Electrical-Analog Analysis of Ground-Water Depletion in Central Arizona

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1860

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By T. W. ANDERSON

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An electrical model of the hydrologic system indicates probable water-table conditions in 1974 and 1984

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CONTENTS

	Page
Abstract	1
Introduction	2
Purpose and scope of investigation	3
Physical and geologic setting	4
Hydrologic system	5
Predevelopment conditions	5
Postdevelopment conditions	7
Aquifer characteristics	9
Electrical system	10
Model construction	12
Generalizations and limitations	14
Original model design	16
Final model design	17
Future ground-water conditions	18
Summary and conclusions	20
References cited	21

ILLUSTRATIONS

[Plates are in pocket]

		Page
PLATES 1–4.	Maps showing—	
	1. Altitude of the water table and water-level declines in central Arizona.	
	2. Transmissibility and pumpage in central Arizona.	
	3. Depth to water, spring 1964, in central Arizona.	
	4. Predicted depths to water in central Arizona.	
FIGURE 1.	Map showing area of report and Arizona's water provinces	2
2.	Graph showing annual water use, 1923–64	7
3.	Photographs of the electrical-analog model	12
4.	Graph showing method of generalizing pumpage data for model input	15

ELECTRICAL-ANALOG ANALYSIS OF GROUND-WATER DEPLETION IN CENTRAL ARIZONA

By T. W. Anderson

Abstract

The Salt River Valley and the lower Santa Cruz River basin are the two largest agricultural areas in Arizona. The extensive use of ground water for irrigation has resulted in the need for a thorough appraisal of the present and future ground-water resources. The ground-water reservoir provides 80 percent (3.2 million acre-feet) of the total annual water supply. The amount of water pumped greatly exceeds the rate at which the ground-water supply is being replenished and has resulted in water-level declines of as much as 20 feet per year in some places. The depletion problem is of economic importance because ground water will become more expensive as pumping lifts increase and well yields decrease.

The use of electrical-analog modeling techniques has made it possible to predict future ground-water levels under conditions of continued withdrawal in excess of the rate of replenishment. The electrical system is a representation of the hydrologic system: resistors and capacitors represent transmissibility and storage coefficients. The analogy between the two systems is accepted when the data obtained from the model closely match the field data—in this instance, measured water-level change since 1923. The prediction of future water-table conditions is accomplished by a simple extension of the pumping trends to determine the resultant effect on the regional water levels.

The results of this study indicate the probable depths to water in central Arizona in 1974 and 1984 if the aquifer characteristics are accurately modeled and if withdrawal of ground water continues at the same rate and under the same areal distribution as existed between 1958 and 1964. The greatest depths to water in 1984 will be more than 700 feet near Stanfield and more than 650 feet in Deer Valley and northeast of Gilbert. South of Eloy and northwest of Litchfield Park, a static water level of more than 550 feet is predicted. The total water-level decline in the 20-year period 1964–84 at the deepest points of the major cones of depression will range from 150 to 300 feet, and the average decline in the entire central Arizona area will be about 100 feet.

INTRODUCTION

The extensive use of ground water for irrigation in central Arizona (fig. 1) has resulted in the need for appraisals of the present and future ground-water resources. The central Arizona area consists of 3,500 square miles in western Pinal and eastern Maricopa Counties, of which about 1,250 square miles (800,000 acres) is under cultivation. The largest irrigated areas in the State are the Salt River Valley and the lower Santa Cruz River basin. The agricultural economy is dependent on a reliable source of irrigation water.

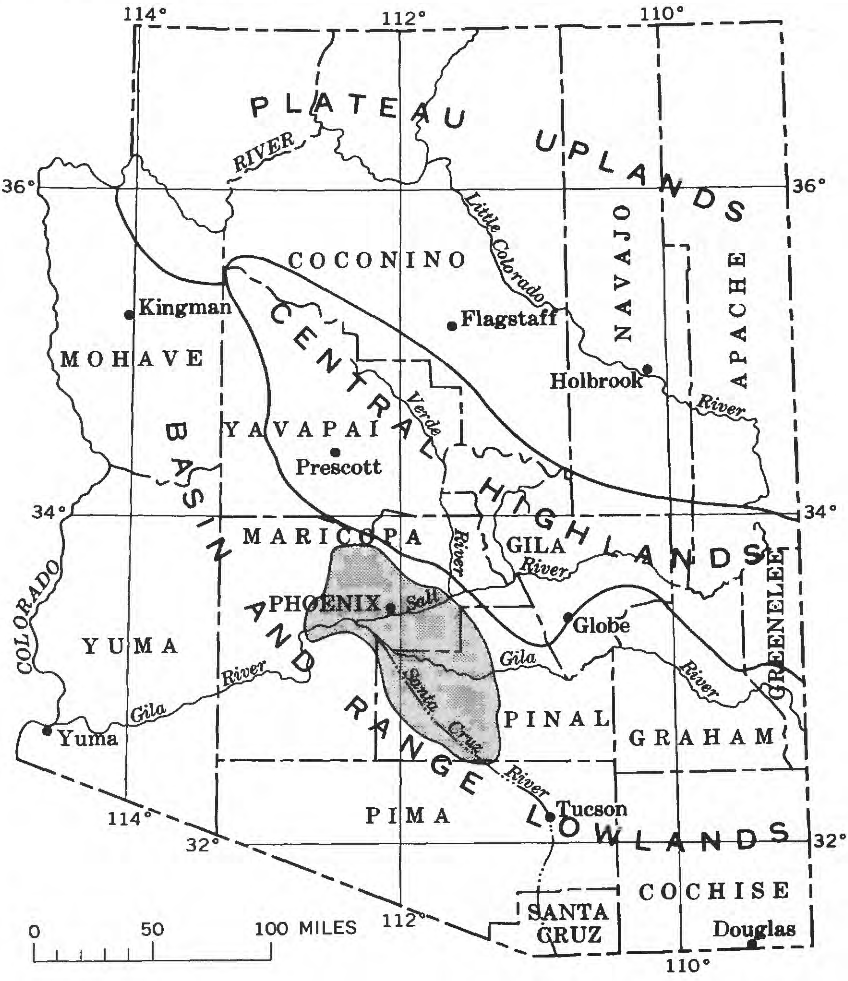

FIGURE 1.—Area of report (shaded) and Arizona's water provinces.

Ground water from more than 4,000 irrigation wells provides 80 percent of the total water used in central Arizona (White and others, 1964, p. 8); this ground water amounts to 3.2 million acre-feet per year, which is greatly in excess of the rate at which water is being recharged to the ground-water reservoir. The overdraft from the ground-water reservoir is causing the water levels to decline as much as 20 feet per year in some places. The ground-water supply may never be exhausted, but if the present rates of decline continue, pumping lifts may become so great that further use of ground water for agricultural purposes could be uneconomical.

PURPOSE AND SCOPE OF INVESTIGATION

The purpose of the investigation was to analyze the ground-water data by means of an electrical-analog model and to determine the probable future effects of continued ground-water withdrawal in central Arizona. A model was constructed by using the known hydrologic characteristics of the water-bearing rocks and the pumping history through 1964. The model electronically duplicated the changes that occurred in the aquifer system from 1923 to 1964 and enabled the prediction of ground-water levels for 1974 and 1984 based on the same pumping rate and areal distribution that existed in 1964.

The model averaged hydrologic cause-and-effect conditions in the upper 1,000 to 1,200 feet of alluvial material. Although alluvial material deeper than 1,200 feet contains ground water and is tapped by wells, the existing data were insufficient for quantitative evaluation and were not included in the model. Data used in the construction of the model included measurements of surface-water flow, ground-water pumpage, water levels, and specific capacities of wells and also included estimates of the storage capacity of the alluvial material.

The model defined the entire hydrologic system by reconstructing the entire history of ground-water development in the basin. It was necessary to analyze the aquifer characteristics in order to establish numerical values for the transmissibility and storage coefficients of the system. These data were then converted to a conceptual design of the system in the form of an analog model, which, after its similitude to the actual system was proved, could be used as a hydrologic tool to predict future water-level conditions; future uses of the model may include analyses of well-field management problems or the effects of artificial recharge on the regional water levels.

PHYSICAL AND GEOLOGIC SETTING

The central Arizona area is in the north part of the arid to semiarid Basin and Range Lowlands province of Arizona. Rainfall averages about 8 inches per year and, except for unusual floods, most of the streambeds are dry. In the area is the junction of three major rivers—the Salt, Gila, and Santa Cruz. The rivers drain large areas and flow southwestward to the Colorado River. The Salt River and its tributary, the Verde River, drain the less arid Central Highlands province, which is north of the central Arizona area. The Gila and Santa Cruz Rivers drain southeastern Arizona, which is mainly in the Basin and Range Lowlands province. The Salt and Gila Rivers rarely carry surface flow, either because of dams or because of the lack of precipitation. The Santa Cruz River, although unchecked by dams, also rarely carries surface flow.

Central Arizona is characterized by low mountains surrounded by very broad flat-lying valleys or basins. The mountains, which are composed mainly of impermeable crystalline rocks with minor amounts of sedimentary rocks, form physical boundaries to surface-water drainage and hydrologic boundaries to ground-water flow. The valleys are underlain by thousands of feet of unconsolidated to consolidated alluvial deposits, which range in size from gravel to clay (Hardt and others, 1964; Hardt and Cattany, 1965; Kam and others, 1966). The alluvium is an aquifer and stores large quantities of water that may be removed by wells. Hardt, Cattany, and Kister (1964, p. 6) divided the alluvium into an upper sand and gravel unit 0 to 600 feet thick, a middle silt and clay unit 0 to 2,000 feet thick, and a lower sand and gravel unit 0 to 500 feet thick. In most of central Arizona, the water table is in the highly permeable upper sand and gravel unit, and most of the water is produced from this unit. The middle silt and clay unit is less permeable and yields less water to wells; however, the unit does not extend over the entire area. The lower sand and gravel unit is more permeable than the medial silt and clay unit but is not as productive as the upper sand and gravel unit (Hardt and others, 1964, fig. 4).

The information used in this report is mainly from wells that tap the uppermost 1,000 to 1,200 feet of alluvium, and the results dominantly reflect or can be used to interpret ground-water conditions only in the upper sand and gravel and part of the silt and clay units.

HYDROLOGIC SYSTEM

In central Arizona, the major part of the hydrologic system consists of ground water, which is stored in the very thick and permeable alluvium of the broad basin. In 1923, ground water flowed slowly northwest and toward the Salt River and was replenished through recharge from runoff from the three major river basins. The ground-water storage and flow system has since been changed owing to the effects of pumping.

The amount of water that enters the ground-water reservoir annually is very small. The water enters the reservoir by seepage from stream channels during surface flow, seepage from canals and irrigated land, and underflow from adjacent ground-water basins. When the rate of pumping in an area exceeds the rate of replenishment, some water must be taken from storage, and the result is a decline of the regional water table. Since the early 1920's, pumping has exceeded replenishment in central Arizona. Beginning in the early 1940's, pumping was greatly accelerated and within a few years reached a rate many times greater than the rate of recharge. Water levels have declined in the entire area, and the rate of decline in some places is as much as 20 feet per year.

PREDEVELOPMENT CONDITIONS

Prior to 1923, the hydrologic system in central Arizona was considered to be about in equilibrium; that is, inflow was equal to outflow. The first development of ground water began about 1900 (Lee, 1905). In the Eloy and Maricopa-Stanfield areas in the lower Santa Cruz basin, ground-water development was necessary to irrigate the land because of the lack of surface water. Development in these areas was sparse, and the amount of water pumped annually was small and did not increase markedly until the early 1940's. West of Phoenix along the Salt River, most of the pumping from wells was done to drain land that had become waterlogged owing to the application of surface water.

Surface water has been diverted for irrigation along the Salt and Gila Rivers since the time of the prehistoric Indians. The surface-water diversion and distribution systems in use in 1923 had been constructed in the late 1800's (Skibitzke and others, 1961). The surface-water resources available for distribution during the equilibrium period (1923) were much the same as they are today.

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In 1923 the configuration of the ground-water surface generally conformed to that of the land surface, and the direction of flow was at right angles to the contour lines (pl. 1). A general view of the ground-water system during the equilibrium period would show that water entered the ground-water reservoir by infiltration of surface-water flow, seepage from canals and irrigated land, and underflow from adjacent ground-water basins. Outflow from the system resulted from pumping, surface runoff where ground water discharged to streams, evaporation from open water surfaces and shallow ground water, and plant transpiration.

The direction of ground-water flow in the lower Santa Cruz basin during the undisturbed conditions was, in general, from southeast to northwest. Inflow to the basin occurred along its periphery as underflow or infiltration from surface flow in the many desert washes entering the valley. Inflow from canal seepage was limited to the Florence–Coolidge–Casa Grande area, the only area in Pinal County that had a surface-water distribution system. Outflow from the system occurred as pumpage or underflow. The underflow out of the lower Santa Cruz basin into the adjacent Salt River Valley occurred near the confluence of the Salt and Gila Rivers southwest of Phoenix. There is no absolute division between these two ground-water systems, which are hydraulically connected along the course of the Gila River from the Santan Mountains to the Sierra Estrella. The division of central Arizona into two units is for simplicity of discussion and does not mean that the units represent separate entities in the ground-water system.

In the Salt River Valley, ground-water flow was generally from east to west. Inflow occurred along the periphery of the valley and as infiltration in streambeds during surface flow. Ground-water inflow in this part of the area also resulted from canal and irrigation seepage, as indicated by the fact that part of the land was becoming waterlogged prior to and during the equilibrium period (1923) selected as the base period for this study. The area where true equilibrium conditions did not exist because of this waterlogging was relatively small and is considered negligible in its effect on the entire system. The waterlogged area was along the Salt River above its confluence with the Gila and extended downstream along the Gila for several miles. In 1923 the Gila River was a gaining stream in this area and represented one of the methods of outflow from the ground-water system

(Thomas and others, 1963, p. 46). The shallow water-table area also represented a source of discharge from the system through direct evaporation from the shallow water table and through plant transpiration.

POSTDEVELOPMENT CONDITIONS

Since 1923 the ground-water system has been developed extensively in central Arizona. The surface-water resources were already being fully utilized and continue to provide an important source of irrigation water for a part of the area. Except for floodwater, all the flow in the Gila-Salt Rivers system is diverted for irrigation. The increasing water requirements of an expanding agricultural economy have been met by the ground-water supply (fig. 2). The withdrawal of ground water to meet the increasing needs of agriculture caused the rapidly declining water levels.

From spring 1923 to spring 1964, the water levels declined as much as 360 feet in central Arizona (pl. 1). In the lower Santa Cruz basin the water-level declines ranged from 0 near Casa Grande to as much as 340 feet in the large cone of depression near Stanfield (pl. 1). A similar cone exists around Eloy; here

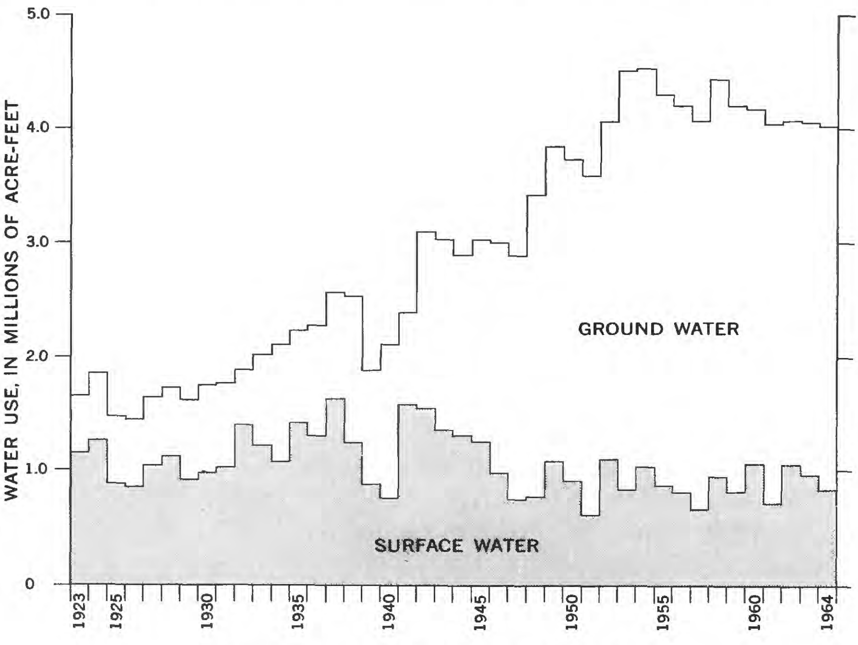


FIGURE 2.—Annual water use, 1923–64.

the maximum water-level decline was only 200 feet, but it extends over a much larger area. In the Salt River Valley there are three large cones of depression—northeast of Gilbert, in Deer Valley northwest of Phoenix, and northwest of Litchfield Park. The largest is northeast of Gilbert where the maximum decline was 360 feet. The water level in Deer Valley declined as much as 300 feet, and northwest of Litchfield Park the maximum decline was about 250 feet. The average decline for the entire central Arizona area is about 140 feet.

The annual withdrawal of ground water from the Salt River Valley and the lower Santa Cruz River basin increased from about 450,000 acre-feet in 1923 to 3,700,000 acre-feet in 1953 (fig. 2). In 1964 the annual withdrawal of ground water was about 3,200,000 acre-feet, of which about 2,200,000 acre-feet was from the Salt River Valley and 1,000,000 acre-feet was from the lower Santa Cruz basin. The total volume of water pumped in central Arizona from 1923 through 1964 was 80 million acre-feet.

The large withdrawal from the ground-water reservoir has changed the regional flow pattern from a relatively uniform undisturbed state to a series of individual systems, each one located at a relative center of pumping (pl. 1). In places, the gradient was reversed after ground-water development, and the water now moves in the opposite direction. A general regional flow pattern no longer exists, and the flow is directed radially toward the center of the large cones of depression.

Increased pumping from the ground-water reservoir has resulted in less natural discharge. The Gila River no longer flows as it once did in the reach downstream from its confluence with the Salt. Because the regional water table has declined in this reach, the amount of water lost to evapotranspiration is less than when the area was waterlogged. It also is possible that some small change has occurred in the amount of underflow entering the system between 1923 and 1964; however, the change is small enough to be considered negligible.

All the factors that affect the ground-water system must be considered in an analog-model study, and all changes in stress on the system that have occurred since the assumed steady-state time (1923) must be included in the model. The stresses that existed during steady-state time were not included in the model because they were not causing depletion of the ground-water supply. Increased pumping that resulted in water-level declines and other major changes in the regional flow system, such as reduced evapotranspiration and changes in recharge, are simulated in the model.

AQUIFER CHARACTERISTICS

The aquifer system can be defined in terms of two parameters —the coefficient of transmissibility and the coefficient of storage. The coefficient of transmissibility has been defined by Ferris, Knowles, Brown, and Stallman (1962, p. 72–73) as the rate of flow of water, in gallons per day, through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent. A map of the regional transmissibility pattern must be prepared before it is possible to utilize the analog techniques. The map provides the basis for the construction of an electrical-resistor network analogous to the aquifer system. The ideal means of developing a quantitative pattern of regional transmissibility is provided by aquifer tests; however, this means was not used in this study because sufficient aquifer-test data were not available. The only data available in sufficient quantity that were a function of aquifer characteristics were values of specific capacity. Specific capacity is the yield of a well, in gallons per minute, divided by the pumping drawdown in the well, in feet. Discharge and drawdown data have been collected in central Arizona by personnel of the U.S. Geological Survey, irrigation districts, and pump companies for many years.

The method of converting specific-capacity data to values of transmissibility is based on the work of Thomasson, Olmsted, and LeRoux (1960), who computed a coefficient of proportionality ranging from 1,460 to 1,990 for similar alluvial deposits in Solano County, Calif. This method was applied to several sites of known transmissibility in the Salt River Valley, and the average coefficient of proportionality was computed to be about 2,000. The specific-capacity data used are dependent on the construction and performance characteristics of the wells and on the aquifer characteristics. In order to use the same relating coefficient for the entire area, the assumption was made that the entrance losses were fairly consistent throughout the area.

Using the empirical relation between specific capacity and transmissibility, an approximate areal pattern of transmissibility ranging from 10,000 to 200,000 gallons per day per foot was determined for central Arizona (pl. 2). Plate 2 is a general representation of the areal pattern of transmissibility for only the upper 1,000 to 1,200 feet of alluvial material, as the wells from which specific-capacity data were obtained penetrated less than 1,200 feet. The accuracy of the map is limited by the inherent restrictions of the method used to determine the transmissibility.

The storage coefficient of an aquifer has been defined by Ferris, Knowles, Brown, and Stallman (1962, p. 74) as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. Storage coefficients have been computed for large areas in central Arizona based on the ratio of a known volume of pumpage to a known volume of sediments dewatered by that amount of pumpage. The average coefficients of storage for these areas range from 15 to 20 percent. These calculations provided the basis for the storage-coefficient values used in the electrical-analog model. A storage coefficient of 19 percent was used, except where further refinement based on known subsurface characteristics was possible.

ELECTRICAL SYSTEM

The resistor-capacitor network is the basic element in the analysis of a ground-water system by electrical-analog methods. The network is simply a scaledown electrical version of the actual ground-water system and is analogous to the ground-water system in shape and aquifer characteristics. The resistors are analogous to the energy-dissipation characteristics of the rock matrix through which the ground water flows, and their value is inversely proportional to the transmissibility. Capacitors store electrical energy in a manner that is analogous to the storage of ground water in the pore spaces of the aquifer. The capacitor values are directly proportional to the storage coefficient of the aquifer.

The stress imposed on the aquifer system by the withdrawal of ground water is simulated electrically by the withdrawal of electric current. The change in voltage that occurs on the model as a result of the current withdrawal is analogous to the change in water levels that occurs when ground water is pumped. Voltage and current in the electrical system are equivalent to the head and volume rate of flow in the ground-water system. The analogous units of the electrical and hydrologic systems are as follows:

Hydrologic system	*Electrical system*
Transmissibility, in gallons per day per foot	Electrical resistance, in ohms.
Storage coefficient	Electrical capacitance, in farads.
Pressure or head of water, in feet	Voltage potential, in volts.
Time, in years	Time, in microseconds.
Volume of water, in gallons	Coulombs of electrical charge.

The response of the model to the simulated pumping stress is shown on an oscilloscope in the form of a hydrograph. Thus, the oscilloscope acts as a water-stage recorder, which continually measures the water level in an observation well. The horizontal scale of the hydrograph is in time units, and the vertical scale is in voltage. By the application of appropriate constants, voltage is converted to feet of water-level change. By measuring with the oscilloscope at different points, it is possible to prepare a contour map of water-level changes caused by a specific stress applied for any specific length of time. The maps prepared from the model data are compared with maps showing water-level changes measured in wells. If the maps are similar, it can be assumed that the conceptual design of the model is reasonably correct.

MODEL CONSTRUCTION

To construct an electrical-analog model that properly represents the real ground-water system, it is necessary to define the real system in terms of transmissibility, storage coefficient, amount of pumping, distribution of wells, and the historical pumping pattern. It is also necessary to make certain generalizations that tend to simplify the overall picture and the construction of the model. Robinove (1962) gives a general description of the required data and procedures for the construction of an electrical-analog model.

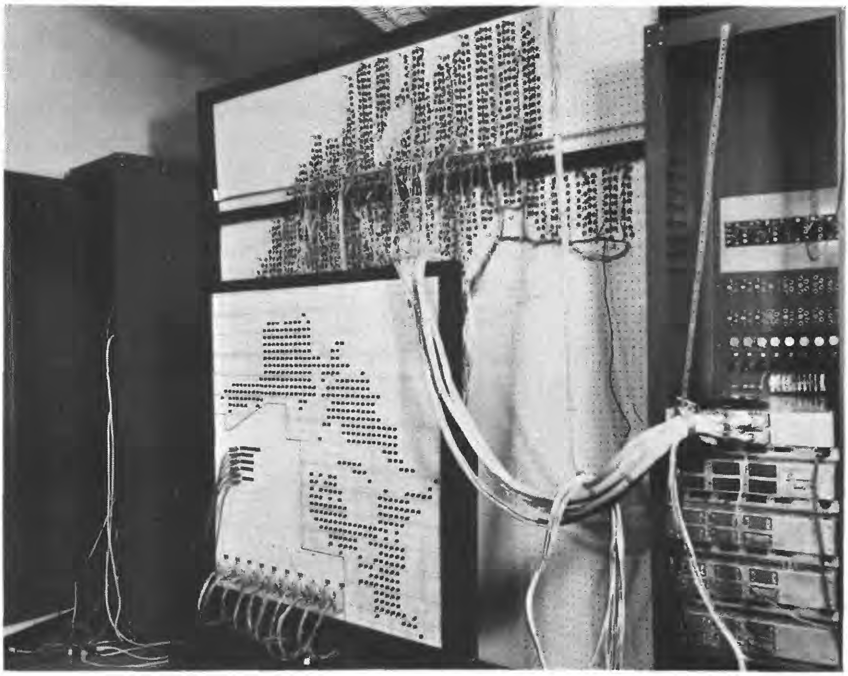
The electrical-analog model for central Arizona was constructed on a scale of 1 inch equals 1 mile. The scale was governed by the size limitations of the model and the accuracy of the available data. Resistor junctions were placed at 1-inch intervals. Because each resistor in the network represents the resistance to flow of a specific part of the aquifer, local variations in transmissibility can be simulated by changing the value of a resistor. The transmissibility this resistor represents is the aver-

A

FIGURE 3.—Electrical-analog model. *A*, Front view. *B*, Back view.

age value for the upper part of the aquifer to a maximum depth of about 1,200 feet.

A front view of the model and the required electronic apparatus are shown in figure 3*A*. The resistor grid is superimposed on the base map, and the dark areas indicate the land under cultivation. Figure 3*B* shows the reverse side of the model with the pumpage-programming board attached. The board consists of a half-scale map, and the pumping centers are represented by the black junctions. Additional resistors on the back of this board control the amount of current withdrawn from the analog system. Five time periods are used in the model—1923–37, 1937–42, 1942–52, 1952–58, and 1958–64. The pumpage for a given period was assumed to occur at a constant annual rate, and the break between periods was made at a time when there was a significant change in pumping in some part of the area. Each resistor simulates the average amount of ground water withdrawn annually from a 4-square-mile area for a certain time period. Thus, the entire pumping history for 1923–64 and the



B

FIGURE 3.—Continued.

predicted pumping regimen for 1964–84 are duplicated electronically on the board.

GENERALIZATIONS AND LIMITATIONS

The model is a generalization of the real hydrologic system. The averaging and generalizing techniques used in the construction of the model were designed to remove some of the extreme complexities from the hydrologic system. These techniques by no means degrade the analysis but serve to keep it within the realm of accuracy of the basic data used to design the model and the electrical components used in its construction.

The most important generalization probably was the modeling in two dimensions of a system that is variable in three dimensions. As previously described, the ground-water aquifer is made up of three units or layers of material having very different hydraulic characteristics. The lowering of the water table and the dewatering of the upper unit will result in greater pumping stresses being imposed on the underlying units. Because the underlying units generally yield less water, the reaction of the system to constant pumping will change with time and water-table decline. Two possible changes in the system will result: either the rate of water-table decline will increase or the amount of water pumped will decrease. In either instance, the assumption of uniform transmissibility and storage coefficients for the upper 1,200 feet of the aquifer may be seriously in error where more than one unit supplies water to wells. At the present time (1964), there are only a few small areas where the middle clay unit is causing the aquifer characteristics to change with time. In the next 20 years, these areas will expand, but the growth will be small compared to the entire central Arizona area. The primary limitation that this factor places on the analog model is the length of time to which the data may be extended to predict future conditions.

Another generalization made in the construction of the model is the method of simulating pumpage. The average annual pumpage, by township, was modeled without considering any variations that occur during the year as a function of the growing season. The pumpage input to the model system for each township for 1923–64 is shown on plate 2. The pumpage figures were based on well records from irrigation districts and electric and gas companies for private wells. Figure 4 shows the method used

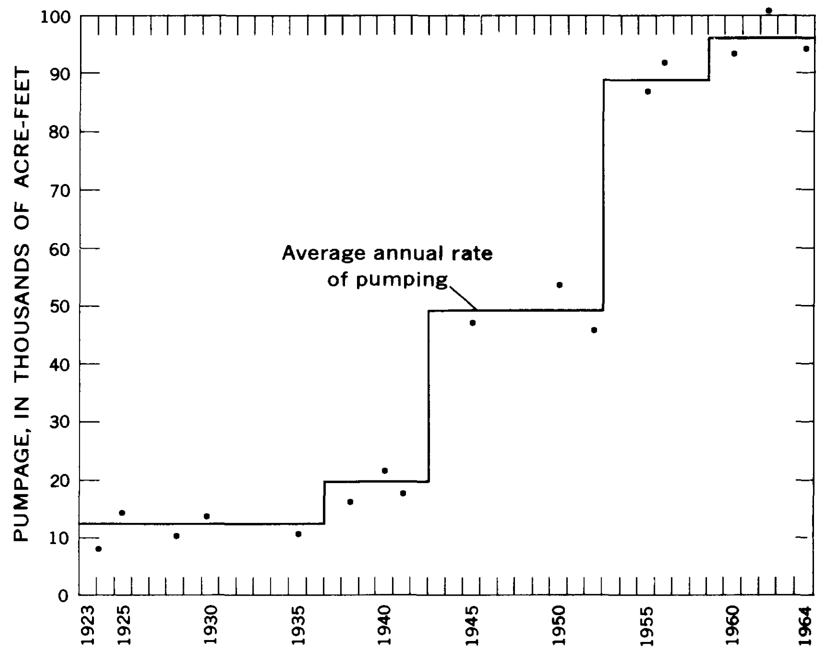


FIGURE 4.—*Method of generalizing pumpage data for model input for one township.*

for determining the average annual rates of pumping for the time periods used in constructing the model. For model simulation, the pumpage by township was further divided into 4-square-mile units.

The generalizations of aquifer and pumping conditions were necessary because of the data and time available for this study. Limitations are placed on the accuracy of the results by these generalizations; however, the model is sufficiently accurate to serve as a useful tool for determining how the system may react to a change in a particular stress. Changes in the system or stresses on the system may be programmed into the analog system to determine the new reaction. Therefore, the model can be used to predict changes in the water level for a reasonable time in the future under present water-use practices, or it can be used to predict changes that might occur under different changes that might be anticipated in the water-use system. One of the major advantages of an electrical-analog model is that it can be modified simply as additional data are obtained.

ORIGINAL MODEL DESIGN

After the original analog model had been designed, it was recognized that some changes might be necessary in order to make the conceptual design more accurately simulate the field conditions. Transmissibility, storage coefficients, and pumpage are the three parameters in the model system, and if these parameters are reasonably accurate in simulating the hydrologic conditions, the outputs of both systems should be similar.

The transmissibility values are inversely proportional to the resistor values, and the smaller the resistor value, the higher the relative transmissibility that it represents. Areas that have equal values of transmissibility are represented on the model by similarly shaped areas in which the resistor network is composed of resistors of equal value. At first, the storage coefficient of the aquifer was assumed to be uniform throughout the area because there were no data available to prove otherwise. An assumed value of 19 percent was used as a reasonable first approximation of the probable storage coefficient based on previous determinations made in parts of the area.

The pumpage data were simulated in 4-square-mile units, and the amount of water pumped from a 4-square-mile area was simulated by a single point of withdrawal in the center of the area. The pumpage information was the only parameter in the model that could not be altered.

The simulation of the depletion environment was, from this point on, one of trial and error. If the model did not react to the applied stress in a manner similar to that of the real system, the cause of the discrepancy had to be determined and corrected.

The initial results indicated that about 50 percent of the model area was incorrectly simulated. There were three main areas where the water-level decline map obtained from the initial test of the model did not match the field data for the test intervals. The largest area was near Stanfield. The cone of depression indicated by the model was not as extensive nor as deep as that measured in the real system. The same problem occurred northeast of Gilbert where the general configuration of the potential distribution was similar to the field data, but the indicated declines were not as great as those measured in the field. The storage coefficient probably was wrong because the volume of dewatered sediments determined from the model was not comparable to that determined in the field.

The other problem area was near the Gila River from above the confluence of the Salt and the Gila downstream to the western extent of the model area at Buckeye. Here, the model indicated more drawdown than that measured in the real system. This could have been caused by an incorrect storage coefficient; however, through recognition that this was the exact area where waterlogging had been a problem and where ground water had formerly been discharged by evapotranspiration and to the Gila River, it became apparent that some other factor had not been accounted for. Under equilibrium conditions, water left the aquifer in this area through seepage and evapotranspiration. Later, pumping resulted in a lowering of the water table, which, in turn, resulted in decreased seepage and evapotranspiration losses. Since development, the decrease in water losses can be considered as recharge to the system because that amount of water is no longer leaving the system as natural discharge. The natural discharge, if treated as recharge, could correct the discrepancy between the drawdown measured on the model and that determined from the field data.

FINAL MODEL DESIGN

Changes were made in the model design only when the data indicated that there was some basis for making the change. The final design included several alterations in the original design. The transmissibility map and pumpage distribution were not altered; only the storage coefficient was changed in the three problem areas.

Although the storage coefficient in most of the area was left at the original 19 percent, several small areas were assigned a storage coefficient of 15 percent, such as in Maricopa County east of Mesa along the southwest slopes of the Superstition Mountains and in the Deer Valley area north and slightly west of Phoenix. The storage coefficient was reduced in these areas because of the high proportion of fine-grained material in the water-bearing zones. A storage coefficient of 10 percent was assigned to an area underlain by a highly cemented gravel zone west of Casa Grande in Pinal County (Hardt and others, 1964). This area extends from the Sacaton Mountains on the north to the Table Top Mountains on the south.

The only other modification of the original system was made at the confluence of the Salt and Gila Rivers and downstream along the Gila. As previously discussed, this area had formerly been a zone of discharge, and it was necessary to add recharge at this point because the amount of water leaving the area had decreased since the equilibrium period. The amount of water that formerly had been lost by seepage and evapotranspiration was now available to be discharged by wells. The model system was manipulated on the basis of potential distribution rather than on quantity of flow because of the relative ease of analysis and because it was impossible to compute exactly the quantity of discharge lost through evapotranspiration prior to ground-water development. The method of handling the discrepancy was based on a similar problem described by Robinson (1964); the method of solving the problem is different, but the cause and type of problem are similar. Once these alterations were made, it was possible to duplicate the historic water-level-change data.

The method of verifying the analogy between the ground-water system and the electrical system is the reproduction of historic data in the form of water-level declines for different time periods. When the water-level-decline data from the model match the field data, it is assumed that the model design is similar to the actual system. Therefore, the model can be used to determine the reaction of the actual system to the application of any specific stress. In central Arizona the duplication of historic data was done for three different periods, and the model proved to be a valid representation of the actual hydrologic system for 1923–64. The check periods used were 1923–42, 1923–52, and 1923–64. The close comparison of the field and model data for these periods is the basis for the assumption that the electrical-analog system can be used to predict future ground-water conditions.

Plate 3 shows the measured depth to water in the spring of 1964 (White and others, 1964) and the data from the electrical-analog model for the spring of 1964. The data from the model have been converted from water-level decline since 1923 to depth to water by superimposing the 1923 depth-to-water data on the model data. This was done to make the model information more easily comparable with the field data.

FUTURE GROUND-WATER CONDITIONS

Once the analogy between the hydrologic and electrical systems had been confirmed, predictions of future water-level declines were made on the basis of an assumed pumping regimen. The pumping conditions used in the prediction were based entirely on past trends. The amount and areal distribution of pumping were assumed to be the same as the average conditions of the past 6 years (1958–64) for simplicity and because no other information was available to show that any significant change will occur. The amount of water pumped probably will be less because the ever-increasing pumping lifts will make pumping increasingly expensive, and economically marginal lands may be withdrawn from cultivation. It is assumed that 3.2 million acre-feet of water per year for the next 20 years will be pumped in central Arizona and that the areal distribution will be as at present. This assumption will cause the predicted water-level declines to be greater than are actually probable. The degree to which the prediction differs from actuality will be dependent upon the amount and location of any changes in ground-water withdrawal and the degree that the geologic approximations built into the model differ from the real system.

The predicted regional water-table decline will average about 50 feet from 1964 to 1974 (pl. 4). The water levels in the present areas of heavy withdrawals will continue to decline at about the same rate as in the past, and the depth to water in 1974 will be more than 550 feet northeast of Gilbert and in the Deer Valley area and nearly 550 feet near Eloy. No significant change will be apparent in the general shape of the regional water table.

The predicted regional water-table decline will average 100 feet from 1964 to 1984 (pl. 4). Water levels in the major areas of withdrawal will continue to decline at nearly the same rate. Northeast of Gilbert and in the Deer Valley area, the depth to water will be more than 650 feet, and south of Eloy and northwest of Litchfield Park, the depth to water will be more than 550 feet in 1984. The total increase in the depth to water in the 20-year period 1964–84 will range from about 10 feet along the Gila River west of Phoenix, where the water table is relatively shallow, to as much as 300 feet in the Stanfield area, where the water table will be more than 700 feet below the land surface. A great deal of lateral expansion will occur in the cores of depression in areas of greatest pumping.

The depth-to-water predictions correspond to nonpumping water levels obtained in the spring when there is relatively little pumping throughout the area (pl. 4). When a well is being pumped, the depth to water at the well is greater than when the well is not being pumped by the amount of drawdown required to allow water to flow into the well. Therefore, the pumping lift will exceed the predicted water-level depths by the amount of drawdown in the individual wells.

SUMMARY AND CONCLUSIONS

The amount of ground water pumped in the central Arizona area increased from 450,000 acre-feet in 1923 to 3,700,000 acre-feet in 1953. In 1964, the amount of ground water pumped decreased to 3,200,000 acre-feet. The total volume of water pumped from the ground-water reservoir from 1923 to 1964 was 80 million acre-feet, which constitutes a serious overdraft from the aquifer system. The overdraft is causing water levels to decline as much as 20 feet per year in places. If this trend continues, the cost of pumping will become more expensive and will result in the possible curtailment of agriculture.

An electrical-analog model was constructed to determine the effects of continued future withdrawal on the regional water levels in the area. The predicted water levels are based on the assumption that the model system will be valid for the next 20 years and that the areal distribution and amount of water pumped will remain constant.

An electrical-analog model is an electrical system that is analogous to the ground-water system. Resistors simulate the ability of the sediments to transmit water, and capacitors simulate the storage of water within the soil pores. The electrical-analog model is a general representation of the ground-water system in the lower Santa Cruz and Salt River basins. The accuracy of the results from the model is limited by the accuracy of the field data and by the applicability of certain simplifying assumptions.

The electrical-analog model was used to extrapolate water-level conditions to 1974 and 1984. The results of the extrapolation to 1974 indicate that water levels will decline at about the same rate as in the past. No change will occur in the general shape of the regional water table if the amount of water pumped remains the same as in the last 6 years, 1958–64. Further extrapolation of data to 1984 shows continued declines at about the same rates as before, and the cones of depression will continue to expand laterally. The total increase in the depth to water in the 20-year period 1964–84 will range from about 10 feet along the Gila River west of Phoenix to as much as 300 feet in the Stanfield area.

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