why traditional methods of analyzing aquifer-test data are unsuitable.

GROUND-WATER WITHDRAWAL

The effects of ground-water withdrawals from an aquifer depend greatly on the geologic environment in the area of withdrawal. In the present context, "withdrawal" does not refer to the total amount of water pumped, because much of this water returns to the aquifer. Rather, the withdrawal is the amount of ground water that is converted to water vapor (consumed water) or escapes in surface drainageways. Thus, the withdrawal is the net amount that is removed from the aquifer. "Water depletion" is often used in this sense, but usages vary so much that either term must be defined to be understood.

In the arid regions of the West, water loss in the form of vapor generally is of more significance than liquid outflow because water is seldom pumped in sufficient quantities to yield much "waste" into streams. In much of the Snake River Plain, there is no surface drainage, or the drainage is interior and streams carry water only for short distances before it returns to the ground. Streams in some border areas of the plain contain much direct return flow of diverted surface water and indirect return flow from effluent seepage of artificially recharged ground water. On the whole, however, in the areas where crops are irrigated with ground water, the only significant withdrawal is the net withdrawal that is vaporized. The magnitude of drawdown of water levels in the areas where ground water is pumped is controlled by the rate of withdrawal, the geometric arrangement of wells, and the hydrologic properties of the aquifer. The geometric arrangement of wells may be simplified for mathematical analysis of the problem. Assume, for example, that withdrawal is concentrated at a point within the NRTS. This assumption does not introduce any error in determinations of withdrawal effects at considerable distances from the pumped area. The assumption would be invalid, of course, for determining local effects, such as local drawdown and interference among wells on the NRTS or nearby. The detailed local geometry of the withdrawal sites could not be ignored in such a determination.

The effects of pumping in an isotropic and homogeneous medium may be determined mathematically by solving the Laplace equation for the boundary conditions that describe the region of interest. This equation is an interpolation function which describes the internal state of the physical system under study. If the force field along the external boundary of the system is known, the differential equation may be used to determine the internal state.

The first requirement is that the external boundaries of the system being analyzed be known and be amenable to mathematical description. If this requirement is met, a determination can be made of the force field at points other than those where the force field was derived from field experiments. For the problem considered in this report, the geology is expressed by coefficients of transmissibility which either have been measured or have been estimated by geologic inference, so that a differential equation can be written which describes the aquifer, at least approximately. Artificial changes in the aquifer, such as those caused by pumping, drainage, and construction of canals, alter the hydrologic boundaries of the aquifer. For example, a new well, even if it is not pumped, immediately forms a new boundary in the aquifer at the well bore, and this new boundary actually may have some important local effects, especially in a detailed description of paths of waste migration.

The second requirement is that the force field along the entire external boundary of the system be known. Commonly, this force field must be estimated by interpolation for much of the external boundary. This requirement is not significant where the distance from the external boundary to the area of withdrawals is so great that effects at the boundary are negligible (conditions approaching those of the "infinite" aquifer).

Idealizations are sometimes made when the geology and the force field at the external boundaries are not known well enough to be described mathematically. Where effects of the external boundary are appreciable, the resulting analysis will be in error. For example, the assumption of infinite areal extent is incompatible with a system of finite dimensions. However, certain hydrologic methods, such as those utilizing image systems, resolve this incompatibility to some extent.

Thus, the two significant hydrologic parameters required for unambiguous analysis of a system such as the Snake River Plain are a description of the internal state of the aquifer (the stratigraphy, in the sense of spatial distribution of permeability) and the geometry of the external boundary and the force field around it. For many hydrologic systems it is difficult to determine these two parameters accurately, and approximations must be used. In the Snake River Plain, however, the external boundary is marked by mappable surface features, such as the edges of mountains that border the plain. Many data are available also concerning the internal state of the aquifer. The two parameters being known, under the hydrologic conditions assumed, the effects in the aquifer produced by changes in these variables may be determined.

The use of mathematics to find general formulas that describe changes in head is prohibitively difficult because, where geologic conditions are complex, the number of permeabilities is practically infinite, and an infinite number of formulas would thus be necessary to interrelate such permeabilities. Therefore, formulas can be used only for simple symmetrical boundaries that can be described by simple curves. For complex boundaries, the differential equation must be reduced to an approximate interpolation formula which, in turn, may be solved by "numerical methods." These methods are expensive and time consuming, but they can be used sometimes with advantage.

Most homogeneous fields of force in a steady-state system may be described by the Laplace equation. This equation described the force fields of ground water, electricity, heat, or light equally well. Therefore, any ground-water system may be described by an analogous model, such as an electric model. By dimensional analysis, the equivalent electric model can be reduced to laboratory dimensions. In the model, the fundamental aquifer variable (transmissibility) is simulated by an electrical variable (conductance). The electric model is a convenient means for computing the distribution of potential (or head) under complex boundary conditions.

HYDROLOGIC SYSTEM OF THE SNAKE RIVER PLAIN

The purpose of collecting and analyzing data is to resolve problems. The immediate problem is to determine the ground-water flow system of the Snake River Plain. The immediate task, therefore, is to relate the geohydrologic data to that system. The interrelated variables in virtually every ground-water problem are the permeability and transmissibility of the aquifer, quantity of liquid flow, and hydraulic gradient. Analysis of data on these variables seeks to establish the relations between them.

AREAL DISTRIBUTION OF PERMEABILITY

Computed coefficients of permeability of the many aquifers about which information is available range from 2×10^{-4} to 9×10^{4} meinzers (gallons per day per square foot at 60°F)—a range of about half a billion—according to Wenzel (1942, p. 13). Later data extend this range considerably. Moreover, within many single aquifers the permeabilities of materials vary by at least several orders of magnitude.

Neither the permeability nor the transmissibility of the aquifer beneath the Snake River Plain is uniform through any large part of the region. Variations in permeability of course complicate the ground-water flow system in the plain. The full range of variations in transmissibility has not been established, but sufficient data are available to show that those variations strongly affect the flow system.

For simplicity, the aquifer is assumed to be uniform in thickness. Hence, changes in transmissibility reflect only changes in permeability (nonhomogeneity). In the rest of this report, reference will be made only to permeability, except where actual determinations of transmissibility were made. This fact will be illustrated below. The flow system in the plain has prime importance, for example, in the waste-disposal problem and in disposal practices at the NRTS; it is necessary, therefore, to appraise the effects of variable permeability in the flow system and its relative importance.

The piezometric map of the Snake River Plain on plate 1 is assumed to represent the natural hydrologic system before it was disturbed artificially. The map is an essential first step toward analysis of the system.

A rule of thumb in the analysis of a ground-water contour map is that the direction of flow is perpendicular to the equipotential (contour) lines. Where the aquifer is reasonably homogeneous and isotropic, the rule is generally applicable. However, in nonhomogeneous and anisotropic systems, analysis is more complicated.

The rate of flow in a ground-water system is inversely proportional to the distance between the equipotential lines. Therefore, if streamlines are drawn so that the distance between any two adjacent streamlines is directly proportional to the distance between equipotential lines crossed by the streamlines, then pairs of adjacent streamlines will enclose areas through which equal quantities of water are flowing. Where a flow system is bounded by impervious boundaries, the equipotential lines must be normal to the boundaries.

The streamlines shown on plate 1 were drawn in the following steps:

1. Streamlines were drawn so that the distance between any 2 adjacent streamlines where they cross the 3,800 and 3,900-foot equipotential lines is equal to the distance between those 2 equipotential lines. A series of "squares," called the "unit areas," was thus obtained. The ratio between the streamline and equipotential-line intervals is called the unit ratio (obviously, in this case it is equal to 1).
2. The streamlines were extended in both directions from the unit-ratio areas. Two methods are available for extending the streamlines: (a) They may be drawn so that each is perpendicular to each equipotential lines that it crosses, or (b) the streamlines may be drawn in such a way that the ratios in the rectangles are held constant throughout the flow system. In method (*a*), the index ratios will vary from rectangle to rectangle unless the aquifer is homogeneous. A net would be drawn by this method to represent the flow system for an isotropic aquifer. If the medium were also homogeneous, the index ratios would all be equal to 1. If method (*b*) were used, the contours and streamlines would not produce orthogonal forms. The aquifer thus represented would be anisotropic, nonhomogeneous, or both. For analysis of the flow system in the Snake River Plain, the aquifer is assumed to be isotropic, and the discussion will be limited to effects of nonhomogeneity and consequent spatial changes in permeability. Therefore, the streamlines were extended by method (*a*).
3. The third step was to determine ratios between the distances separating successive contours and those separating pairs of adjacent streamlines for each rectangle on the map.

Plate 1 shows that the plotted rectangles vary considerably in size. On the assumption that the same volume of water is moving through each portion of the aquifer, as represented by each member of any pair of successive rectangles along the hydraulic gradient, the distance between the piezometric contours varies inversely with the hydraulic gradient. Therefore, the volume of water represented per unit area of rectangle varies, so that larger or smaller rectangles are needed to represent the same volume of water. That is, the permeability is variable.

Other hydrologic factors also can account for the difference in size of succesive rectangles, as shown in the following hypothetical examples.

Consider first a rectangular, homogeneous, and isotropic aquifer which receives recharge uniformly over its surface but from nowhere else; the aquifer discharges uniformly along a line (fig. 13*A*). On a flow-net map of such an aquifer, the equipotential lines are straight and extend across the aquifer parallel to the line of discharge. The streamlines are straight, normal to the equipotential lines, parallel to each other, and equally spaced across the aquifer. The amount of liquid flowing between each pair of streamlines increases downward along the gradient because recharge accumulates downgradient. Therefore, the gradient must increase to move the increasing volume of water, so that the distance between equipotential lines decreases towards the discharge line. For the contour interval used, the streamlines shown in figure 13*A* are perpendicular to the upstream impermeable wall of the aquifer, and thus, at that bounadry, the hydraulic gradient seems to be normal to it. This example illustrates, in idealized form, flow in many real aquifers.

A somewhat more complicated problem is illustrated in figure 13*B*. All conditions are the same as in the previous example, except that the line of discharge is changed to a point—a corner of the rectangle. The equipotential lines and streamlines are curvilinear because the flow converges toward the point of discharge. The space between the streamlines diminishes toward the point of discharge, so that the recharge per unit of distance along a streamline and between successive equipotential lines is not the same as that illustrated in figure 13*A*.

Increase in rectilinear flow through an aquifer of known permeability can be determined readily from the flow net by measuring the increase in hydraulic gradient along the streamlines. Flow in the system shown in figure 13*B* is more difficult to determine because of the more complicated variations in flow in the aquifer.

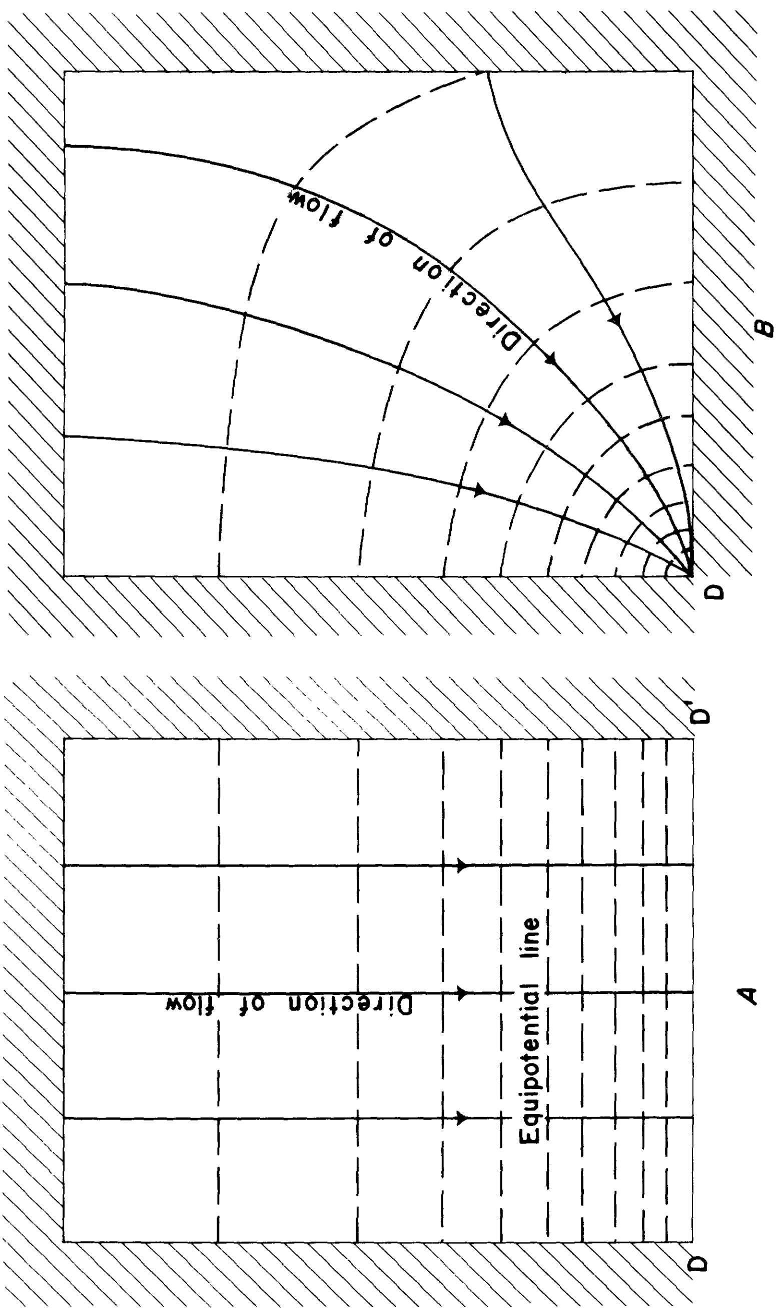

FIGURE 13.—Schematic diagram of rectangular aquifier which receives recharge uniformity over its area. Hachures represent impermeable boundaries. *A*, Discharge uniform along *D–D'*. *B*, Discharge at point *D*.

Despite the variety of complex hydrologic conditions that obviously may be represented by a flow-net map, it is possible to develop a useful analysis from it. This may be done, for example, with data from plate 1, as follows:

1. Draw in the centerline between any two adjacent streamlines on the map.
2. Prepare a graph on which the altitude of the equipotential lines along this centerline is the abscissa, and the map area between the two adjacent streamlines up the hydraulic gradient from each equipotential line (figure 14) is the ordinate.

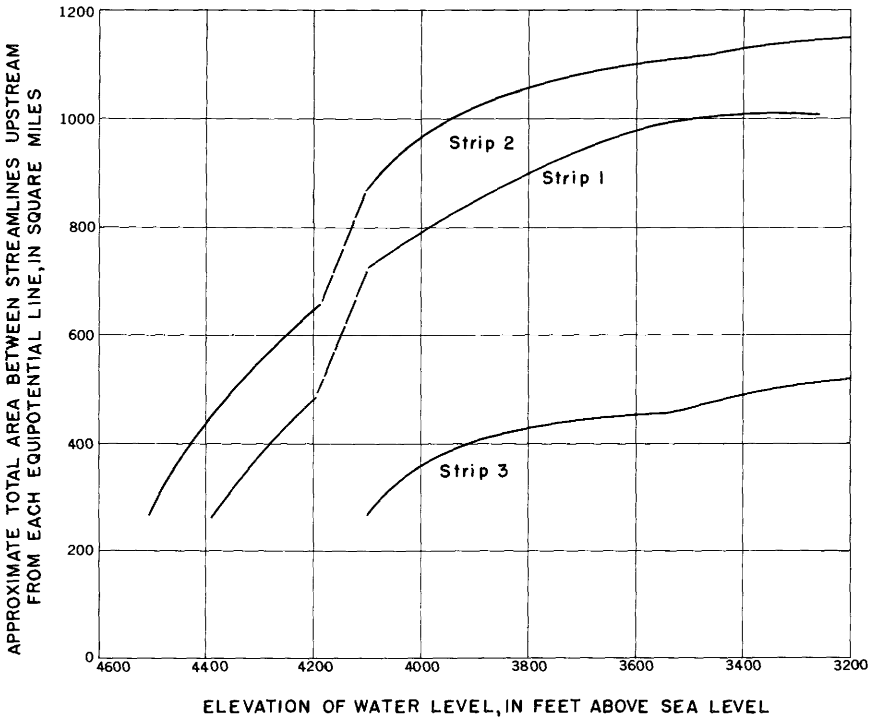

FIGURE 14.—Relation between elevation of water level and areas of sections between the streamlines shown on plate 1.

If the ground-water system resembled that shown in figure 13*A*, the lines of figure 14 would be parabolas. If there were no recharge within the mapped area, they would be sloping straight lines.

The streamlines on plate 1, however, are not parallel and straight, but curvilinear and convergent. Thus, the complexity of the lines plotted in figure 14 shows the combined effects of increasing flow and of convergence of flow lines. The effect of streamline convergence may be removed by replotting the data of figure 14, in the following manner:

1. The area between adjacent streamlines from a given contour line upstream to the termination of the streamline is plotted as the abscissa (fig. 15).

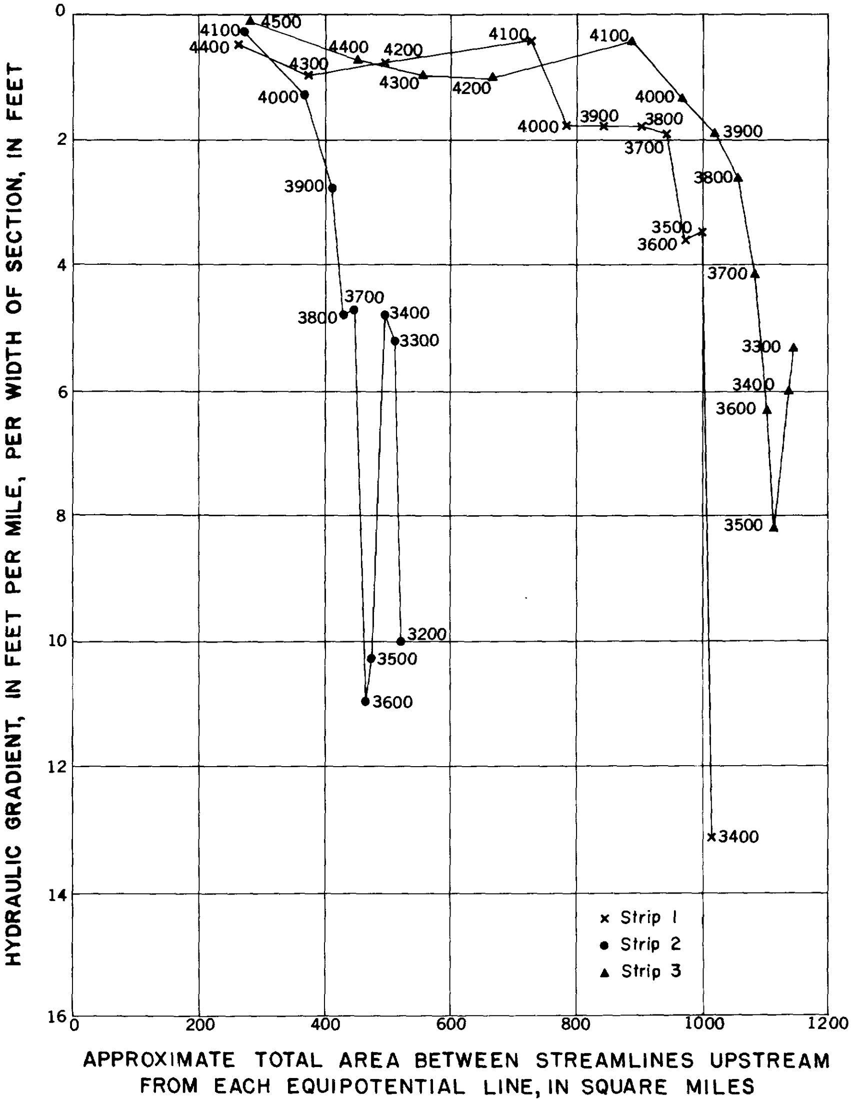

FIGURE 15.—Relation of area, hydraulic gradient, and width of sections between the streamlines shown on plate 1.

2. The ratio of the hydraulic gradient to the distance between adjacent streamlines is plotted as the ordinate.

If there were no recharge and the permeability were uniform and constant, this ratio would be constant, and the plots would yield straight lines parallel to the x axis to represent each of strips 1, 2, and 3 shown on plate 1. If for the same stated conditions, recharge over the area were appreciable, the lines representing each of the strips would curve downward to the right. The reversal of direction in the lines corresponding to strips 1, 2, and 3 shown in figure 15 can represent physical changes in the corresponding part of the aquifer or differences in the amount of flow. However, in this situation, available data suggest that the reversal represents physical changes.

If the flow net based on the field data shown on plate 1 were drawn so that each rectangle had equal sides, the net would not be orthogonal because of regional and local nonhomogeneity. Direct evidence from wells shows that the aquifer is nonhomogeneous.

The index ratios shown on plate 1 are inversely proportional to the permeability of the aquifer, and these ratios may be used to compute absolute coefficients of permeability (and transmissibility) at any point. This is possible because discharge from the aquifer into the Snake River is known from stream-gaging data, and the absolute coefficient of transmissibility in the discharge area can be computed and used as the base (index=1) from which to compute permeabilities (and transmissibilities) at other places.

EFFECTS OF PUMPING

Areal variations in the permeability of the aquifer, indicated by index numbers in the flow-net rectangles on plate 1, formed the basis for construction of an electric model analogous to the aquifer in the Snake River Plain. Economic factors being disregarded, the quantity of water that may be withdrawn indefinitely from the aquifer in the Snake River Plain depends on the ultimate drawdown. Thus, an analysis of the system may consider steady-state conditions alone, if the long-term effects of withdrawals are the principal questions involved. The inverse-permeability indices on plate 1 were plotted on a topographic map at a scale of 1:250,000. The map was cemented onto a piece of masonite through which holes were drilled on a grid of 1-inch squares. Terminals of resistors whose electrical-resistance values were inversely proportional to the permeability indices were inserted through the holes in the masonite board and soldered at each hole.

The electric model (fig. 16), which represents the permeability parameter of the region, was used to determine the effects that may

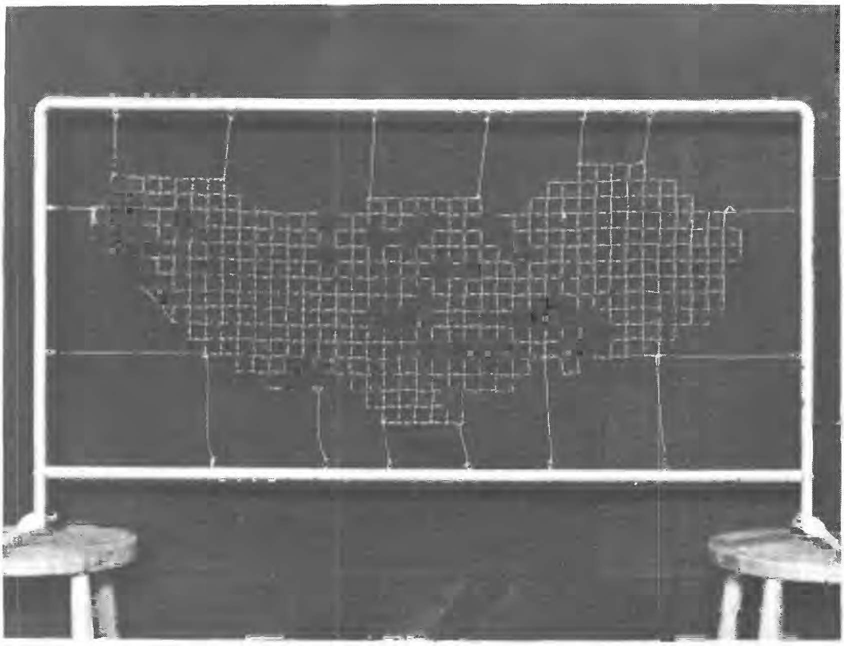

FIGURE 16.—Electric analog model of the aquifer system of the Snake River Plain.

be expected from pumping at the NRTS and in the Minidoka North Side Pumping Division of the Minidoka project. The effects were predicted by determining the distribution of potential, on the basis of certain necessarily idealized assumptons.

Assumption (*a*) postulates that the Snake River, which is adjacent to the aquifer, is hydraulically connected with the aquifer along its whole length. Under that assumption, lowering of levels in the Snake River Plain by pumping would induce recharge from the Snake River.

It was assumed also that the total rate of pumping will be less than the total amount of recharge that could be induced from the Snake River.

Assumption (*b*) postulates that the river and the aquifer are not connected. Under that assumption, pumping of ground water would not induce recharge from the river, and all pumping would be reflected ultimately in depletion of ground water discharged in the Snake River valley below Milner. It was assumed that discharge in the Snake River valley would exceed ground-water pumpage. Condition 1 assumes pumping only at the NRTS. Condition 2 assumes pumping only on the Minidoka project.

CONDITION 1.—PUMPING ONLY AT THE NATIONAL REACTOR TESTING STATION

In order to analyse the effects of pumping at the National Reactor Testing Station the following assumptions were made:

(a) The aquifer is assumed to be in hydraulic connection with the river (pl. 2). It is assumed that neither the projected pumping nor any other factor, such as upstream storage, can completely deplete the river flow. The data show the relative effect through the system resulting from pumping at the NRTS only.

(b) The aquifer is assumed to have no hydraulic connection with the river (pl. 3).

No recharge is induced from the river, and all discharge by pumping at the NRTS will be reflected ultimately in depletion of the ground-water discharge through the springs in the valley of the Snake River below Milner Dam.

It is apparent that under this condition the total rate of discharge at the NRTS, or anywhere else in the plain, cannot exceed the total natural discharge for an indefinite period.

The contour intervals shown on plates 2 and 3 represent steady-state conditions. Probably several decades would elapse before steady-state conditions were approached. Until then, the drawdowns would be less than those shown on the plates. The water pumped at the NRTS must be derived by (a) drawing water from the Snake River or intercepting ground water, tributary to the river; (b) drawing from ground-water storage during pumping in the transient state because, even if pumping were stopped, the cone of depression would be filled by water that under natural conditions would have flowed into the Snake River. The periods of time required for development of the cone of depression would depend on the ratio of storage coefficient to transmissibility; the smaller this ratio, the shorter the time of development. Although this ratio in the Snake River basalt is small, the time required for reaching approximate equilibrium would be great because of the great distance between the river and the pumping site.

CONDITION 2.—PUMPING ONLY ON THE MINIDOKA PROJECT

If aquifer conditions similar to those postulated for plates 2 and 3 are assumed again, except that pumping occurs solely on the Minidoka project, two assumptions again may be considered:

(a) The aquifer is assumed to be in hydraulic connection with the river (pl. 4).

(b) The aquifer is assumed to have no hydraulic connection with the river (pl. 5).

The contour maps representing the two assumptions under each of conditions 1 and 2 are nondimensional. Thus, any amount of current may be drawn from the chosen point in the electric model, and the resultant pattern of electric contours will be the same regardless of the amount of current withdrawn. The contour intervals show only the percentage of drawdown. The drawdown in feet may be determined by relating the contour intervals to the transmissibility and pumping rates.

The nondimensional contour intervals shown on plates 2–5 may be used directly to determine the dimensional ultimate equipotential lines that would result from pumping drawdown of any chosen magnitude either at the NRTS or at Minidoka. The effects of pumping simultaneously at both places could be determined by adding the effects of pumping at each place.

In all four cases described, the effects in the plain are those that would exist after approximately steady-state conditions were reached. Whether steady-state conditions can exist for a given discharge rate, remains to be determined. The question is, "What is the maximum drawdown possible without ultimate depletion?"

CONCLUSIONS

If withdrawal by pumping does not exceed the natural discharge from the aquifer, equilibrium might be reached. If the volume of water that may be derived by induced recharge from the Snake River or by intercepting natural discharge, or both, were less than total withdrawals from the aquifer, equilibrium might not be reached, and the aquifer might be depleted eventually. Whether, or when, equilibrium would be reached cannot be determined at present because essential data are lacking.

The fact that the degree of connection between the aquifer and the river is only incompletely known complicates the problem. If dams are constructed or the river is diverted, the amount of water flowing in the river channel will be affected. If the river and the aquifer are not connected, manipulation of the flow of the Snake River will have no direct effect on the ground-water system. If the river and the aquifer are connected, the aquifer will not be recharged from the river where water levels in the aquifer are as high or higher than the water level in the river, but raising of the river level might cause recharge to occur. Wherever the aquifer is hydraulically connected with the river and the water level of the aquifer is lower than that of the river, changes in the river regimen would affect the amount of river recharge to the aquifer.

Where additional water entered the ground-water system, the hydraulic gradients would have to steepen to move the additional water. The resulting increase in head would counteract part of the lowering of head produced by pumping at Minidoka, the NRTS, and elsewhere.

The magnitude of pumping that could develop on the plain in the future generally cannot be predicted because the percentages of vaporizing (consuming) use and of return recharge to the ground-water system generally are not known. Because consumed water would be removed from the system, the total amount in the system would be reduced and the gradients would be reduced. Therefore, water levels would be lowered.

The magnitude of present ground-water recharge from sources other than the Snake River is another unknown. However, the amount of recharge would not enter into determinations of the decline of water levels caused by pumping unless the amount of recharge were changed in the future.

If part of the water that now contributes to recharge is consumptively used in the future, the new problem again would be to determine what part of the water will be consumed, for only permanent removal of water would affect the ground-water system.

Analysis of the water-table contour map of the Snake River Plain shows that much additional information about the aquifer throughout the plain would be required for an adequate understanding of the hydrologic conditions.

Analysis leading to even an approximate description of the flow system would require considerably more knowledge of the aquifer variables, which includes its thickness, areal variation in the coefficients of permeability and storage, degree of connection between permeable zones in the main aquifer and between the main and secondary aquifers, and definitions of the regional factors of anisotropy and heterogeneity.

Other factors also are important, but these few illustrate why an aquifer system such as this can be analyzed only approximately. Quantitative expressions such as those for effects of large-scale pumping mean little because the quantities are derived from hydrologic variables that are either unknown or only estimated. The subsurface geology is of primary significance, both for an understanding of the functional characteristics of the system and for analyzing them quantitatively. Therefore, whatever geologic data are available have first-rank importance in the problem. The hydrologic data—that is, data obtained from pumping tests, water-level measurements, and other means—have little significance by themselves, though they add to geologic knowledge of the characteristics of the system.

SELECTED REFERENCES

Nace, R. L. McQueen, I. S., and Van't'Hul, Arthur, 1958, Records of springs in the Snake River Valley, Jerome and Gooding Counties, Idaho, 1899–1947: U.S. Geol. Survey Water-Supply Paper 1463, 62 p.

Stearns, H. T., Crandall, Lynn, and Steward, W. G., 1939, Geology and ground-water resources of the Snake River Plain in southeastern Idaho: U.S. Geol. Survey Water-Supply Paper 774, 268 p.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods: U.S. Geol. Survey Water-Supply Paper 887, 192 p.

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