Some Techniques Used in the Appraisal of Ground-Water Resources*

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The United States Geological Survey throught its Ground Water Branch engages in several types of ground-water studies, ranging from rapid appraisal of small areas to detailed quantitative study of an entire ground-water basin and including investigation of basic principles of ground-water occurrence and movement. The scope of a study may range from information as to the expected yeild of a single well at a particular site to a determination of the availability of water and the probable response of an entire aquifer to the development of water for a large industry or irrigation project.

The ground-water hydrologist has a large number of investigative tools at his disposal, and he may need to use a great many of them even in the study of a small area. Many of the techniques are simple, for a technique does not have to be complicated to be useful. Some of the methods are complicated, however, for in detail the movement and the availability of ground water and the changes in water level caused by development of an aquifer are complex. In this brief period, I can touch on only a few of the methods used in our work and comment on their effectiveness. In particular, I shall discuss in some detail the methods used for determining the hydraulic characteristics of an aquifer, the coefficients of transmissibility and storage, and utilizing them in ground-water appraisals.

The availability and movement of ground water are related primarily to the hydraulic properties of the rocks, to the position of these rocks in the hydrologic system, and to climate. The rocks form the framework through which the water moves and in which the water is stored; commonly the water is in what can be called transient storage. The more accurately the picture of the ground-water conditions is to be drawn the more important are the details of the geology. Hence, knowledge of the geology is essential to all our studies, along with information on wells and springs, streamflow, and chemical quality of the water.

During the initial phases of our investigations, particularly that phase involving collection of well data, we have depended and

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will continue to depend on the cooperation of well owners and well contractors--the individual well owner primarily. Each well is a probe into, and potentially adds to our knowledge of, a particular aquifer, and commonly, enough wells exist in a given area to obviate the need for special test holes. Data obtained include the depth of each well, depth to water, yield of the well as related to drawdown of the water level, a log of the geologic material at the well, temperature of the water, and chemical quality of water samples. Thus, a great many of you participate in the collection of a part of the basic data needed.

These basic data are then assembled and studied and may be used to prepare a report describing the water-bearing beds in an area, the yield that can be expected from additional wells tapping a specific aquifer, and the quality of the water that the wells will produce. A report of this nature is qualitative, in that it describes only the general ground-water features.

A qualitative report will provide a part of the background needed, or a starting point, for more intensive quantitative studies. the objective of a quantitative study usually is an answer to the question of how much water is available, or how a system will respond to a certain development, the response to be measured in terms of changes in water levels or in the flow of a stream. Such studies require the collection of additional data.

Some of the factors needed are the characteristics not only of the aquifers but also of the poorly productive beds, changes in water level with time, the amount of water used, and the base flow of streams within the area.

The hydraulic characteristics of an aquifer are defined essentially by two properties: (1) the ease with which water will move through the aquifer (measured by its coefficient of transmissibility), and (2) the amount of water taken into or released from storage in an aquifer in relation to changes in head (measured by its coefficient of storage). These characteristics of an aquifer determine to a great extent the rate at which water levels will decline when a well is pumped and, hence, the effect that pumping will have on the water-bearing formation. Data on transmissibility are needed also to determine the rate of flow of ground water. The ability of the aquifer to store water enters into the computations of the amount of water available.

One of the techniques for determining coefficients of transmissibility and storage makes use of laboratory tests of the various rock types in a particular aquifer system. Undisturbed samples of the rock are the most desirable, for obvious reasons, but disturbed samples may be usable where a rather uniform silt, sand, or gravel is involved.

The actual coefficient of transmissibility is not determined directly by this method but rather the coefficient of permeability, which is a hydraulic characteristic of a unit cross section of the material. The coefficient of transmissibility of an aquifer is the sum of the individual unit coefficients of permeability--that is, the average coefficient of permeability multiplied by the thickness of the aquifer. The standard, or laboratory, coefficient of permeability is determined by observing the rate of movement of water through the sample under a known head at a standard temperature. The field coefficient is the same except that it is measured at the prevailing water temperature in the field. It is the field coefficient that is multiplied by the thickness to obtain the transmissibility, which is a field coefficient.

The coefficient of permeability should be determined not only in two directions in the plane of the bedding but also at right angles to the bedding. The specific yield, which under water-table conditions is approximately equal to the coefficient of storage, is determined by draining or wetting the sample, according to the initial state of the sample. The coefficient of storage may approach the porosity of the sample, particularly in coarse-grained material.

The coefficient of permeability can be expressed in a number of ways. The units commonly used in ground-water work are the gallon, the foot, and the day. The coefficient of permeability is expressed as the number of gallons of water a day that would move through a 1-square-foot section of the material under a unit hydraulic gradient, at 60°F (laboratory coefficient) or field temperature (field coefficient). The coefficient of storage is a ratio of the water yielded from or taken into, storage per unit surface area of the aquifer per foot of change in head.

The laboratory method of obtaining the coefficients of permeability and storage has some disadvantages over other methods and is not applicable in some cases. For one thing, a sample represents only a very small part of an aquifer, and hence a large number of samples from different parts of the aquifer are required if even approximately representative coefficients of permeability and storage are to be obtained. The transmissibility of a formation may differ from the permeability of the constituent rocks. In other words, a formation containing open joints and caverns certainly will have a greater coefficient of transmissibility than would be indicated by averaging permeability determinations of a number of small samples not containing such openings. This is particularly true of formations composed of limestone and gypsum. Another disadvantage is that the samples commonly must be collected from the outcrop areas, and the hydraulic characterisitcs of these weathered rocks may differ considerably from these of rocks at depth in the zone of saturation. Further, the coefficient of storage of an aquifer under artesian conditions differs markedly from the specific yield determined by the laboratory method cited above, for under artesian conditions the coefficient represents mostly water squeezed out by compression of the aquifer rather than water drained out of the pores.

Nevertheless, this laboratory technique is useful in determining the characteristics of that part of an aquifer composed of unconsolidated sediments and, to some extent, of consolidated rocks that lack large open joints or caverns.

A method used to obtain a larger and a more representative "sample" of the aquifer is by the aquifer test in the field. Some years ago Theis (1935) developed the relation between the rate of decline of water levels in the vicinity of a well and the rate of pumping of that well. Under certain conditions a carefully conducted test will provide data from which the coefficients of transmissibility and storage can be computed. Since Theis' original work, he and others have developed methods whereby certain modifying and complicating factors, such as imperable boundaries created by geologic structure or topography and effects on the aquifer caused by nearby streams or leaky artesian systems, also can be taken into consideration in aquifer testing. Although the method of making field tests is a powerful tool in determining aquifer characteristics, the range of conditions under which it can be used is small compared to the range of conditions in our realm of interest. Thus, aquifer testing is not always applicable, and judgment is required in applying the results.

In some areas a useful method of measuring the coefficient of transmissibility of an aquifer is to relate the gradient of the water table or piezometric surface of the aquifer to the discharge from it. In New Mexico the use of such a method is complicated by modifications of streamflow caused by growths of phreatophytes along the valleys. The use of water by such plants diminishes the base flow that otherwise would be contributed by discharge from the aquifer. Other complications result from actual diversions and use of water from the streams. If such modifying factors can be estimated, however, this method can be used to advantage in estimating the transmissibility of an aquifer.

The coefficient of storage often can be determined by observing long-term declines in water levels and relating the volume of aquifer unwatered to the net amount of water pumped. This method offers particular promise in areas where the use of water is remote from areas of discharge or recharge. Such places include some closed basins, such as the Estancia Valley, the Tularosa basin, and areas in the southwestern part of the State, such as the Animas, Playas, and Deming basins.

The methods mentioned so far give the coefficients of transmissibility and storage at selected points or the average coefficients of transmissibility and storage over somewhat larger areas. To obtain values of these coefficients in detail over an entire system, values must be estimated for those areas for which aquifer-test data are not available. This usually requires detailed examination of well samples, electric logs, and the like, and correlating the information thus obtained with conditions at the site of the spot determinations of permeability and storage coefficients.

With information on the coefficients of transmissibility and storage, the effects of existing or proposed developments on that system can then be analyzed.

If the wells are few, the discharge rate of individual wells can be determined by obtaining from the operator an estimate of the duration of pumping during a year, or by measuring the fuel or electric power used and correlating this measurement with the overall efficiency of the pumping plant.

In large irrigated areas, measurement of the discharge of all the wells becomes impractical. Here sampling methods are used. One method used in the Roswell basin, where most of the ground water is pumped by electrically driven pumps, is to correlate the power consumed, the efficiency of the pumping plant, and the amount of water pumped by selected wells. Then by means of average pump efficiency, depth to water, and total power consumed in the area, the amount of water pumped is computed.

Still other methods involve determining the amounts of water applied to sample tracts of land and extending this rate of use to the total acreage irrigated.

These values for pumpage, however, are gross diversions, whereas the actual diversion from the system is the consumptive use. The gross pumpage therefore needs to be corrected by the amount of water, if any, that returns to the system by seepage from canals or irrigated fields.

If all the necessary data are now at hand, it may be desirable to estimate the decline in water levels throughout a certain area after 20 years of pumping under a certain assumed pattern of development and use of the water. One method used in New Mexico is to determine the cumulative effect that pumping of each well in the area will have at selected points. This is done by use of a map on which all the wells are located and by use of a special drawdown scale. The scale is laid out in this case to show the decline in water levels that will have occurred at various distances from the pumped well at the end of 20 years, with a certain pumping rate and the assumed aquifer characteristics. The drawdown caused by a particular well is usually determined at section corners, inasmuch as these form a convenient grid in most of the areas. The drawdown indicated at these section corners is multiplied by the factor needed to adjust the scale pumping rate to the actual pumping rate at the well. The number of section corners at which the drawdown is determined for any one well depends on the distance at which a discernible drawdown can be expected to occur. The drawdown effect caused by each pumped well is listed at each section corner and then added to give the total drawdown at each corner. A contour map of the declines at the various section corners can be drawn to show the cone of depression that would have resulted under the pattern of development. Such techniques are applicable particularly in areas where the principal draft on the aquifer is pumpage from ground-water storage, such as in most of the High Plains and in some of the topographically closed and hydrologically nearly closed basins in the southwestern part of the State. In addition, the effects of boundaries, such as the impermeable boundaries formed by granitic mountain blocks and the boundary formed by a river are taken into account.

Relaxation methods offer an approach to problems involving steady-state conditions. This does not mean that the hydrologist relaxes in an easy chair and waits for the answer, although some time devoted in this manner to such problems might be fruitful. Rather, the relaxation technique is one of relaxing control at one point and making adjustments at surrounding points until an entire system, in this instance a hydraulic system, is brought into balance. This technique is rather laborious but does permit the solution of some flow problems. An extension of this method, known as Schmidt's method, permits the solution of nonsteady-state problems such as the effects of pumping on an aquifer.

A less laborious technique for some steady-state problems involves the use of an analog plotter. A sheet of electrically conductive paper is trimmed to fit the boundaries of an aquifer or to represent a part of the aquifer. A pattern of holes can be punched in the paper to change its resistance so as to represent changes in transmissibility, or blocks can be cut out to represent impermeable areas as volcanic plugs or dikes. A flow net can then be determined by passing current through the system and plotting the lines of equal potential (equivalent to the hydraulic potential) by means of a probe connected through a voltmeter to the power source. Lines drawn perpendicular to the equipotential lines define the flow net.

Another method that shows promise involves the construction of an electrical model representing the aquifer under study. A network of resistors to represent the transmissibility or permeability of the aquifer and condensers to represent storage are constructed in such a way as to simulate the geometry of the aquifer. An electrical circuit then will represent the flow of water from recharge to discharge areas. By means of additional leads the well sites can be put into the model and by regulation of the power supply the pumping effects can be simulated. If a probe is placed at a particular spot, the oscilloscope shows the change in water level with time in the form of a hydrograph. This particular hydrograph can be traced or photographed and the process duplicated at a sufficient number of points on the model to obtain a complete picture of the decline in water levels at any time at any place in the system. The hydrographs are realistic to the extent that the data on the hydraulic characteristics of the aquifers and other basic data supplied for the analysis, are correct.

Another phase of the Survey's studies that has received increased attention in recent years is the actual movement of ground water under various conditions. This increased interest has developed as the result of disposal or contemplated disposal of wastes, particularly radioactive wastes, into ground-water reservoirs. Various tracers have been considered for use in tagging water so that it may be identified elsewhere in the system. Many substances are unsuitable as tracers of ground water because they either change the character of the water appreciably or are adsorbed by the rocks through which the water passes. In fact, the difficulty with even ideal tracers is that ground water moves so slowly that either the area to be studied must be small or else a large number of injection points are needed.

One of the more promising tracers is tritium. Tritium is radioactive hydrogen which has a half life of 12½ years. This means that half the original tritium induced into a system will have decayed in 12½ years. Tritium is a good tracer in that it is a part of the water itself and appears to be only slightly adsorbed as it moves through the water-bearing formations. Techniques have been developed to determine the presence of very slight amounts of tritium, and thus a tritium "spike" need not be large to take a large amount of water.

Libby (1953) and others have suggested that the tritium content of natural waters might be useful as a tracer and as an aid in solving some water problems. In addition to its use for determining where the water will migrate, the tracer will indicate the rate of movement of the water, which together with determinations of the porosity and the head from one place in an aquifer to another, may give values of permeability; all these will then be useful in quantitative studies.

Natural tritium is produced in the atmosphere and comes to the earth with rains. Tritium is produced also by hydrogen bombs, and since 1954 the tritium content of the atmosphere and of the rains has been increased briefly after each detonation, to amounts higher by several orders of magnitude. The Research and Development Division of the New Mexico Institute of Mining and Technology was one of the first to construct equipment for tritium analysis and to explore the possibilities of using tritium as a tool in ground-water studies. The results of the initial work of Dr. Haro von Buttlar (1958) of the Institute on this subject appeared recently in the Transactions of the American Geophysical Union. The Geological Survey now has a laboratory in operation for the determination of tritium and is working on the possible uses of tritium as an aid in water-resources studies.

A few of the techniques at our disposal for use in the various phases of ground-water studies have been touched upon. Many of the techniques used in the compilation of qualitative reports are tried and true, and they will continue to be the backbone of our stock of tools. Some of the more recently developed techniques for solving quantitative problems, powerful though they are, can yield results no more accurate than the basic data supplied, and considerable effort will be required to obtain and refine the basic data, especially those involving determination or estimation of aquifer characteristics. These techniques may prove to be inadequate to handle some of the problems that may develop. More adequate techniques surely will come into being, however, as we continue our appraisal of water resources.

References

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