



Ground-Water Studies and Analog Models

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By Charles J. Robinove



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ABSTRACT

Hydrologists make ground-water studies to aid managers and users of water resources in solving their problems in the development and management of ground water. Geologic and hydrologic information provides the basic knowledge for construction of electric analog models that portray the ground-water system in miniature. Analog models can be analyzed electrically, and the results of the analysis are presented in terms of the ground-water system so that the effects of alternative methods of water development can be assessed.

INTRODUCTION

All parts of the United States have water problems because expanding population and industry create ever-increasing needs for large supplies of good water. To cope with these problems, basic information is needed about water--its availability, quantity, quality, and use. This information is provided by hydrologists.

People feel an individual and a community responsibility to be aware of national and local water problems, but they cannot always find the information they want and need. This report explains how the United States Geological Survey studies ground-water systems and uses electric analog models. It is one of a series of reports being prepared by the U. S. Geological Survey to help people understand their water supply and how to manage it.

The electric analog is not new to science. However, its application to ground-water problems is new. It is one of the tools used to analyze ground water, which cannot readily be studied directly.

Although not all water problems are the same, all have certain basic features in common. Let us consider a ground-water

situation that is typical of many places in the southwestern States. Our problem consists of determining how best to use the ground-water resource. Alternative methods of developing the ground water, such as spacing wells close together or far apart, and the possible effects of each alternative method can be determined from studies of the area. The water users then have a basis for deciding what action they should take in developing the ground water.

THE GROUND-WATER SITUATION

Our example is a desert basin that is underlain by sand, gravel, and other rock materials, and surrounded by mountains. (See fig. 1.) These mountains are composed of rock that

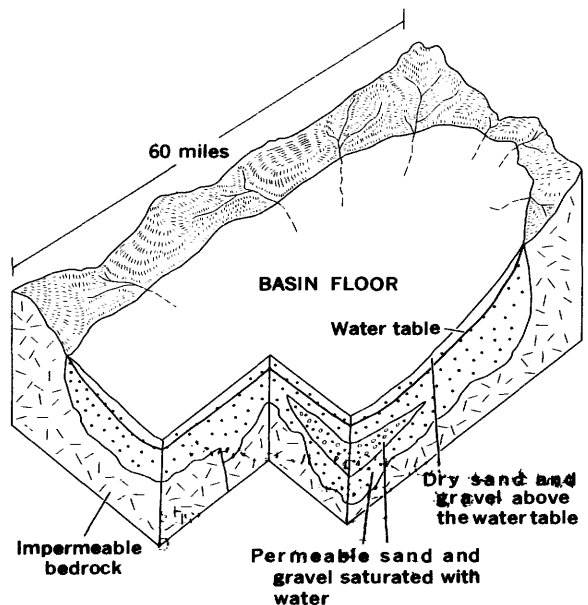


Figure 1.—The ground-water basin contains water in the underlying sand and gravel.

is quite dense and contains little water. Water moves readily through the underlying deposits of sand and gravel, however.

Rain and snow are the sources of water in the basin. Some water evaporates, some runs off in streams, and some seeps into the ground. Some of the water absorbed by the soil is taken up by the roots of plants. The rest of the water moves down deeper, pulled by gravity. At some distance below the floor of the basin, the spaces between the sand and gravel grains are saturated with water. This subsurface water is called ground water. The upper surface of the saturated zone is called the water table. The water table and the saturated zone are shown in figure 1.

Although some ground water is everywhere below the surface of the soil, it may not always be free to come into a well. Rocks through which water can move easily are said to be permeable. A layer of permeable rock that yields water in useful quantities is called an aquifer. The word "aquifer" comes from two Latin words: aqua or water, and ferre, to bring. The aquifer literally brings water (underground). An aquifer may be a layer of gravel and sand, sandstone, or cavernous limestone. In our example, the aquifer consists of deposits of sand and gravel, through which water moves readily. An aquifer may be only a few feet thick, or tens or hundreds of feet thick. It may be just below the surface, or hundreds of feet below. It may underlie a few acres or many square miles. In our example, the aquifer is about 500 feet thick and underlies about 1,800 square miles and the water table lies 20 to 100 feet below the surface.

The words "aquifer," "ground-water basin," and "ground-water reservoir" are used interchangeably here to mean the layers of rock in which ground water is stored by nature. Water in the ground-water basin is always moving. However, the rate of movement is so slow, compared with that of streams, that for all practical purposes, the ground-water basin is considered a storage reservoir.

Ground water moves very slowly through the aquifer--sometimes only a few feet per year, whereas water in streams and rivers travels as much as several feet per second. Many problems of ground-water development and use arise from the fact that ground water moves very slowly from one place to another and more water is available in one place than another.

PEOPLE ARE CONCERNED WITH WATER PROBLEMS

Residents of the valley have drilled wells into the water-saturated sand and gravel. They have begun to pump water for irrigation, home supplies, industries, and public water supplies. As people realize that more water is being used and that more wells are needed, they become concerned about their future supply of water. The ground-water basin shown in figure 1 is an example of many areas where development of ground water is taking place or is contemplated. Problems concerning possible depletion of the ground-water resource, proper spacing of wells, increased pumping lifts, and many other problems confront users of water in such an area and they begin to ask searching questions about their particular uses of water and about the ground-water situation in general. (See fig. 2.) The hydrologist must answer these questions, must aid water users to recognize the nature of their water problems, and must help them to choose between various alternative solutions to their water problems.

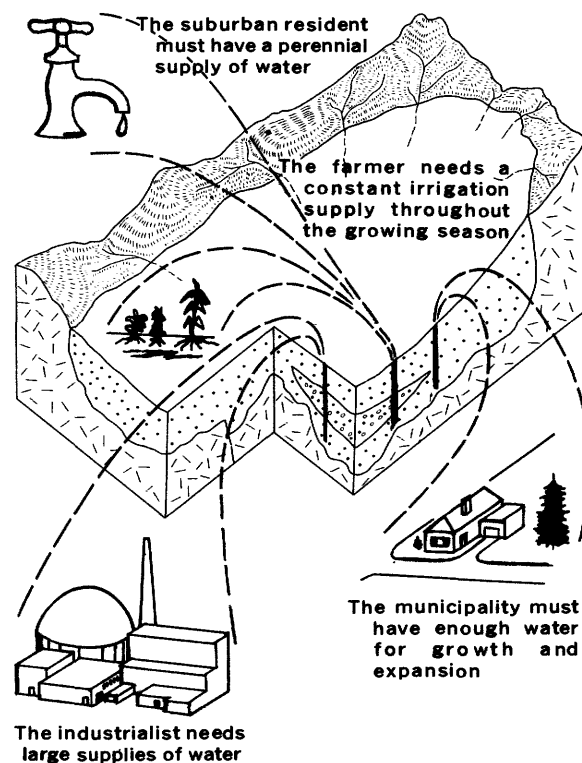


Figure 2.--Water is needed for many uses.

HOW DOES THE HYDROLOGIST COLLECT INFORMATION NEEDED TO ANSWER THE QUESTIONS?

One basic requirement for study of a ground-water system is a geologic map. The geologist maps the extent, thickness, and types of deposits in the ground-water basin and the location of the impermeable rocks which bound it. The geologist has thus described for the hydrologist the shape, size, and physical boundaries of the ground-water system. The block diagram (fig. 1) shows the surface and cutaway sections of the basin and surrounding mountains. If we were to look directly down on the top of this block diagram, we would see the land surface as it would be portrayed on a geologic map.

Data on the ground water reservoir also are obtained in many other ways--from records and logs of water wells, records of rainfall and streamflow, descriptions of the rock units as seen on the surface of the ground and as sampled below the surface, measurements of the water-bearing properties of the rocks, and much other basic information. Data on the rocks and water are collected in the field (fig. 3 and 4). Measurements of depth to water in wells while the wells are idle or pumping are made to determine the decline of water level caused by pumping.

The cuttings brought to the surface by the drill from test holes are sampled and some of the properties of the material are measured (fig. 5). Such information includes data on the size of the individual sand and gravel particles; the amount of space between these particles that can be filled with water; the rate at which water moves through the material; and the composition, layering, and other physical and chemical properties of the material.

All these data help the hydrologist to determine three major characteristics of the ground-water basin: first, its shape and size; second, the amount of water that can be stored; and third, the rate at which the earth materials allow water to move through them.

We use the term "storage coefficient" to describe the ability of the earth materials to release water that is stored in them and the term "coefficient of transmissibility" to describe the rate of movement of water through the material.



Samples of material at the ground surface are collected and tested for porosity and permeability.



Power augers and well-drilling rigs are used to collect samples of earth material at depth and to drill holes for further testing.

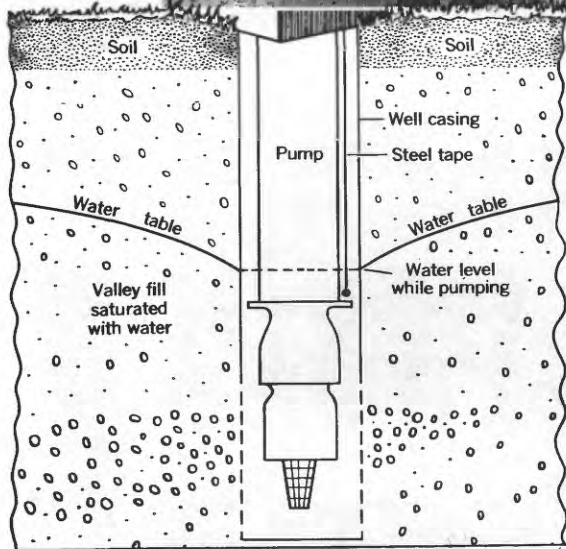


The electric logger records the electrical properties of rocks in a test well. Much valuable geologic and hydrologic data can be interpreted from the electric logs.

Figure 3.—Geologic and hydrologic data are collected in the field.



The discharge of wells is measured with a current meter inserted in the end of the discharge pipe.

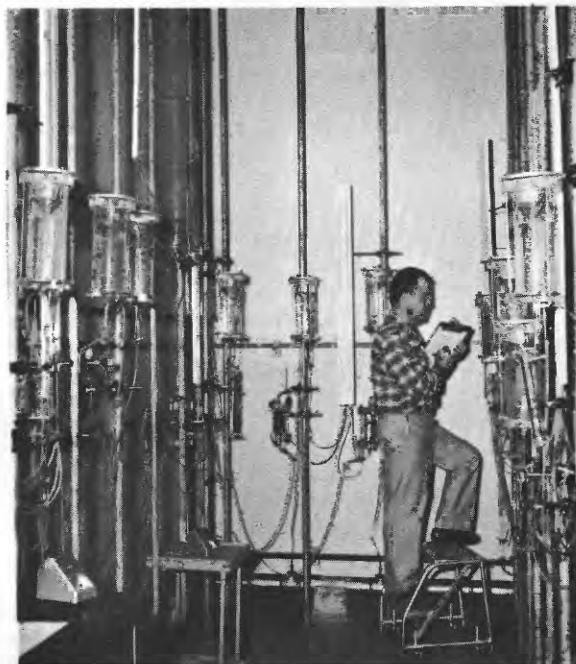


Water levels are measured by lowering a steel tape into the well.

Figure 4.—Water-level and well-discharge measurements are made in the field.



Samples of sand and gravel are analyzed with sieves and a mechanical shaker to determine the size and sorting of the grains.



Samples of earth material enclosed in the large tubes are tested for their capacity to transmit water.

Figure 5.—Laboratory investigations and tests supplement field data.

HOW DOES THE HYDROLOGIST USE THE BASIC INFORMATION TO DESCRIBE THE GROUND-WATER SYSTEM?

The ability of the ground-water reservoir, or aquifer, to transmit water is shown in figure 6. Each line connects points of equal transmissibility of the aquifer. The number represents the number of gallons of water a day that can pass through a 1-mile width of the water-bearing sand and gravel across that line for each foot-per-mile slope of the water

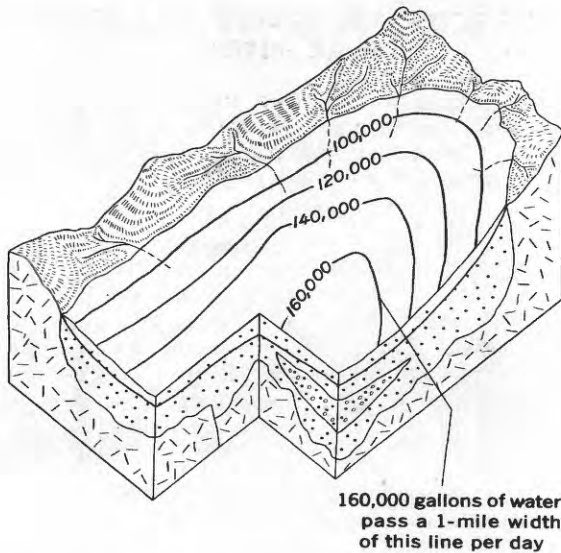


Figure 6.—Lines of equal transmissibility show the ability of the valley fill to allow movement of water.

table. Thus, if the water table has a slope of 10 feet per mile in the vicinity of the 160,000 line, the flow through a 1-mile width of aquifer would be 1,600,000 gallons of water per day.

The water-storage capacity of the valley fill is described by the storage coefficient and is shown in figure 7). As mentioned before, storage coefficient represents the amount of water that is released from storage in a given unit of the aquifer material when the water level is lowered a unit distance. For example, 1 cubic foot of sand and gravel in the valley fill may, when filled with water, contain 0.2 cubic feet of water. If the water table is lowered 1 foot by pumping and this material is drained, only about 0.15 cubic feet of water will be released. The rest remains in the rock as water that clings tightly to the individual particles and will not move toward the well. The storage coefficient is then considered to be 0.15. A water-table aquifer, 1 square mile in extent and 100 feet thick, with a storage coefficient of 0.15, can store more than 3 billion gallons of water. The storage coefficient is important because it indicates the maximum amount of water that can be withdrawn for use from an aquifer at a given time.

The shape of the water table, or upper surface of the saturated zone, before pumping begins is shown in figure 8. Note that the water table slopes toward the lower end of the basin. The ground water moves in the direction shown by the arrows.

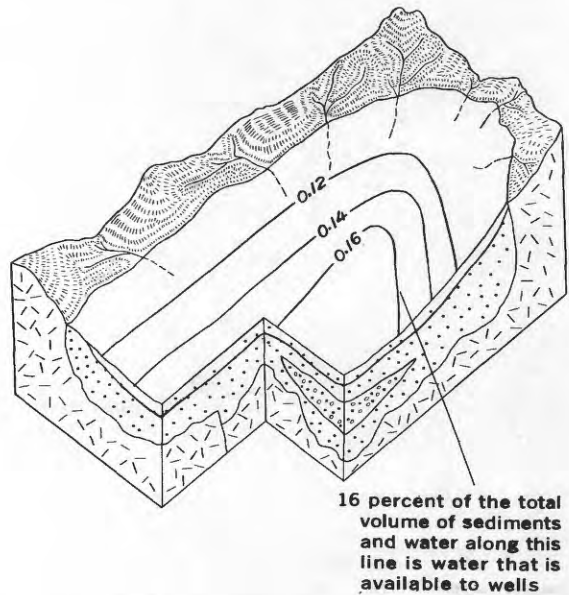


Figure 7.—Lines of equal storage coefficient are useful in describing the capacity of the valley fill to store water.

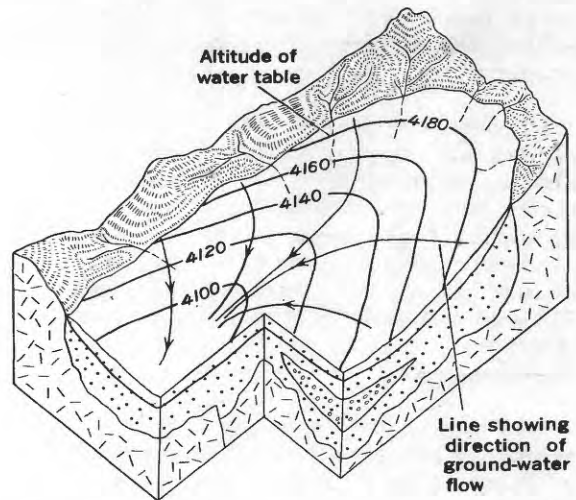


Figure 8.—The natural shape of the water table and the direction of flow of ground water.

When a well is pumped, as in figure 9, the shape of the water table is altered drastically and it assumes the shape of a funnel or cone around the pumped well. Within the cone the water flows radially toward the well. The longer the well is pumped, the larger and deeper the cone becomes. Eventually the water table is lowered throughout a broad area. Additional wells that are drilled within this area of influence will reach the water table at a depth lower than that occurring naturally and consequently pumping lifts will be

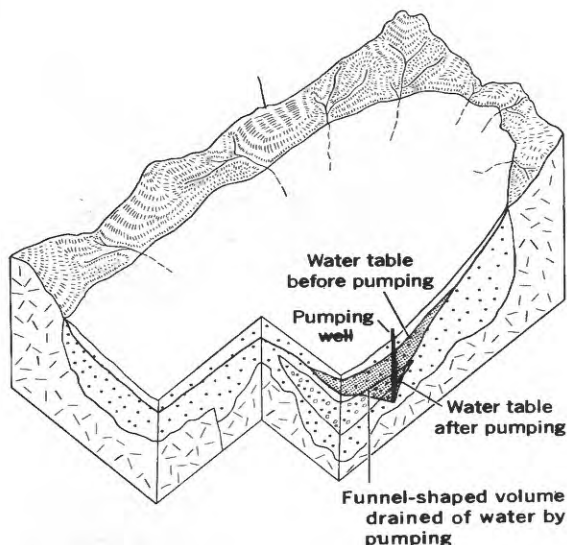


Figure 9.—The decline of water level in an area of pumping.

greater. The changes of water level caused by pumping water commonly are known only in the areas where water development has taken place. The effects of withdrawal of water outside of the immediate area of development may be largely unknown.

Predictions of water-level changes are needed not only in the developed area but also in adjacent areas of potential development. One of the major problems in management of ground water is the prediction of future changes in water levels in the aquifer as water continues to be pumped. Various patterns of pumping can be analyzed to determine answers to the following questions.

1. Which areas in the basin are capable of producing enough water for use over a period of many years without the water levels declining to depths from which it is uneconomical to pump?
2. What is the maximum amount of water that can be pumped from an individual well or well field over long periods of time?
3. If wells are closely spaced, will their pumping interfere with each other to the extent that water levels will be lowered to depths too great for economical pumping?
4. How long will the water last if sustained large-scale pumping is undertaken?

THE ELECTRIC ANALOG MODEL OF A GROUND-WATER SYSTEM

We want to find out what the effect of pumping wells on the flow of water in the aquifer will be. The decline of the water table caused by pumping water from the aquifer is one of the major factors we wish to analyze. A large-scale approach would be to pump the actual wells and then measure and analyze the effects of the pumping. But if we want to find out what the effects will be 50 years from now, it is hardly practical to pump the wells for 50 years and then measure the effects. The answer would come too late to be of use.

Many ground-water systems can be analyzed by mathematical methods. Mathematical formulas can take into account the shape, size, and hydrologic properties of the system; the amount and rate of water development, and the effect of water development on the system. The more complex the system is, however, the more complex the mathematical techniques must be, the more tedious and time-consuming is the analysis, and the less clearly the mathematics describe the system.

The hydrologist must look for some way to scale down the problem that he is studying—to look at it in miniature and with a reduced time scale, and to apply certain stresses, such as pumping, in a manner that will show effects on the ground-water system.

If the ground-water system being studied departs greatly from an ideal situation in which the flow of ground water is regular and the aquifer is uniform, the mathematical model may be replaced by constructing an electrical model of the ground-water system and analyzing it by electrical means.

The ground-water hydrologist can construct and analyze a model of the ground-water system in much the same way that the aeronautical engineer tests model planes in a wind tunnel, and the ship builder tests scale models of ships in tanks of water. An electrical model of the ground-water system is a useful analogy because an electrical circuit reacts to changes in the flow of electricity in the same way that the ground-water system reacts to changes in the flow of ground water. The electrical terms used to describe this relation and a description of

THEORY

Flow of water in a ground-water system is analogous to flow of electricity through an electrical circuit. Scaled electrical models can be built to simulate ground-water systems. The principal features of this analogy are compared below.

GROUND WATER SYSTEM

TRANSMISSIBILITY
STORAGE COEFFICIENT
PRESSURE OR HEAD OF WATER
DAYS OR MONTHS OF TIME
QUANTITY OF WATER FLOW

ELECTRICAL SYSTEM

ELECTRICAL RESISTANCE
ELECTRICAL CAPACITANCE
VOLTAGE
MICROSECONDS
COULOMBS OF ELECTRICAL CURRENT

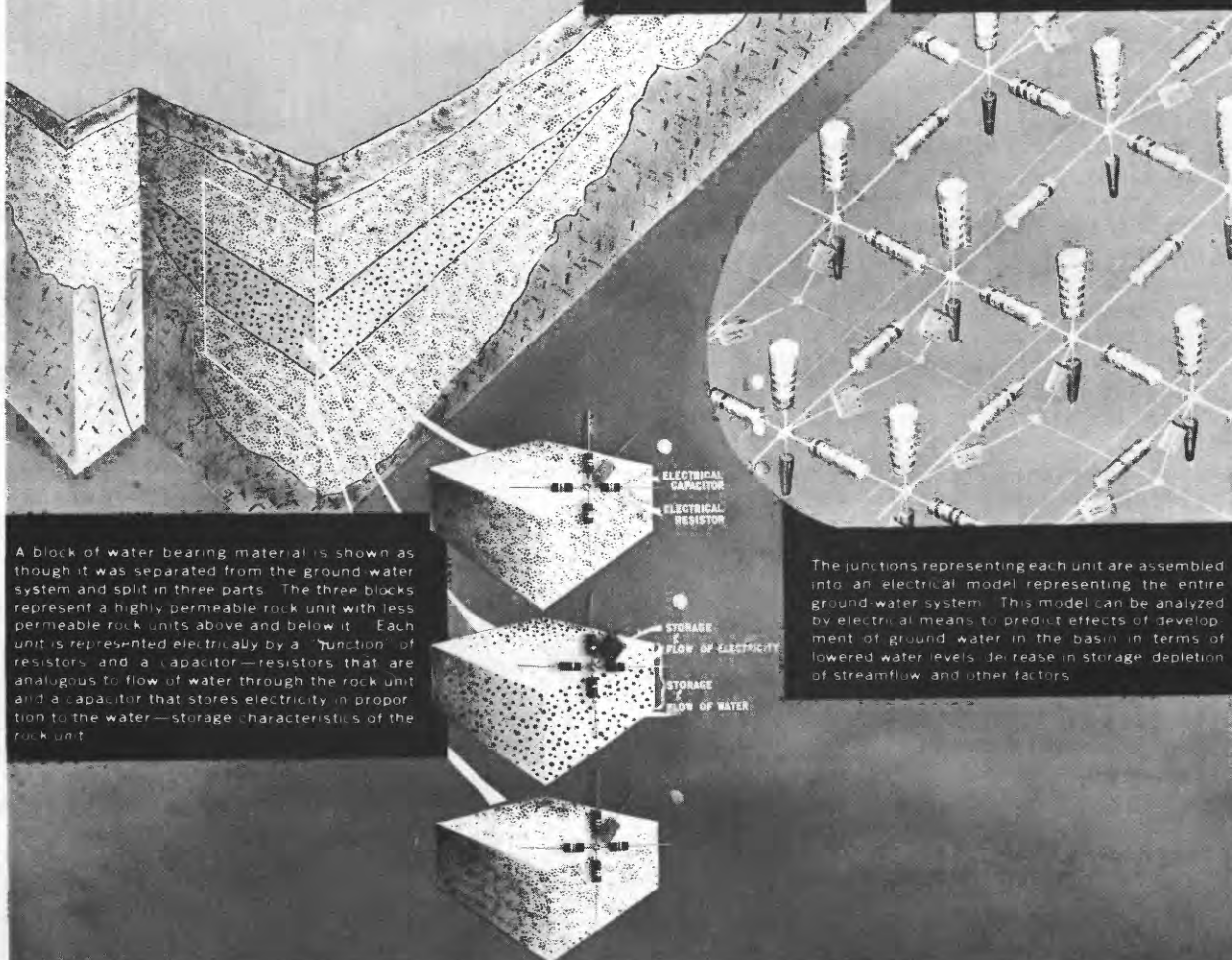


Figure 10.—Electric analog models of ground-water systems.

the analogy between ground-water systems and analog models are shown in figure 10.

Readers who are unfamiliar with electricity and electrical terms may find that the terms used here are not very clear. However, it is not really necessary to understand the terminology of electricity to appreciate how the analog model is used. The point is that the electric analog model is illuminating for the hydrologist. For him, using the analog model is akin to putting the whole aquifer under a microscope.

The electrical model is constructed in a shape similar to that of the actual aquifer system; that is, it is built upon a small-scale map of the aquifer. The thickness of the aquifer and the properties of water storage and transmittal are represented by electrical properties. For example, the water table, which rises and falls as water is added to or removed from the aquifer, is represented by a changing electrical voltage in the model.

You will see by looking at figure 10 that a small piece of the aquifer has been removed to show how its properties are modeled. A certain amount of water is stored in this unit of the aquifer. Our model has an electrical capacitor that stores a certain amount of electricity. Water flows through the aquifer at a certain rate; in the model an electrical resistor limits the rate of flow of electricity to that amount that is analogous to the flow of water through the ground-water system.

At any particular point in the ground-water system there is a combination of these factors. In the electrical model, we call this a junction--a joining of several resistors and a

capacitor that represent a rate of flow and an amount of storage at that particular point. The electrical model is constructed by connecting together enough of these junctions to simulate the entire ground-water system.

Figure 11 shows how the lines of equal transmissibility of the water-bearing rocks are transferred to a sheet of pegboard. The resistors are placed on the pegboard and are soldered together (fig. 12); they then are removed from the pegboard and hung in a frame and the capacitors are added (fig. 13). The model is now complete and is ready for analysis (fig. 14).

The model is a physical entity representing the shape, size, and characteristics of the aquifer. The analyzer computes the electrical changes that take place in the model and records the effect of the changes on the model.



Figure 12.—A technician is placing and soldering electrical resistors in the model to represent the ability of the sediments to transmit water.



Figure 11.—A technician transfers the lines of equal transmissibility to a sheet of pegboard on which the electrical model will be constructed.

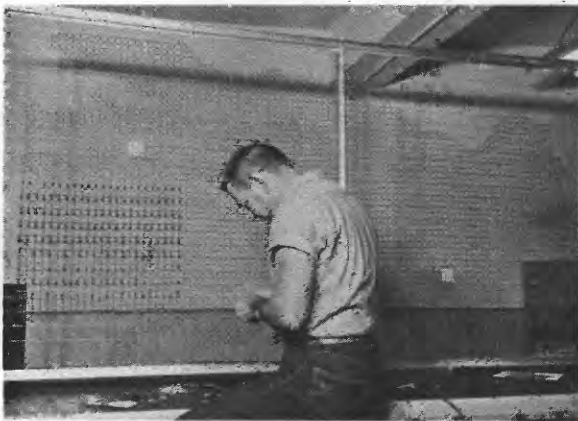


Figure 13.—The electrical capacitors that represent the capacity of the sediments to store water are added to the model.

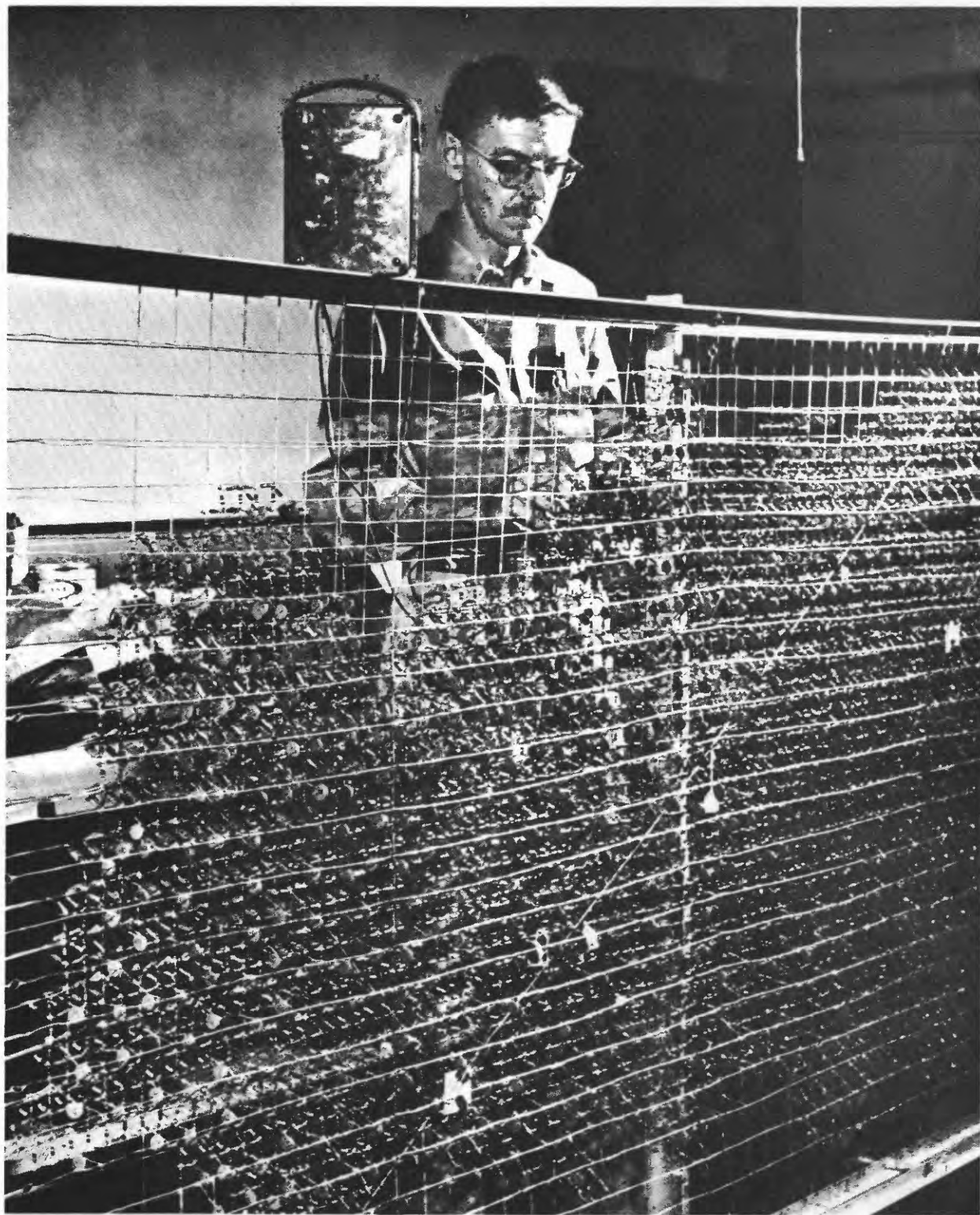


Figure 14.—The completed model is ready for analysis.

We wish to simulate the pumping of water from the aquifer, so we will "pump" or withdraw electricity from the model. We know that pumping water causes a decline of the water table which is analogous to changes in voltages in the model, and so we will measure the decline in voltage in the model as a measure of the decline of the water table. Figure 15 shows the electronic apparatus used to produce the stimulus in the model that is analogous to pumping of water from the ground-water system. This stimulus is fed into the model and is shown as a graph on the oscilloscope.

The effects of the stimulus are measured electrically and demonstrated on another oscilloscope screen. Figure 16 shows a graph of the decline of the water level for one point in the model. The graph shows the water-level drawdown at a well if a given amount of water were pumped in a given period of time. The scales of the graph on the oscilloscope screen can be read directly in feet of change of the water level and in days, months, years, or any unit of time that is desired. Various patterns and rates of pumping are tried and their effects are measured.

With this model it is possible to analyze quickly the long-term effects of pumping a

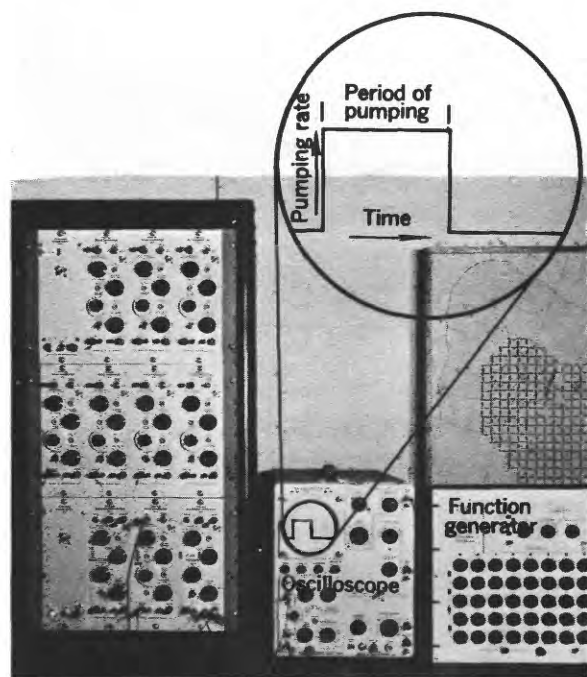


Figure 15.—An electrical stimulus, representing pumping of ground water, is applied to the model by electrical function generators. The graph on the oscilloscope screen represents a well pumping a certain amount of water for a given period of time.

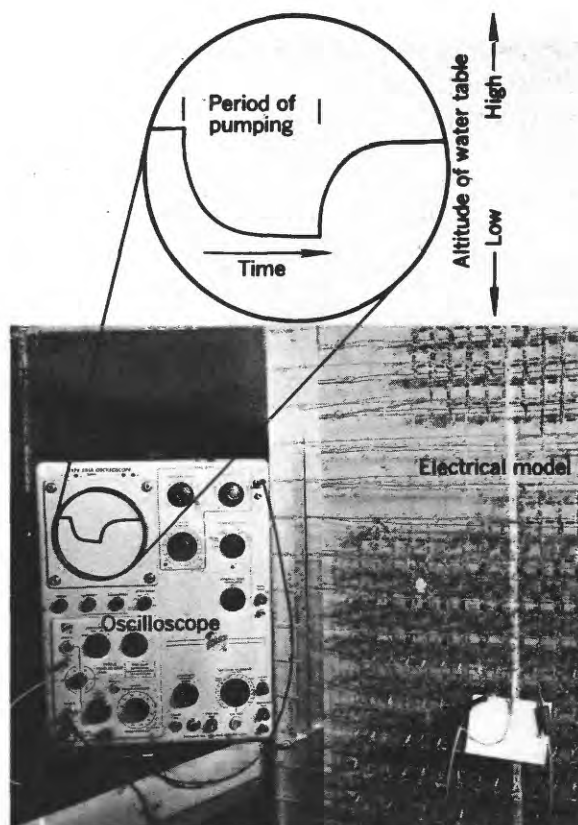
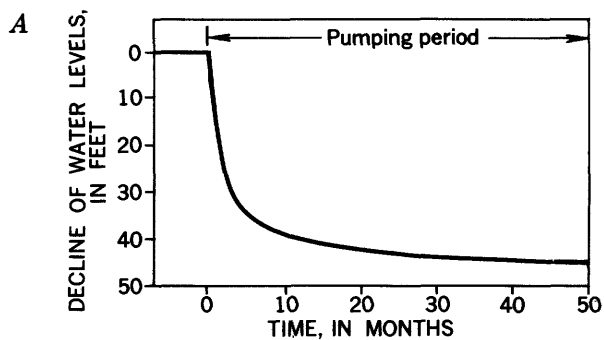


Figure 16.—The effect of pumping water from the system is pictured on the oscilloscope screen as a graph showing the decline of water level in the aquifer at some distance from the pumping well during the period of pumping.

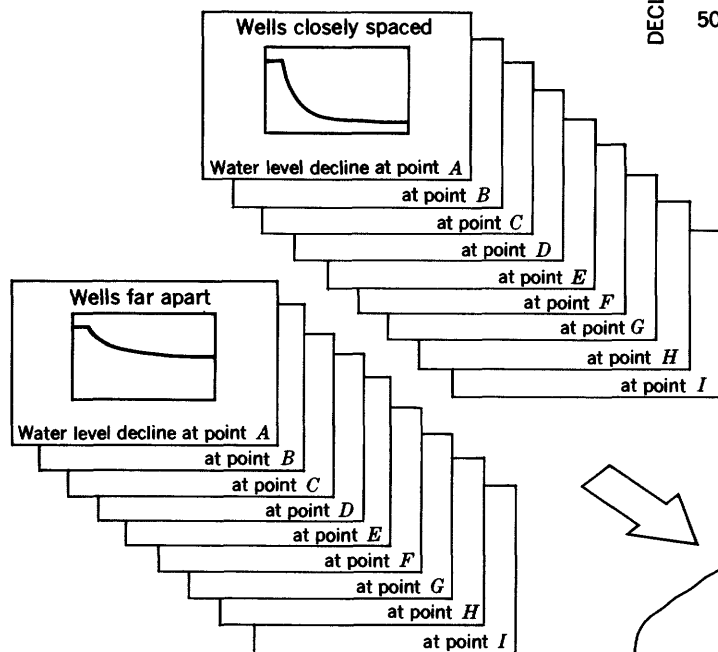
large ground-water system. A few weeks or months are required to construct and analyze the model; most of the time is spent in calculating the design of the model and in the construction of the model itself. Actual analysis of the model may take only a few days.

The information obtained by using the analog model is presented in graphs and maps, as shown in figure 17. The first graph (A) shows the decline of water levels at different intervals of pumping. Two sets of graphs (B) illustrate the water-level decline at a given time in closely spaced and widely spaced wells. Finally, two sets of contour maps (C) show water-level declines at the end of several periods of time, one with wells placed close together, the other with wells spaced far apart. With this information available, hydrologists can recommend the best pattern of water development for this particular aquifer. The water users then have a basis for deciding what pattern and rate of water development will be most efficient and beneficial.

Example of graph representing decline of water levels with time as taken from the oscilloscope screen



B



The water-level changes at the various points are used to construct maps showing, by contours, the water-level declines throughout the aquifer at various times since pumping began

C

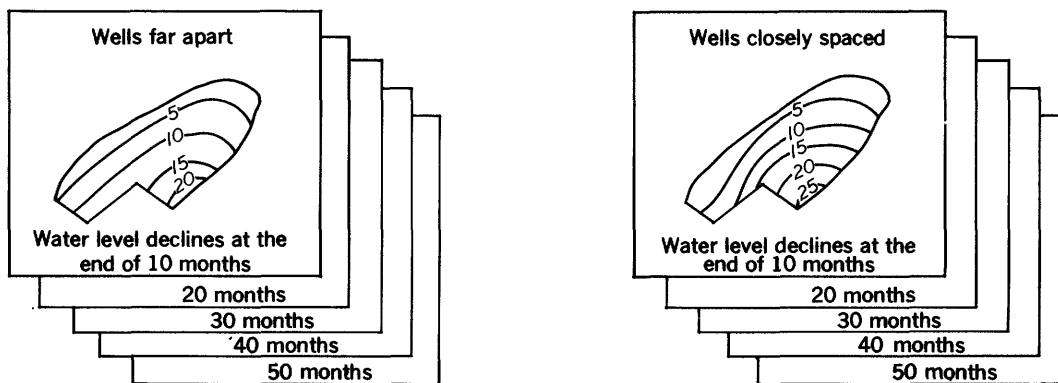


Figure 17. —The results of the analog model analysis are portrayed on maps and graphs.

HOW ARE THE RESULTS OF GROUND-WATER STUDIES PRESENTED TO THE PUBLIC?

Each year the Geological Survey publishes many reports describing the results of ground-water studies throughout the Nation. These reports are published as water-supply papers, hydrologic investigations atlases, professional papers, circulars, and bulletins. Some are also printed in technical journals of scientific societies. Reports also are published by the State agencies with which the Geological Survey cooperates in hydrologic studies.

The maps and graphs resulting from the electric analog model analysis are published in reports along with the maps of the ground-water system, the basic data on the geology and water resources, and the interpretations of the data made by the hydrologist.

All these reports are available to the public and are announced in monthly lists or other releases. Geological Survey Water-Supply Paper 1492 "Bibliography of Publications Relating to Ground Water Prepared by the Geological Survey and Cooperating Agencies, 1946-55," by R. C. Vorhis, 1957, is recommended for further information on ground water. Water-Supply Paper 1536-D "The Ground-Water Flow System in the Snake River Plain, Idaho-An Idealized Analysis," by H. E. Skibitzke and J. A. daCosta, 1962, describes the use of an electric analog

model in predicting the drawdown that could be caused by pumping in the Snake River Plain, Idaho. These two papers may be obtained from the Superintendent of Documents, Washington, D.C.

Two articles outline the methodology and use of analog model studies: "From Geologic Data to Aquifer Analog Models" by R. W. Stallman, *Geo-Times Magazine*, v. 5, no. 7, April 1961, and "Electronic Computers as an Aid to the Analysis of Hydrologic Problems" by H. E. Skibitzke, publication 52 of the International Association of Scientific Hydrology, 1960.

GROUND-WATER STUDIES AND THE FUTURE

The use of electric-analog-models in the solution of hydrologic problems provides the scientist and engineer with an effective new method of evaluating our water resources. They have been used in the science of ground-water hydrology for only a few years but already many improvements have been made. Let us make clear, however, that the analog model is not a final answer to our water-resource problems. It is an excellent tool which, in the hands of capable hydrologist, can be of great benefit and help. Research for new techniques and improved methods of solving water problems is, and will remain, the key to the proper management and conservation of our water resources.