Electrical-Analog Analysis of Hydrologic Data for San Simon Basin Cochise and Graham Counties, Arizona

By NATALIE D. WHITE *and* WILLIAM F. HARDT

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ELECTRICAL-ANALOG ANALYSIS OF HYDROLOGIC DATA FOR SAN SIMON BASIN, COCHISE AND GRAHAM COUNTIES, ARIZONA

By NATALIE D. WHITE and WILLIAM F. HARDT

ABSTRACT

The San Simon basin is part of a northwest-trending structural trough that extends from south of the international boundary to Globe, Ariz.; it is bounded on the east by the Peloncillo Mountains and on the northwest and west by the Chiricahua, Dos Cabezas, and Pinaleno Mountains.

The present analysis is a supplement to an earlier study reported in U.S. Geological Survey Water-Supply Paper 1619-DD (White, 1963a). The purpose of this study is to make further analysis of the hydrologic data wherever possible and particularly to analyze the data by means of an electrical-analog model.

In the San Simon basin ground water is under artesian conditions in the lower aquifer and water-table conditions in the upper aquifer and also in the marginal zone where the upper and lower aquifers form a hydrologic unit. Analysis of well data gave a transmissibility of the lower aquifer of about 20,000 gallons per day per foot; analysis of the effects of ground-water withdrawal from the lower aquifer indicated a storage coefficient of about 0.1. A storage coefficient of this magnitude generally is indicative of a water-table aquifer. The significance of this result cannot be explained fully; however, because similar values were obtained for several increments of time—including long and short periods—the value of about 0.1 was used to estimate the amount of water available from the aquifers in the San Simon basin. For the lower aquifer, only the water made available by lowering the artesian head to the bottom of the confining layer was considered. The volume of water available under these conditions was determined to be about 10 million acre-feet.

The analogy between the flow of electrical current and laminar flow of fluid has been used as the basis for electrical-analog instrumentation, which may be used to study the nonsteady response of a nonhomogeneous aquifer. Use of electrical-analog methods provides a more thorough analysis of an entire hydrologic system under the complex conditions imposed by increased development.

The analog model is a physical entity that represents the shape, size, and hydrologic characteristics of the aquifer system. An electrical stimulus, representing the pumping of ground water, is applied to the model by excitation-response apparatus.

On the basis of an hypothesized amount and distribution of pumpage, the decline in ground-water levels in the San Simon basin until 1980 is predicted by electrical-analog-model analysis. The predicted decline from 1960 to 1980 is as much as 120 feet in the Bowie area and 160 feet in the San Simon area. By superimposing these decline data on known data for 1960, the altitude of the water level for 1980 is predicted. The correspondence of the projected water-level conditions to future field conditions depends directly on how closely the future pumpage conforms to the hypothesized values, both in areal distribution and the total for the basin.

INTRODUCTION

The hydrologic data available for the San Simon basin consist of drillers' logs of many wells, lithologic logs and sample analyses from a few wells, measurements of the water level in many wells for a long period of time, and measurements of the discharge of wells. These data were collected as a part of the U.S. Geological Survey's continuing statewide ground-water program in cooperation with the Arizona State Land Department; the data were studied and analyzed in 1960 and 1961 by several of the techniques in use by the Geological Survey. White (1963a) concluded that more data and further analysis were necessary to describe completely the effects of the prolonged use of ground water on the overall water resources of the basin. The present study is an attempt to analyze the original data more completely by using a recently developed technique; the additional data collected since the earlier study are also included.

LOCATION AND EXTENT OF THE AREA

The San Simon basin, near the southeast corner of Arizona (fig. 1), is part of a structural trough that extends from south of the international boundary to Globe, Ariz.; the trough includes the San Bernardino, San Simon, and Safford Valleys and also part of the Gila River and San Carlos River valleys. The trough trends slightly northeast to near Rodeo, N. Mex., and then northwest to Globe, Ariz. San Simon basin is bounded on the east by the Peloncillo Mountains, which extend southeastward into New Mexico; the Chiricahua, Dos Cabezas, and Pinaleno Mountains bound the basin on the northwest and west. In this study the southern boundary of the basin is chosen arbitrarily as the east-west line between Tps. 16 and 17 S. The San Simon and Safford basins merge on the north, and the two basins are separated arbitrarily by the line between Tps. 9 and 10 S. San Simon Creek enters the basin in New Mexico at an altitude of about 4,000 feet and flows into the Gila River in the Safford basin near Solomon at an altitude of about 3,000 feet. The gradient of San Simon Creek is about 20 feet per mile; on the sides of the valley the slopes are much greater, and gradients of about 80 feet per mile are common.

Ground-water development in the basin is centered in the areas of San Simon, which is near San Simon Creek on the east side of the basin, and Bowie, which is on the west side of the basin about 3 miles from the base of the Dos Cabezas Mountains. The two areas are hereafter referred to as the San Simon and Bowie areas, respectively. The well-numbering system used in Arizona is explained and illustrated in figure 2.

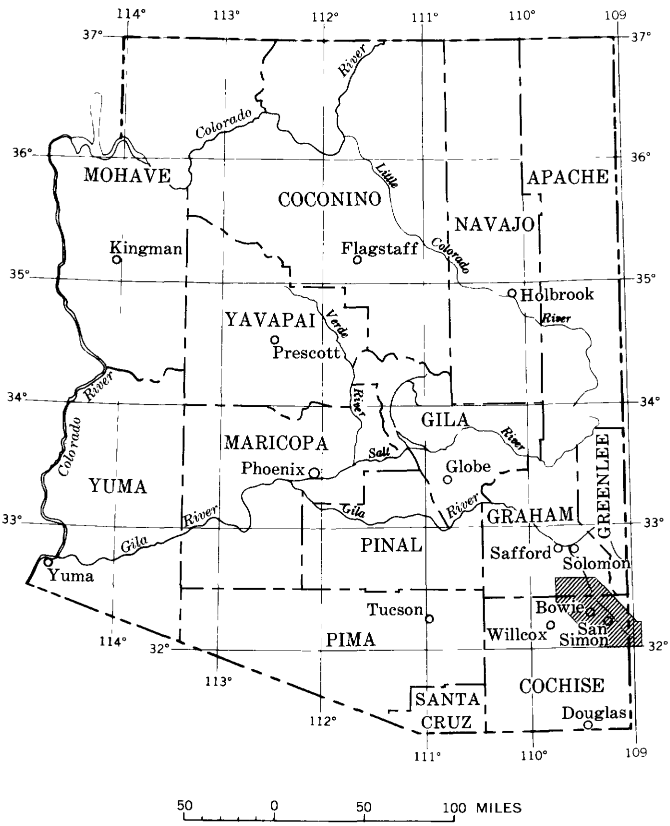
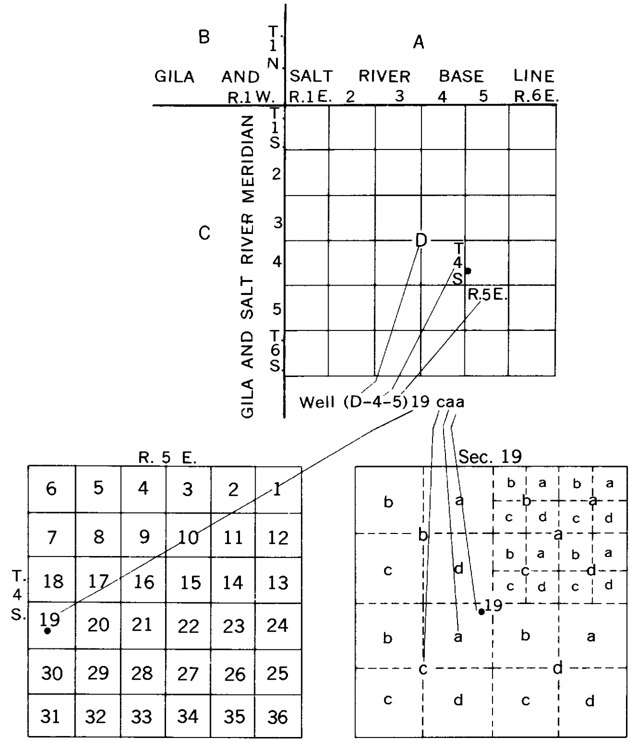


FIGURE 1.—Location of San Simon basin, Arizona.



The well numbers used by the Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants. These quadrants are designated counterclockwise by the capital letters A, B, C, and D. All land north and east of the point of origin is in A quadrant, that north and west in B quadrant, that south and west in C quadrant, and that south and east in D quadrant. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction, beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. In the example shown, well number (D-4-5)19caa designates the well as being in the NE$\frac{1}{4}$NE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 19, T. 4 S., R. 5 E. Where there is more than one well within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes.

FIGURE 2.—Sketch showing well-numbering system in Arizona.

PREVIOUS STUDIES

The geology and ground-water resources of the San Simon basin have been discussed in the several reports listed chronologically and summarized below.

1919. Schwennesen, A. T., Ground water in San Simon Valley, Arizona and New Mexico, with a section on agriculture by R. H. Forbes: U.S. Geol. Survey Water-Supply Paper 425–A. Describes the physiography and geology of the valley, the upper water horizon, and the deep artesian horizon of the San Simon and Bowie areas. The investigation, made in 1913 and 1915, included the measurement of the discharge and the pressure head for many of the artesian wells in the area. These data were used by White (1963a) and in the present study to construct the maps showing the altitude of the artesian-pressure surface as it was in 1915.

1947. Cushman, R. L., and Jones, R. S., Geology and ground-water resources of the San Simon basin, Cochise and Graham Counties, Arizona, with a section on quality of water by J. D. Hem: U.S. Geol. Survey open-file report. Describes the geology of the San Simon basin in relation to the occurrence of ground water and supplements the earlier report with additional water-level and discharge measurements. Also describes the chemical quality of the ground water in relation to use and in relation to recharge and source of dissolved matter.

1952. DeCook, K. J., San Simon basin, Cochise County, *in* Ground water in the Gila River basin and adjacent areas, Arizona—a summary, by L. C. Halpenny and others: U.S. Geol. Survey open-file report.
Summarizes available hydrologic data to spring 1952.

1957. Sabins, F. F., Geology of the Cochise Head and western part of the Vanar quadrangles, Arizona: Geol. Soc. America Bull., v. 68, p. 1315–1342. Describes in detail the geology of the two quadrangles, which include a small part of the San Simon basin.

1958. Gillerman, Elliot, Geology of the central Peloncillo Mountains, Hidalgo County, New Mexico, and Cochise County, Arizona: New Mexico Bur. Mines and Mineral Resources Bull. 57. Describes the volcanic and older sedimentary and granitic rocks of the Peloncillo Mountains, which bound the San Simon basin on the northeast.

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1959. Johnson, P. W., Test holes in southern Arizona valleys: Arizona Geol. Soc., Southern Arizona Guidebook 2, p. 62–65. Tabulation of data on deep test holes drilled in the San Simon basin.

1963. White, N. D., Analysis and evaluation of available hydrologic data for San Simon basin, Cochise and Graham Counties, Arizona: U.S. Geol. Survey Water-Supply Paper 1619–DD. Analyzes the available hydrologic and geologic data by standard methods in an attempt to determine if the data are adequate for quantitative analysis. The report concludes that more data and other methods of analysis are needed in order to evaluate fully the ground-water resources of the basin.

The San Simon basin is included on the Arizona Bureau of Mines geologic map of Cochise County (1959).

PURPOSE AND SCOPE

The present analysis is a supplement to an earlier study made by White (1963a). The purpose of this study is to analyze further the hydrologic data wherever possible and particularly to analyze the data by means of an electrical-analog model. The overall purpose of most ground-water investigations is to determine the regional effect of the withdrawal of ground water for long periods of time. It is not feasible to predict mathematically the effects of additional pumping in developed areas or of adding new areas of development in a basin; in this study, predictions of these regional effects are made by the use of an electrical-analog model.

METHODS OF ANALYSIS

The methods of analysis used in the earlier study of the San Simon basin (White, 1963a) included the preparation and interpretation of hydrographs for selected wells, contour maps of the altitude of the artesian-pressure surface for several different dates, and maps showing contours of the change in the altitude of the artesian-pressure surface for different increments of time. These techniques and the information gained from them are described in detail in the previous report and will not be discussed here. Other methods of analysis employed in the present study include the determination of hydrologic characteristics of the aquifer—on the basis of flow-net analysis, well data, and analysis of the effects of ground-water withdrawal—and the determination of the amount of water available from the hydrologic system in the basin. The most important method of analysis was the study of the effects of ground-water withdrawal by means of an electrical-analog model.

Prior to the development of ground water in a basin, the aquifer is in approximate hydrologic balance; that is, on a long-term basis, the amount of water moving into the basin is approximately equal to the amount moving out of the basin, although short-term inflow and outflow rates may be far out of balance. Water may move into and out of a basin as streamflow, underflow, and precipitation and by evaporation and transpiration. Water levels in the aquifer are a function of the difference between inflow and outflow and the characteristics of the materials through which the water is moving, particularly the permeability and porosity of the subsurface rocks. The flow, in its natural state, is from areas of higher to areas of lower head in the aquifer. If water levels are measured in the undisturbed state, flow lines drawn at right angles to the contours of equal head will show the direction of movement. Then, the equation $Q=TIL$—in which Q is the volume rate of ground-water movement, T the transmissibility, I the hydraulic gradient, and L the width of the section through which the water is moving—would describe the system. If the permeability and thickness of the subsurface materials are known or can be estimated, the amount of water moving through the basin can be determined; theoretically, this is the amount of water available from the basin without drawing from storage (see "Flow-Net Analysis," p. 10).

When new stresses are imposed on the system in the form of new discharge points, such as wells, the response of the ground-water system is a change in the flow pattern. When a well is being pumped, water is removed from the aquifer, the head in the aquifer surrounding the well is reduced, and water moves toward the well. The lowering of the water surface near a well is described as the cone of depression or cone of influence of the well; the amount of lowering decreases with distance from the well and increases with time. The response of the aquifer system to the withdrawal of water from a single well, a small closely spaced group of wells, or even from several widely scattered wells can be determined by using mathematical formulas (Ferris and others, 1962). These formulas can be used to determine aquifer characteristics on the basis of data from a pumping well and nearby observation wells; conversely, if the aquifer coefficients of transmissibility and storage are known, the effects of pumping can be predicted for short distances and for comparatively short periods of time. (See "Well-Data Analysis," p. 12, and "Analysis of the Effects of Ground-Water Withdrawal," p. 17).

All the foregoing methods provide valuable information that, to some extent, describes the ground-water system and its response to certain cause-and-effect relations. If many stresses are placed on an aquifer system, however, a complete solution of the response of the aquifer requires equations that are too complex for ordinary mathematical solution. However, inasmuch as the flow of fluid through porous media is analogous to the flow of current through conducting materials, an electrical model can be constructed that approximates an actual ground-water system and the stresses applied to it. The analog model can be built so that it is quantitatively proportional to the ground-water system by selecting the proper circuit components. The technique of electrical-analog-model analysis has been employed in this study to describe more fully the ground-water system of the San Simon basin and principally to predict the response of the system to complex stresses.

HYDROLOGIC SYSTEM OF THE BASIN

The subsurface material in the San Simon basin is predominantly alluvial fill, which consists of interfingering beds and lenses of clay, silt, sand, and gravel derived from erosion of rocks in the surrounding mountains. White (1963a) divided the alluvial fill into four geologic units—the "lower unit," the "blue clay unit," the "upper unit," and the "marginal zone." Hydrologically, the lower unit constitutes the "lower aquifer," and the upper unit constitutes the "upper aquifer." Figure 3 is a generalized section showing these units.

Ground water is under artesian conditions in the lower aquifer and under water-table conditions in the upper aquifer and in the marginal zone where the upper and lower aquifers form a hydrologic unit. A detailed description of the occurrence of ground water in the San Simon basin is given in a previous report (White, 1963a) and will not be discussed here.

HYDROLOGIC CHARACTERISTICS

In areas where most of the ground water withdrawn comes from storage and where further ground-water development is contemplated, it is important to ascertain the hydrologic characteristics of the aquifer that control the storage capacity, the amount of water that can be withdrawn, and the transmission rate of the water. The rate at which an aquifer will yield water to wells is a function of the permeability and transmissibility of the aquifer. The coefficient of permeability is defined as the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot. The coefficient of transmissibility is defined as the

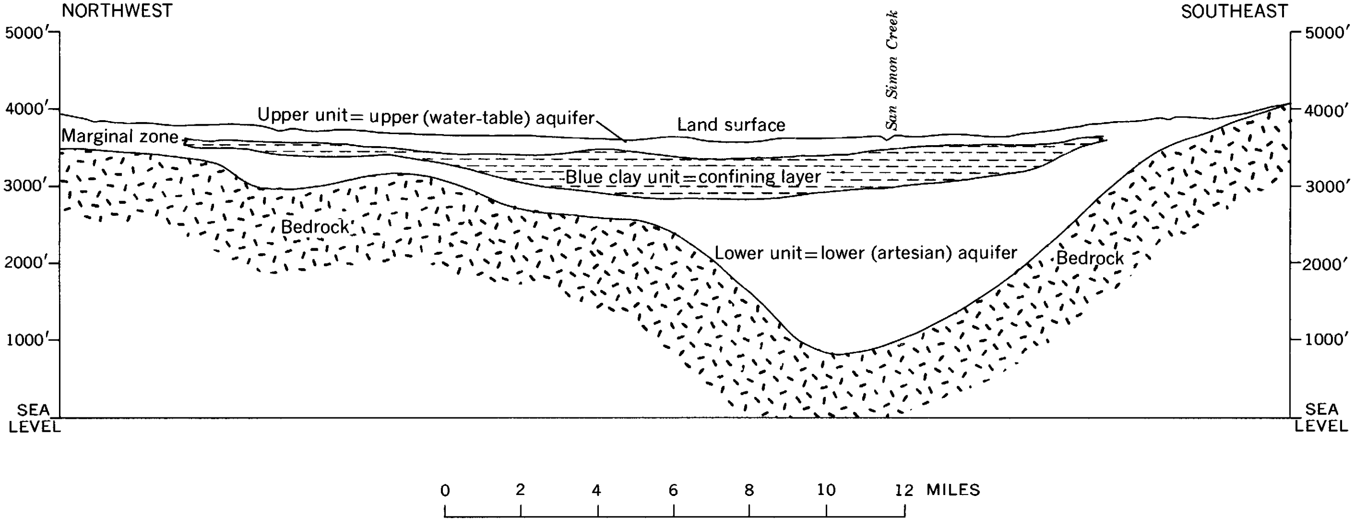

Figure 3.—Generalized geohydrologic section, San Simon basin, Cochise and Graham Counties, Arizona.

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 1 foot per foot. Thus, the transmissibility is equal to the permeability multiplied by the saturated thickness of the aquifer. The volume of water that the aquifer releases from or takes into storage per unit surface area per unit change in head normal to that surface is called the coefficient of storage. The ratio of the storage coefficient to the transmissibility of the aquifer determines the rate at which the cone of depression will form around a pumping well.

Many methods have been devised for determining the values of these aquifer characteristics. The methods used in this study and the results obtained are described below.

FLOW-NET ANALYSIS

Aquifer characteristics for large areas where the aquifer is areally nonhomogeneous can be determined by flow-net analysis. A flow net constitutes a graphical solution of the pattern of ground-water movement in the aquifer. It is composed of two sets of curves—equipotential lines that represent contours of equal head in the aquifer and stream lines or flow lines that represent the path a particle of water follows as it moves through the aquifer in the direction of decreasing head. Equipotential lines and flow lines intersect at right angles. Thus, the drop in head between two equipotential lines divided by the distance traversed by a particle of water moving along the flow paths between consecutive potential lines is the hydraulic gradient of the water surface in that part of the net. If the amount of water added to or removed from the aquifer is known, the coefficient of transmissibility of the aquifer can be computed. A simplified form of Darcy's law allows transmissibility to be calculated if the formula is applied to a part of the flow net where the rectangles formed by the intersecting flow lines and equipotential lines are nearly square, that is, the ratio of their length to their width is unity. The form of Darcy's law that may be applied to parts of a flow net is:

$$T=\frac{Q}{Nh}$$

where

T=coefficient of transmissibility, in gallons per day per foot;
Q=discharge, in gallons per day;
N=number of flow channels;
h=difference in head between two equipotential lines, in feet.

Conversely, if the transmissibility of the aquifer is known, the amount of water moving through the cross-sectional area between the equipotential lines where the squares are formed can be computed.

For those parts of the flow net where the intersecting equipotential lines and stream lines do not form squares, the transmissibility of the aquifer varies as the ratio of the length of the flow line in that area to the length of the flow line in the area where the flow net is nearly square. Taylor (1948) gives a more thorough discussion of the theory of flow nets, and several practical applications are given in the literature (Bennett and Meyer, 1952; White, 1963b).

Two flow nets based on contours of the water level for 1915 (pl. 1*A*) and for 1963 (pl. 1*B*) were prepared for the San Simon basin during the present study. The flow net based on the 1915 contours shows the direction of ground-water movement prior to any large-scale development in the basin (pl. 1*A*). In general, the flow lines show that ground water moves from the mountain fronts toward the center of the basin and from south to north along an axis parallel to San Simon Creek. The convergence of the flow lines along this axis and in an area northwest of Bowie may indicate an increase in aquifer transmissibility; however, the convergence may indicate the leakage of water from the lower (artesian) aquifer through the blue clay unit to the upper (water-table) aquifer. As indicated by the generalized geologic section (fig. 3), the thickness of the lower aquifer is greatest in the area beneath San Simon Creek. Therefore, the increase in transmissibility indicated by the converging flow lines probably is due to increases in aquifer thickness rather than to changes in permeability. Between Bowie and San Simon the flow net shows a slight steepening of the hydraulic gradient. This steeper gradient also may be the result of differences in aquifer transmissibility due to differences in thickness. There are two ways in which water may have been lost from the artesian aquifer in 1915. Several wells that tapped the lower aquifer were drilled as early as 1913. In the area of flowing wells near San Simon, most of the wells were allowed to flow continuously, and in the Bowie area the wells were pumped intermittently. In addition to the discharge of ground water at the surface, some inter-aquifer flow may have occurred. Most of the wells were cased only a few feet into the blue clay unit and were uncased through the rest of this unit and in the lower aquifer; some water from the lower aquifer was thus permitted to move upward in the borehole and into the blue clay unit.

The flow net for 1915 was constructed in such a way that the intersecting flow lines and equipotential lines form squares between the

3,700- and 3,660-foot contours. On the basis of an assumed transmissibility of the aquifer in this section of about 20,000 gpd (gallons per day) per foot (see "Well-Data Analysis" p. 12), application of the formula discussed above indicates that about 22 mgd (million gallons per day) or about 24,000 acre-feet of water per year moves through this cross-sectional area.

The flow net based on the contours of the altitude of the water level for 1963 (pl. 1*B*) shows the pronounced effects of the withdrawal of ground water from storage from 1915 to 1963. In the San Simon area, the convergence of the flow lines for the 1963 period is more distinct than it is for the 1915 period, and the shape indicates that water is being drawn into the area near San Simon to satisfy the pumping demands; in the Bowie area, a cone of depression has formed.

The flow net for the 1963 data (pl. 1*B*) was constructed in such a way that the intersecting flow lines and equipotential lines form squares between the 3,760- and 3,720-foot contours. Use of the formula indicates that about 14 mgd or about 15,000 acre-feet of water per year moves through this cross-sectional area. This pair of equipotential lines (3,760- and 3,720-foot) abuts the no-flow boundary southeast of the Bowie area. From this boundary to the northwest edge of the cone of depression formed by the 3,520-foot contour, some additional water moves between succeeding pairs of equipotential lines toward the depression. The amount probably is only about 2,000 acre-feet per year because the aquifer thins near the hard-rock outcrop or no-flow boundary. Additional water is moving toward the center of the valley from along the mountain front northwest of Bowie; the amount is estimated to be about 4.8 mgd or 5,000 acre-feet per year.

WELL-DATA ANALYSIS

The determination of hydrologic characteristics on the basis of the performance of wells scattered throughout an area can be accomplished in several ways. For the most part, these methods are based directly or indirectly on the specific capacity of the wells. In the present study the computations of hydrologic characteristics consist of estimating transmissibility from the specific capacity of individual wells by two methods and determining a yield factor for these wells from which the coefficient of permeability can be estimated. The specific capacity of a well is the relation of yield to drawdown, that is, its yield in gallons per minute per foot of drawdown caused by pumping. The yield factor of a well has been defined by Poland (1959) as the specific capacity divided by the saturated thickness of sediments from which the well draws water, multiplied by 100. Multiplication by the factor of 100 is for convenience of units only and has no significance in the evaluation of the characteristics. The specific capacity and the yield factor are functions not only of the hydrologic characteristics of the aquifer but also of the construction of the well itself, particularly the condition of the perforations in the casing, the distribution of the perforations within the saturated zone, and the depth that the well penetrates the saturated zone.

The specific capacities of the wells may be used to estimate the transmissibility of the aquifer for given values of the coefficient of storage from a graph based on the Theis (1935) nonequilibrium formula; this method has been described by Meyer (Theis and others, 1954). Another method for determining transmissibility from the specific capacity of a well was described by Thomasson and others (1960, p. 222). This method consists of multiplying the specific capacity by an empirical factor (determined experimentally) to obtain an approximate value for the coefficient of transmissibility. Thomasson and others (1960) also suggested an empirical relation between the yield factor and permeability. The results of computations by both methods for data for the San Simon basin are shown in table 1.

Table 1 shows values of the hydrologic characteristics estimated from data from individual wells grouped by area and by the zone or aquifer in which the well is completed. Although the numerical differences are not great and may not be significant, there is some indication that in the Bowie area the permeability of the marginal-zone aquifer may be less than that of the lower aquifer. The difference, however, may be due to the characteristics of the wells—particularly in relation to the saturated thickness of the aquifer penetrated. The wells in the marginal zone are open through a greater thickness of saturated material than those in the lower aquifer of the Bowie area. In the San Simon area, data were available for eight wells that penetrate the lower aquifer; however, all the wells were open through part of the blue clay unit and some were also open in the upper aquifer. Therefore, the hydrologic characteristics estimated from data for these wells would represent a combination of the characteristics of the upper aquifer, the blue clay unit, and the lower aquifer. The permeability estimated from data for these wells is somewhat lower than that for the lower aquifer or the marginal zone in the Bowie area.

Data were insufficient to compute average values of the hydrologic characteristics of the upper aquifer in the San Simon area. Data for three wells open only in the upper aquifer indicate permeabilities considerably higher than those for the lower aquifer.

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TABLE 1.—*Hydrologic characteristics estimated from well data*

Perforated zone: OH, open hole.
Blue clay: NP, blue clay not present.
Total saturated thickness: Based on water levels at time of specific-capacity measurement.
Specific capacity: Gallons per minute per foot of drawdown.

Yield factor: $\frac{\text{Specific capacity} \times 100}{\text{Saturated thickness penetrated by well, in feet}}$
Transmissibility: A, estimated from specific capacity after Theis and others (1954). B, estimated from specific capacity after Thomasson and others (1960).
Permeability: Estimated from yield factor after Thomasson and others (1960).

Well	Total depth (ft)	Perforated zone (ft)	Blue clay		Total saturated thickness (ft)	Saturated thickness			Discharge (gpm)	Draw-down (ft)	Date meas-ured	Specific capacity	Yield factor	Transmissibility (gpd per ft)		Perme-ability (gpd per sq ft)
			Top (ft)	Bottom (ft)		Upper aquifer	Blue clay	Lower aquifer						A	B	
BOWIE AREA																
Lower aquifer																
(D-12-28) 22cdc	660	550–648	185	550	110	0	0	110	1,170	76	6–51	15	13.6	28,000	25,000	230
		OH 648–660							770	72	5–52	11	10.0	20,000	19,000	170
33abc	550	403–550	148	283	147	0	0	147	860	48	5–52	18	12.2	34,000	30,000	204
									830	45	7–52	18	12.2	34,000	30,000	204
35cdc	620	475–620	255	475	145	0	0	145	632	76	5–52	8	5.5	14,000	14,000	93
									506	100	5–53	5	3.4	8,000	8,000	58
36ccc	715	410–650	180	370	305	0	0	305	1,600	129	4–53	12	3.9	22,000	20,000	67
		OH 650–715														
(D-13-29) 20acc	616	320–560	198	280	296	0	0	296	2,260	154	8–56	15	5.1	28,000	25,000	86
		OH 560–616														
27acc	1,040								1,490	96	5–52	15		28,000	25,000	
									1,227	93	5–53	13		23,000	22,000	
28bcc	629	365–500	189	313	234	0	0	234	2,000	190	12–52	11	4.7	20,000	19,000	80
		OH 530–629														
Average												13		23,500	21,500	132

Marginal zone

(D-13-28) 9bcc	700		NP						1,460	92	8-56	15		28,000	25,000	
15ccc	455	242-452	NP		210				1,210	132	8-52	9	4.2	16,000	15,000	72
16ccc	895	437-895	NP		458				2,150	150	12-52	14	3.1	25,000	24,000	53
16dcc	671	200-671	NP		471				2,100	100	1-53	21	4.5	39,000	36,000	76
22acc	465	221-441	NP		244				900	93	5-53	10	4.1	18,000	17,000	70
		OH 441-465														
22dcc	500	185-470	NP		315				2,200	189	7-53	12	3.8	22,000	20,000	65
		OH 470-500														
23acd	511	193-493	NP		318				2,250	100	8-60	22	6.9	41,000	37,000	117
		OH 493-511														
23dcc	530	200-440	NP		330				3,000	210	5-53	14	4.3	25,000	24,000	73
		OH 440-530														
24ccc	520	250-300	NP		220				2,131	120	2-60	18	8.2	34,000	30,000	140
		350-480														
		OH 480-520														
Average												15		27,500	25,300	83

SAN SIMON AREA

Lower aquifer

(D-13-31) 34cda	760	100-760	121	389	660	21	268	371	350	45	4-57	8	1.2	14,000	14,000	20
(D-14-31) 3aba	735	100-160	160	400	395	60	0	335	1,300	58	9-58	22	5.5	41,000	37,000	95
		400-615														
		OH 615-735														
10aaa	750	495-750	102	535	255	0	40	215	1,500	140	3-59	11	4.3	20,000	19,000	73
11cca	712	OH 368-712	96	413	344	0	45	299	500	48	6-48	10	2.9	18,000	17,000	49
14ddb	755	500-755	90	500	255	0	0	255	110	16		7	2.7	12,000	12,000	47
21bcc	711	80-711	60	496	631	0	416	215	900	210	3-51	4	.6	7,000	7,000	11
23cdc	744	OH 133-744	131	500	611	0	367	244	475	42	5-52	11	1.8	20,000	19,000	31
35bcc	800	500-800	150	518	300	0	18	282	1,350	91	12-58	15	5.0	28,000	25,000	85
Average												11		20,000	18,750	51

TABLE 1.—*Hydrologic characteristics estimated from well data*—Continued

Well	Total depth (ft)	Perforated zone (ft)	Blue clay		Total saturated thickness (ft)	Saturated thickness			Discharge (gpm)	Draw-down (ft)	Date meas-ured	Specific capacity	Yield factor	Transmissibil-ity (gpd per ft)		Perme-ability (gpd per sq ft)
			Top (ft)	Bottom (ft)		Upper aquifer	Blue clay	Lower aquifer						A	B	
Marginal zone																
(D-14-32) 16cab3	465	129–406 411–460	NP		253				135	4	5–57	34	13.4		58,000	230
16cab4	470	246–470	NP		224				100		1–63	30	12.5		51,000	212
									300	27	1–63	11	4.9	20,000	19,000	83
Upper aquifer																
(D-13-30) 24cdc	120		NP		52				269	9	8–56	30	57.6		51,000	979
(D-13-31) 29ddd	100		NP		47				240	37	4–50	6.5	13.8		11,000	235
(D-14-31) 6aad	98	65–98	NP		33				275	22	8–54	12	36.4		20,000	620

ANALYSIS OF THE EFFECTS OF GROUND-WATER WITHDRAWAL

When water is withdrawn from an artesian aquifer by flowing or pumping wells, the pressure head in the aquifer is lowered concurrently with the withdrawal of water. This lowering of the pressure head around a well is called a cone of depression; as the cones from many wells in an area begin to overlap, a regional cone develops that eventually may encompass the entire basin. The depth and the spread of this cone are dependent on the rate of withdrawal of water, the length of time of the withdrawal, and the transmission and storage characteristics of the aquifer. Specifically, the volume of the cone is directly proportional to the amount of water withdrawn from the aquifer and inversely proportional to the storage coefficient of the aquifer. The change in pressure head multiplied by the incremental area of aquifer surface over which it is effective determines the volume of the cone.

Several maps showing contours of the change in the artesian pressure in the San Simon basin for different intervals of time are available (White, 1963a). In the present study, several additional maps were prepared for different intervals of time. The volume of the change in artesian pressure was determined by planimetering the surface area along successive contours and multiplying this area by the amount of change represented by the contours. This computation resulted in a "volume of head change" for a particular period of time. The volume of water withdrawn from the aquifer for the same time period divided by this volume of head change gives a value for the storage coefficient of the aquifer. The results of this analysis indicate a storage coefficient of about 0.1. A coefficient of this magnitude generally is indicative of a water-table aquifer. The significance of this result cannot be explained fully, but several factors are involved.

In the San Simon basin, as described earlier, artesian and water-table aquifers are present. For the most part, water-level changes were measured in wells that penetrate the lower (artesian) aquifer, and the maps described above were based only on these data. However, many of the wells are open in the upper (water-table) aquifer and, therefore, may be taking water from it as well as from the artesian aquifer. The blue clay unit also may be contributing some water over a long period of time. In addition to the actual withdrawal of water from the artesian and water-table aquifers due to well construction, there may be some leakage of water into the confining layer and, subsequently, into the artesian aquifer in places and at times when the artesian-pressure head is lower than the static water level in the upper aquifer. This state may exist during pumping of the artesian wells. Conversely, there may be leakage of water from the artesian aquifer through the confining layer to the water-table aquifer under nonpumping conditions.

No definite conclusion can be reached regarding the significance of the phenomena described above. However, because similar values were obtained for several increments of time, including long and short periods, the coefficient of storage of about 0.1 will be used until further study or more data provide a basis for a more precise coefficient.

VOLUME OF WATER AVAILABLE FROM THE SYSTEM

The storage capacity of an aquifer is defined as the volume of space available to contain water; that is, the total volume of saturated sediments multiplied by their porosity. The porosity of a rock or soil is its property of containing interstices (Meinzer, 1923, p. 19) and is expressed as the percentage of the aggregate volume of the interstices to the total volume. However, because a large part of this stored water will be held in the acquifer by molecular attraction or other forces of retention, the amount that can be extracted from the aquifer is much less than the total storage capacity. The coefficient of storage of an aquifer is defined 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 (Ferris and others, 1962, p. 74). In an artesian aquifer, the water released from or taken into storage is governed solely by the compressibility of the aquifer material and of the water. Thus, the volume of water removed from the aquifer divided by the product of the head change and the area of aquifer surface over which it is effective correctly determines the storage coefficient of the aquifer. In a water-table aquifer, the volume of water released from or taken into storage is due not only to the compressibility of the aquifer and of the water but also to gravity drainage or refilling of the zone through which the water moves. In most water-table aquifers the amount of water attributable to the compressibility factor is so small in comparison to the amount obtained from gravity drainage that it can be ignored. Although no rigid limits can be established, the storage coefficients range from 0.00001 to 0.001 for artesian aquifers and from 0.05 to 0.30 for water-table aquifers.

As described in the section "Analysis of the Effects of Ground-Water Withdrawal" (p. 17), the storage coefficient of the lower aquifer is in the order of magnitude of 0.1—a value more nearly indicative of water-table than artesian conditions. Because data are insufficient to determine any other values for this coefficient, this value is used to calculate the amount of water available from the aquifers in the basin.

The determination of the thickness and extent of the different aquifers was based on drillers' logs of wells. The volume of sediments available in which to store water in the upper aquifer and the marginal zone was determined from the saturated thickness, based on the depth to water as measured in the wells. For the lower aquifer, only the water available by lowering the artesian head to the bottom of the confining layer was considered because it probably would not be economically feasible to pump from depths greater than at the bottom of the confining layer. The change in head from the present level of the artesian-pressure surface to the bottom of the confining layer was determined by subtracting contours on the altitude of the bottom of the blue clay unit from contours on the altitude of the artesian-pressure surface for spring 1964. This difference is the amount of artesian head remaining; subsequently, contours of this difference were constructed (pl. 1*C*) and planimetered to aid in determining the volume of available water. The volume of the blue clay unit was determined by means of the contours of the thickness of this unit (White, 1963a).

By using the calculated coefficient of storage of 0.1, as explained in a preceding paragraph, it was determined that about 10 million acre-feet of water is available from the aquifers in the San Simon basin. In addition, over a long period of time some water probably will drain from the large volume of blue clay; however, it is not possible to determine the amount with the data available.

Although 10 million acre-feet of water is theoretically available to be pumped from the basin, the actual volume that can be withdrawn may be contingent upon several other physical and economic factors—such as the depth and distribution of wells, capacity of pumps, depth from which water is pumped, and operation of the ground-water reservoir at optimum rates and schedules of pumping. Another important factor that must be considered is the use of a single value for the coefficient of storage applied to the three aquifers; if this value is not correct, then the amount of water available may be greatly different. The above volume, however, is the best estimate possible with the available information.

ANALYSIS OF THE HYDROLOGIC SYSTEM BY ELECTRICAL-ANALOG MODEL

The mathematical equations necessary to describe completely all the parameters and stresses on the hydrologic system become more complex as ground water is developed in a basin. When only a small amount of ground water is developed, the effects are chiefly local and can be described rather simply by making certain assumptions and idealizations, such as uniform thickness and infinite areal extent of the aquifers and homogeneous and isotropic water-bearing materials. As the effects of ground-water development progressively spread over larger areas and begin to overlap, these idealizations are no longer valid, and the mathematical methods employing them become wholly inadequate. Thus, to provide a more thorough analysis of the entire hydrologic system under the complex conditions imposed by increased development, more complex techniques must be used. Skibitzke and Brown (1961) state: "Electronic computing equipment, particularly the electrical-analog model, seems well adapted for solving the complex mathematics of the partial differential equations involved in describing hydrologic systems. Computer techniques remove the analytical limitations imposed by human frailties in handling mathematics. * * * Theoretically, these computers make possible the solution of almost any problem that might arise in hydrologic studies. Although very real economies in cost and time may be achieved the principal advantage of computer solution is completeness."

The San Simon basin was one of the first ground-water areas in the United States to be analyzed by electrical-analog methods. Consequently, in constructing this model, much of the present-day methodology for electrical-analog models was formulated; these methods now have been improved greatly by the Analog-Model Unit of the Geological Survey in Phoenix, Ariz. For example, the San Simon model was built in a frame as a series of wires spaced 1 inch apart joined together by resistors and capacitors. A high voltage was required to operate the model because of substantial electrical loss in the lines. Analog models are now constructed on peg boards with a plan-view map of the area showing rivers, lakes, mountains, and towns. Construction methods have been improved, and currently, models can be built in a few days to a week after converting hydrologic data into electrical components.

The authors appreciate the work of the personnel of the U.S. Geological Survey Analog-Model Unit—that of the present staff, under the direction of E. P. Patten, and of those who preceded them. The analog model of the San Simon basin (see "Construction of the Model" p. 21) originally was built under the general supervision of H. E. Skibitzke. The model was constructed by C. S. English under the direct supervision of A. E. Robinson. Subsequently, B. J. Bermes, while in charge of the Analog-Model Unit, made several test operations of the San Simon model and formulated methods for operation of analog models.

BASIS OF ELECTRICAL-ANALOG MODEL

The analogy between the flow of electrical current and laminar flow of fluid has been used as the basis for developing electrical-analog instrumentation which may be used to study the nonsteady response of a nonhomogeneous aquifer. The theory and the instrumentation have been described in detail by Skibitzke (1960). Briefly, the electrical-analog unit consists of an analog model, excitation-response apparatus, and an oscilloscope. The model is constructed from a series of resistors and capacitors, and its geometric configuration is a replica of the geologic structure of the basin. The electrical resistors are inversely proportional to the transmissibility, and the capacitors are in direct ratio to the storage coefficient of the aquifer. In an electrical circuit a resistor impedes the free flow of electricity in a manner equivalent to that in which the subsurface materials impede the free flow of water through the aquifer; whereas, a capacitor stores electrical energy in a manner comparable to the storage of water in an aquifer. Likewise, voltage and amperage in an electrical circuit are the equivalents of head and the volume rate of flow in the ground-water system. Thus, stress on the ground-water system is expressed by the electrical equivalents in the model by varying the voltage and amperage through the circuit. An oscilloscope is connected to the model at points where it is desired to determine the response of the aquifer to changes in stress on the system. The response of the aquifer model at each selected point is shown on an oscilloscope screen in the form of a moving beam of light that has been accurately calibrated in terms of voltage (vertically) and time (horizontally). A camera is triggered to take a picture at the same instant that the light beam moves across the screen; the resulting picture is in the form of a time-voltage graph. Application of the proper constants to the graph converts the electrical units into feet of change in water level with time, and the result is a hydrograph of the response of the water level at that point. Hydrographs at many points give a complete picture of the response of the aquifer to whatever stress has been simulated in the model. Figure 4 shows an electrical-analog unit in operation.

CONSTRUCTION OF THE MODEL

The first step in a study of a hydrologic system by electrical-analog methods is the synthesis of as good an interpretation of the subsurface geology of the area as the available geologic and hydrologic data will allow. These data and interpretations are then used to construct an electrical-analog model of the geohydrologic characteristics of the area.

For the San Simon basin, the data available from which to interpret the subsurface geology consisted of many drillers' logs of wells and a few sample analyses from well cuttings. Only meager data were available to determine the configuration of the bedrock floor of the

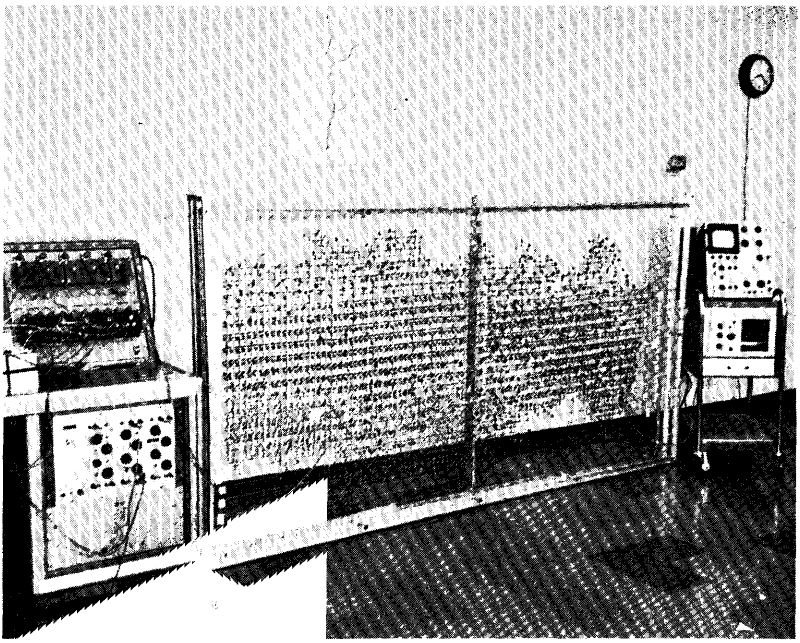

FIGURE 4.—A computer installation.

valley. The hydrologic data available consisted of measurements of the pressure head in artesian wells for 1915; periodic measurements of water levels in selected wells in the water-table and the artesian aquifers, many from 1940 through 1964; and measurements of discharge in flowing and pumped wells. In addition, data were available for computing the specific capacity of a few wells, and these have been used to estimate the coefficients of transmissibility and permeability of the aquifer (table 1).

An electrical-analog model is constructed in a shape similar to that of the aquifer system under study. The thickness of the aquifer and its water transmission and storage characteristics are represented by electrical components that are analogous to the hydrologic system. The San Simon model was constructed on a scale of 1 inch = ½ mile, with junctions at 1-inch intervals. For the artesian aquifer each junction was formed by four resistors and a capacitor. The lower (artesian) aquifer and the marginal zone were modeled as a continuous unit, and the blue clay unit was modeled separately; thus, a two-layer model was constructed The marginal zone and the upper aquifer are only a small part of the entire hydrologic system of the basin.

The amount and distribution of ground-water withdrawal from the aquifers were simulated as a single well, or amperage pulse, at the center of a 4-square-mile grid. This results in an array of pumping wells at 2-mile intervals.

The lower aquifer was simulated, by means of a network of resistors and capacitors, as a system through which two-dimensional unsteady flow occurred. In the construction of the model, owing to lack of data to prove otherwise, the lower aquifer was assumed to be of uniform permeability. Therefore, the ability of the aquifer to transmit water is directly proportional to the thickness of the aquifer at any given place. As determined by the analysis of well logs (fig. 3), the lower aquifer is thickest in the center of the basin and thins toward the edges. Thus, resistor values were chosen to simulate the increasing transmissibility from the edges toward the center of the basin. Along the edges of the basin, where the aquifer is thinnest, resistors of 1 million ohms were placed in the model at 1-inch junctions representing half a mile in the aquifer. Resistors of 680,000, 470,000, 220,000, 150,000, and 100,000 ohms were put into the model as the aquifer thickens toward the center of the basin.

The coefficient of storage, under artesian conditions and for loosely cemented aquifers reasonably free from clay, is a function of the elasticity of water and of the aquifer skeleton. Its value may be determined from the following equation (Jacob, 1950, p. 334, example 4):

$$S=\theta\gamma_0 b\beta\left(1+\frac{\alpha}{\theta\beta}\right)$$

where

S=coefficient of storage of the aquifer, a decimal fraction;
θ=porosity, a decimal fraction;
γ_0=specific weight of water;
b=thickness of artesian aquifer, in feet;
β=reciprocal of the bulk modulus of elasticity of water (3.3×10^{-6} square inches per pound);
α=reciprocal of the bulk modulus of elasticity of the aquifer skeleton, in square inches per pound.

The product $\theta\gamma_0 b\beta$ would equal the storage coefficient if the aquifer were incompressible. Variations in aquifer thickness (b) determine varying values for the storage coefficient. Capacitors built into the model representing storage in the aquifer ranged from 50 $\mu\mu f$ (micromicrofarads) for the thinnest part of the aquifer to 220 $\mu\mu f$ for the thickest part.

The blue clay unit was modeled as a system through which unidirectional vertical movement would occur in response to change in artesian pressure in the lower aquifer. Initially, a vertical permeability of

0.25 gpd per sq ft was assumed for the clay unit. Although this permeability is moderately low per unit area, it probably represents a significant amount of water because of the extensive areal distribution of the blue clay unit.

After construction, the model must be checked and, if necessary, adjusted. When the simulated water-level changes from the model correlate with historical water-level declines resulting from actual pumping rates, it is a reasonable assumption that the model is analogous to the hydrologic system.

The electrical-analog model for the San Simon basin was checked against a map showing the net change in water levels from 1915 to 1960 (White, 1963a). The data from the early trial runs of the model did not correlate closely with the field data. Inspection and study of the model indicated that the vertical permeability of the clay unit as initially constructed into the model was too high, and, thus, the model indicated a greater release of water from the clay to the lower aquifer than actually occurred. A lower coefficient of transmissibility of the clay simulated a lesser amount of water draining to the lower aquifer, and the water-level-decline data from the model more closely corresponded to the field data. However, in places, the simulated change in water levels still did not match the field data. It was determined that these deviations were caused by the simulation of the pumping from many wells as a single unit at a junction in the model. Consequently the pumping pattern was redistributed. After these adjustments were made in the model, simulated data were produced for the net change in water levels from 1915 to 1960 (pl. 1*D*) that closely corresponded to the field data, and the model was ready for use.

A significant and useful part of the contour map of the change in water levels from 1915 to 1960 (pl. 1*D*) derived from the model is the line of zero decline around the perimeter of the pumped area. This information generally is not available from field data and thus does not show on the 1915–60 decline map from actual data (White, 1963a).

USING THE ANALOG MODEL

The analog model is a physical entity that represents the shape, size, and hydrologic characteristics of the aquifer system. An electrical stimulus, representing the pumping of ground water, is applied to the model by excitation-response apparatus. The graph on the oscilloscope screen represents the drawdown of the water level that results when wells pump a certain amount of water for a given period of time at a particular point on the model. If a hydrograph

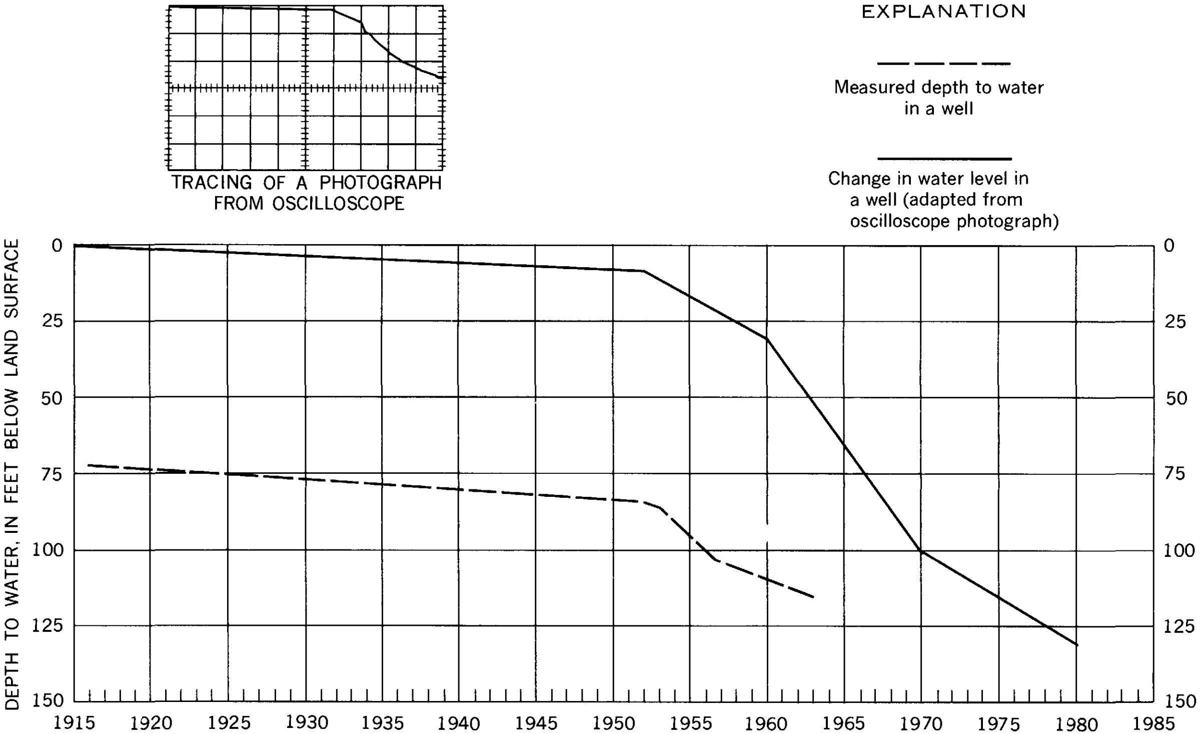

Figure 5.—Results of electrical-analog-model analysis in graphical form.

of any particular junction is desired, a photograph (fig. 5) is taken of the trace on the oscilloscope screen. The trace data are replotted to a larger scale as a water-level hydrograph that shows the amount of change in water level at any time during the test period (fig. 5). Figure 5 shows an example of the correlation between the simulated and measured water level. By recording the simulated water-level changes at many points, maps may be constructed showing contours of equal water-level change in the aquifer at any predetermined time since pumping began.

The projected net change in water level from spring 1960 to spring 1980 was determined from the analog model to predict the water level in 1980. The pumpage for this period was estimated for each 4-square-mile area in the basin (pl. 2*A*); the estimates are based on the increased pumpage trend of the last few years. The pumpage in the San Simon basin in 1960 was about 60,000 acre-feet; the pumpage from 1960 to 1980 is estimated to be 2 million acre-feet. The correspondence of the projected water-level changes to future field conditions depends directly on how closely the future pumpage conforms to the hypothesized pumpage, either in areal distribution or the total for the basin.

The electrical-analog model of the basin was programmed to produce water-level changes from 1915 to 1980, on the basis of known pumpage for 1915 to 1960 and the estimated pumpage as described above for 1960 to 1980. The drawdowns in water level from 1915 to 1980 were determined and were plotted on a map of the San Simon basin; the contours of equal change in water level were then constructed. The maps showing contours of equal change from 1915 to 1960 (pl. 1*D*) and from 1915 to 1980 were superimposed, and a new set of values was determined for the change in water level from 1960 to 1980. Contours of equal change in water level for this period are shown in plate 2*B*. This map shows the general magnitude of anticipated water-level changes in the basin to 1980; the maximum projected decline in the Bowie area is about 120 feet and in the San Simon area about 160 feet.

The contours of the altitude of the water level in the San Simon basin for 1980 were prepared from data taken from the model (pl. 2*C*). In general, the contour map for 1980 is similar to that for spring 1960 (White, 1963a). The main areas of depression in the water surface are near Bowie and San Simon, but the 1980 map shows the expansion of the cones toward the previously undeveloped area between the two towns and also toward the bedrock outcrops at the edges of the basin.

SUMMARY AND CONCLUSIONS

In the northwest-trending San Simon basin the subsurface material is predominantly alluvial fill, which consists of interfingering beds and lenses of clay, silt, sand, and gravel derived from erosion of rocks in the surrounding mountains. The alluvial fill has been divided into four geologic units—the "lower unit," the "blue clay unit," the "upper unit," and the "marginal zone." Hydrologically the lower unit constitutes the "lower aquifer," and the upper unit constitutes the "upper aquifer." Ground water is under artesian conditions in the lower aquifer and under water-table conditions in the upper aquifer and in marginal zone where the upper and lower aquifers form a hydrologic unit.

In areas, such as the San Simon basin, where most of the ground water withdrawn comes from storage and where further ground-water development is contemplated, it is important to ascertain the hydrologic characteristics of the aquifer that control the storage capacity, the amount of water that can be withdrawn, and the transmission of water. The rate at which an aquifer will yield water to wells is a function of the permeability and transmissibility of the aquifer. The volume of water that the aquifer releases from or takes into storage per unit surface area per unit change in head normal to that surface is called the coefficient of storage. The amount of water available for withdrawal from an aquifer system is a function of the storage capacity and the coefficient of storage of the aquifer.

For the San Simon basin, analysis of well data gave a value of transmissibility of the lower (artesian) aquifer in the magnitude of about 20,000 gpd, and analysis of the effects of ground-water withdrawal from the lower aquifer indicated a storage coefficient of about 0.1. A storage coefficient of this magnitude generally is indicative of a water-table aquifer. The significance of this result cannot be explained fully; however, because similar values were obtained for several increments of time—including long and short periods—the coefficient of about 0.1 was used to determine the amount of water available from the aquifers in the San Simon basin. For the lower aquifer, only the water available by lowering the artesian head to the bottom of the confining layer was considered because it probably would not be economically feasible to pump from depths greater than at the bottom of the confining layer. The total volume of water available under these conditions was determined to be about 10 million acre-feet. Although this volume of water is theoretically available for pumping from the basin, the volume that can be withdrawn may be contingent upon several other physical and economic factors—such as depth of wells, distribution of wells, capacity of pumps, depth from which water is pumped, and operation of the ground-water reservoir at optimum rates and schedules of pumping. Another important factor that must be considered is the use of a single coefficient of storage applied to the three aquifers; if this coefficient is incorrect, then the amount of water available may be very different.

As the effects of ground-water development progressively spread over larger areas and begin to overlap, it is necessary to employ more complex techniques to provide a thorough analysis of the hydrologic system than when only a small amount of ground water was developed.

The analogy between the flow of electrical current and laminar flow of fluid has been used as the basis for developing electrical-analog instrumentation, which may be used to study the nonsteady response of a nonhomogeneous aquifer. An electrical-analog unit consists of an analog model, excitation-response apparatus, and an oscilloscope. The analog model is a physical entity that represents the shape, size, and hydrologic characteristics of the aquifer system. An electrical stimulus, representing the pumping of ground water, is applied to the model by excitation-response apparatus at a given point, and the results are shown on an oscilloscope screen in the form of a time-voltage graph. Application of the proper constants to the graph converts electrical units into feet of change in water level with time, and the result is a hydrograph of the water level at that point. Hydrographs at many points give a complete picture of the response of the aquifer to whatever stress has been simulated in the model.

The San Simon model was constructed as a two-layer model—the lower aquifer and the marginal zone as a continuous unit and the blue clay unit separately—at a scale of 1 inch = ½ mile. The lower aquifer was simulated as a system through which two-dimensional unsteady flow occurred and was assumed to be of uniform permeability. The blue clay unit was modeled as a system through which unidirectional vertical movement would occur in response to change in artesian pressure in the lower aquifer.

On the basis of an hypothesized amount and distribution of pumpage from 1960 to 1980, the decline in ground-water levels in the San Simon basin is predicted to be as much as 120 feet in the Bowie area and 160 feet in the San Simon area. By superimposing these decline data on known data for 1960, the altitude of the water level for 1980 is predicted. The correspondence of the projected water-level conditions to future field conditions depends directly on how closely the actual future pumpage conforms to the hypothesized values, both in areal distribution and in the total for the basin. The model analysis can show only what the ground-water conditions will be in the future under the assumed conditions.

In addition to the specific conclusions relative to future hydrologic conditions that were determined from the analog-model analysis, the study also has shown the potential advantages of electrical-analog modeling to a hydrologic study, particularly if more adequate data were available. The analysis reported here indicated areas where data were inadequate and consequently indicated the value of electrical-analog-model analysis in the early stages of a geohydrologic study.

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