TEXAS WATER DEVELOPMENT BOARD

REPORT 28

ANALOG MODEL STUDY OF THE HUECO BOLSON NEAR EL PASO, TEXAS

By

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City of El Paso

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FOREWORD

On September 1, 1965 the Texas Water Commission (formerly, before February 1962, the State Board of Water Engineers) experienced a far-reaching realignment of functions and personnel, directed toward the increased emphasis needed for planning and developing Texas' water resources and for administering water rights.

Realigned and concentrated in the Texas Water Development Board were the investigative, planning, development, research, financing, and supporting functions, including the reports review and publication functions. The name Texas Water Commission was changed to Texas Water Rights Commission, and responsibility for functions relating to water-rights administration was vested therein.

For the reader's convenience, references in this report have been altered, where necessary, to reflect the current (post September 1, 1965) assignment of responsibility for the function mentioned. In other words credit for a function performed by the Texas Water Commission before the September 1, 1965 realignment generally will be given in this report either to the Water Development Board or to the Water Rights Commission, depending on which agency now has responsibility for that function.

Texas Water Development Board

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Chief Engineer

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ABSTRACT

The water needs of the El Paso district, including Ciudad Juarez, Mexico, are dependent largely on ground water. In 1964 about 75 percent of the water used was from the Hueco bolson. Although the supply of ground water in the bolson is large, the supply is being depleted or mined. Consequently, proper management of this resource requires a more thorough analysis of the hydrologic system in order to evaluate the consequences of the many ways in which the reservoir might be developed.

The electrical-analog model, the theory of which is based on an analogy between the flow of electricity and the flow of ground water, is the most effective and most economical tool with which to make a quantitative analysis of the ground water in the Hueco bolson.

The accuracy and reliability of the model was assessed by comparing the water-level changes computed by the model for the periods 1903-53 and 1903-63 with the changes determined from field data for the same periods.

On the basis of a pumping program suggested by the El Paso Public Service Board, the changes in water levels in the bolson for the periods 1903-75 and 1903-90 were predicted by the electrical-analog model. The maximum decline by 1975 would approximate 70 feet in the northern part of the bolson, and by 1990, 110 feet in the same area.

ANALOG MODEL STUDY OF THE HUECO BOLSON NEAR EL PASO, TEXAS

INTRODUCTION

The availability of water in the El Paso district to meet the rapidly growing demands of industry and of an increasing population is of deep concern not only to residents of the district but also to the state and federal governments, because of the relation of water supply to future economy and security.

In 1965, the water needs of the district, as well as those of Ciudad Juarez, were dependent chiefly upon ground water, the principal source being the Hueco bolson. Although the supply of fresh ground water in the bolson is large--about 7.5 million acre-feet in the Texas part of the Hueco bolson--the amount of water withdrawn from the bolson each year exceeds the natural recharge. Consequently, the fresh ground-water supply is being depleted or mined.

Proper management of the ground-water resources in the district depends upon where and how a particular development will fit into the present and future operation of the ground-water reservoir in relation to its existing development and to various plans for future development.

Although much basic geologic and hydrologic data have been collected in the El Paso district since 1935, techniques for analyzing these data relied heavily upon time-consuming mathematical methods. In the use of these methods the ground-water-flow system was highly idealized. Hence, only limited predictions could be made as to how the idealized aquifer would respond to pumping of a small group of wells for limited time periods and over limited distances. As development of the aquifer increased and the effects progressively spread over larger areas and began to overlap, idealizations (such as those concerning the uniform thickness, infinite areal extent, homogeneity, and isotropy of the water-bearing material) were no longer valid; and the mathematical methods proved wholly inadequate. The inadequacy was not only in the complexities of the mathematical analyses and computations, but also in evaluating the consequences of the many ways in which the reservoir might be developed. Thus, more advanced techniques are the prerequisite for a more exact definition of the ground-water system. A better definition of the flow system is important in view of the foreseeable future needs of the district, and the fact that all the known fresh-water supplies in the El Paso area are now being utilized. Because these supplies are limited, they must be developed to the maximum and with the least possible contamination by the more highly mineralized water that everywhere underlies, in some places overlies, and in most places adjoins the fresh water.

Because of the improved analytical methods it employs, the electrical-analog model probably is the most effective as well as the most economical tool for making a quantitative analysis of the ground-water resources of the Hueco bolson. The use of the model of the Hueco bolson in the El Paso district was warranted for four reasons: (1) classical mathematical methods could not accurately describe the hydrologic system because of its complexity and nonlinearities; (2) quantitative interpretations of local hydrologic properties required extrapolations beyond the small areas of observation; (3) predictions of future water levels required definitions of the cause-and-effect (pumpage and changes in water levels) relations governing the response of the regional hydrologic system; and (4) sufficient records of pumpage, water levels, and aquifer coefficients were available.

The primary purpose of this report is to present the results obtained from analyses of the hydrologic data by means of an electrical-analog model. The report also summarizes a few salient facts collected since 1963 regarding the geohydrology of the district and the development of the ground-water supplies.

The ground-water resources in the El Paso area have been studied since 1935 by the U.S. Geological Survey in cooperation with the city of El Paso and the Texas Water Development Board. The studies have determined (1) the areal extent of the fresh ground water in the Hueco bolson in Texas, (2) the areas of recharge and discharge, (3) the approximate amount of fresh ground water in storage, (4) the hydraulic properties of the fresh-water-bearing sediments, (5) the effect of ground-water development on the water levels in the bolson, and (6) the quality of the water. These data were compiled and organized to form the basis of the present study. Electric logs of water wells were used to ascertain the thickness of the fresh-water body underlying the Hueco bolson. The completed maps and tabulations were then sent to the Analog Model Unit of the U.S. Geological Survey at Phoenix, Arizona, where the model was designed, constructed, and interpreted.

Particular thanks are extended to Eugene P. Patten, Jr., of the Analog Model Unit, who aided greatly in the analysis of the computed data.

LOCATION AND GENERAL FEATURES OF THE AREA

The Hueco bolson of the El Paso district, as defined in this report, is in the extreme western part of Texas and northern Mexico, includes all of El Paso County between the Franklin and Hueco Mountains in Texas, and extends southward to the Sierra del Presidio in Mexico. For the purpose of the analog model study, however, only that part of the Hueco bolson was investigated that contains fresh water in Texas and in the vicinity of Ciudad Juarez (Figure 1).

The city of El Paso in the United States and Ciudad Juarez in Mexico, the principal cities in the bolson area, are separated by the Rio Grande. According to the El Paso Chamber of Commerce, the population of El Paso in January 1965 was 314,000 and that of Ciudad Juarez, 350,000.

The area is arid, and its climate is characterized by a wide range in temperature, low humidity, high evaporation, and low precipitation. According to U.S. Weather Bureau records, the mean annual temperature at El Paso from 1887 to 1964 was 63.9°F and the mean annual precipitation from 1878 to 1964 was 8.54 inches. The average relative humidity is less than 50 percent, indicating a high rate of evaporation. The average annual gross lake-surface evaporation for El Paso County for 1940-57 averaged 78 inches (Lowry, 1960), or nearly 10 times the average annual precipitation.

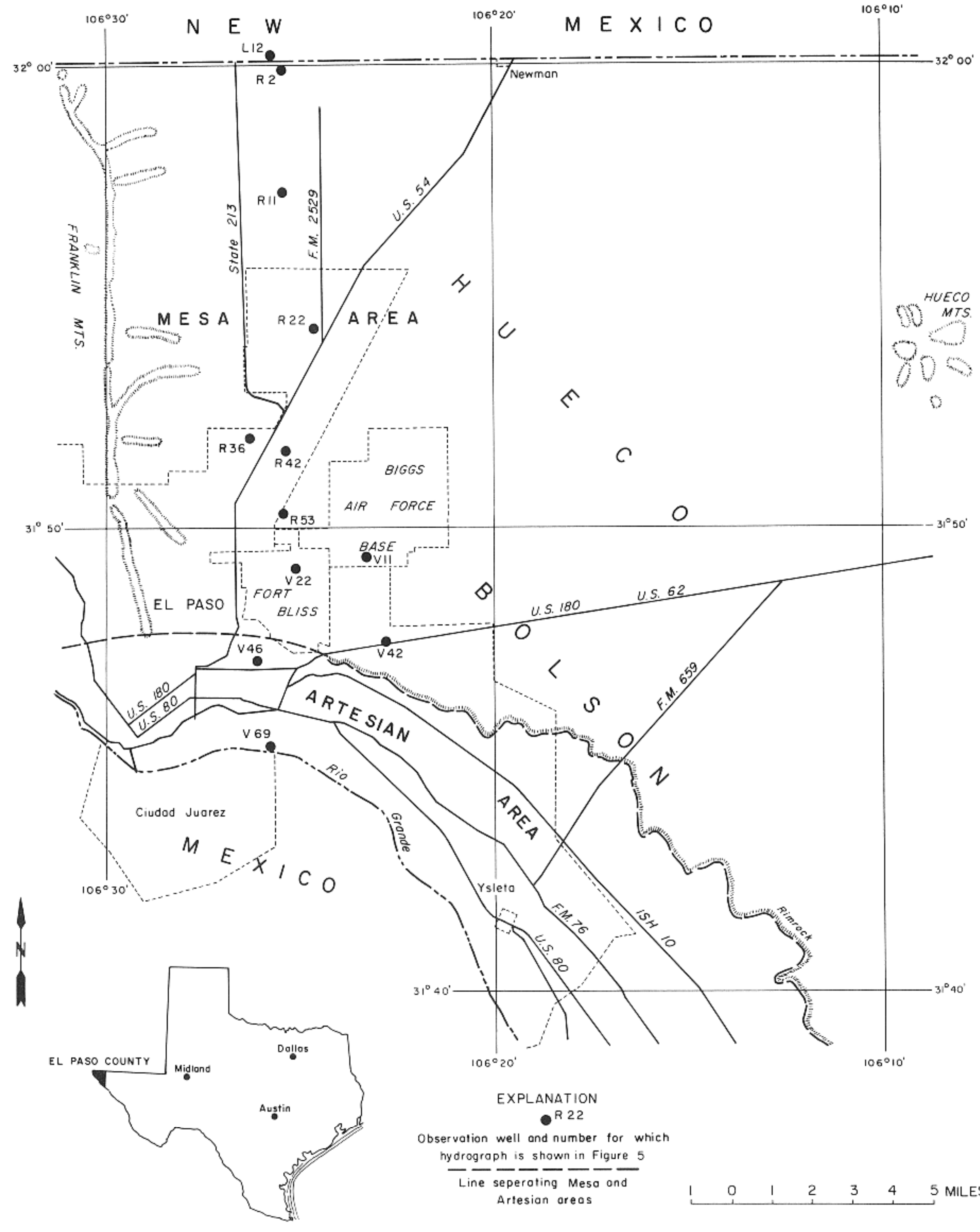

Figure 1

Location of Hueco Bolson and Selected Observation Wells in the El Paso District

U.S. Geological Survey in cooperation with the Texas Water Development Board and the City of El Paso

The Rio Grande enters the Hueco bolson through a narrow gorge at the south end of the Franklin Mountains and flows diagonally across the bolson through the El Paso Valley. The land surface rises abruptly from the floor of the valley to the bolson surface, giving the bolson surface the appearance of a broad table-land, which is referred to as the Mesa area; that part of the bolson underlying the valley, or below the rimrock, is referred to as the Artesian area.

GEOHYDROLOGY OF THE HUECO BOLSON

The geohydrology of the Hueco bolson has been described in many previous reports. The most comprehensive are those by Sayre and Livingston (1945), Knowles and Kennedy (1958), and Leggat (1962). Additional data pertaining to the ground water in the bolson may be found in reports by Scalapino (1949), Smith (1956), Audsley (1959), Davis (1965), and Davis and Leggat (1965).

The sediments of the Hueco bolson, originally a closed basin, consist of unconsolidated deposits of interbedded sand, gravel, clay, and silt. The deposits are poorly sorted and individual beds range in thickness from a few feet to about 100 feet. Because these beds pinch out or grade laterally or vertically into finer or coarser sediments within short distances, correlation of individual beds between wells is almost impossible. The maximum thickness of these deposits is not known; however, 4,920 feet of unconsolidated sediments reportedly was penetrated in an oil test about 2 miles south of Newman, New Mexico (Figure 1).

Ground water occurs under water-table conditions in the northern or Mesa part of the Hueco bolson, and under artesian conditions in the southern part. The movement of water is generally to the south except in local areas where large withdrawals of ground water have formed cones of depression. The water moves from the Mesa to the Artesian area where it becomes confined beneath beds of relatively impermeable sediments. The artesian head is maintained by the higher elevation of the water surface underlying the Mesa area. In deep wells, the water rises to an elevation comparable to the water levels in the Mesa area.

The unconsolidated deposits in the bolson contain fresh (less than 1,000 parts per million dissolved solids) and saline (more than 1,000 parts per million dissolved solids) water. Although the volume of water in the bolson is large, only a small fraction is fresh. The fresh water occurs in a trough of irregular depth and width, the axis of which lies a short distance east of the Franklin Mountains.

In the Mesa area, saline water occurs beneath and east of the fresh-water-bearing deposits. The depth to the saline water ranges widely within short distances, chiefly because of the presence of clay beds and other relatively impermeable materials. Because of the low hydraulic gradients in this area, increases in salinity in wells have not yet been large.

In the Artesian area, the fresh water is underlain, overlain, and adjoined on the east by saline water. The fresh water was originally under higher pressure than the saline water, but pumping from the fresh-water sands has caused a reduction in the hydraulic pressure in these sands, thereby upsetting the original differential balance between the saline and fresh-water bodies.

Consequently, the saline water, now under higher pressure, can move into the fresh-water deposits to contaminate the supply.

Recharge to the Hueco bolson is by infiltration of runoff from the mountains and by precipitation on the surface of the bolson. The principal recharge area extends along the base of the Franklin and Organ Mountains in Texas and New Mexico. According to Sayre and Livingston (1945, p. 72) the average recharge to the bolson deposits is about 13 mgd (million gallons per day).

Discharge from the bolson deposits is by pumping from wells and by the upward movement of water toward the Rio Grande. Before pumping began in the Artesian area, water from the bolson deposits moved upward into the alluvium, and thence to the Rio Grande. However, because of heavy pumping, the direction of movement of the ground water has been reversed in some parts of the area, and in these areas the water in the alluvium is now moving downward into the bolson deposits.

WITHDRAWALS OF GROUND WATER

Prior to 1904, the municipal supply of El Paso was obtained from the Rio Grande or from shallow wells near the river. In 1904, the city and the U.S. Army began drilling deep wells in the Mesa area in and north of Fort Bliss. During the same year, a few industrial wells were drilled in the Artesian area. Pumpage records for these wells before 1906 generally are not available.

The amount of ground water pumped from deep wells in the Hueco bolson has increased steadily since 1906, except for a few short periods (Figure 2). In 1906, 1.2 mgd was pumped, and the pumpage increased to about 26 mgd in 1943. After 1943, however, supplemental water supplies withdrawn from the Rio Grande by the city of El Paso caused a decrease in pumpage to 20 mgd in 1947. Since 1947, a steady increase in population and expansion of industries has resulted in a marked rise in pumpage of ground water to nearly 70 mgd in 1964.

From 1936 to 1955, with the exception of 1942 and 1953, most of the withdrawals were from the Artesian area. Since 1955, however, withdrawals from the Mesa area have increased by 20.8 mgd as compared with an increase of 5.6 mgd from the Artesian area.

Of the 89.3 mgd pumped from all sources in the El Paso district in 1964, slightly more than 75 percent was from the Hueco bolson, where the city of El Paso is the principal user. In 1964, the city pumped 35.2 mgd (about 65 percent of its total water supply) from deep wells in the bolson; Ciudad Juarez pumped 15.1 mgd; industries, 8.4 mgd; military establishments, 4.9 mgd; and irrigators, 5.7 mgd. Of the 35.2 mgd pumped from the bolson by the city in 1964, 25.1 mgd (about 70 percent) was from the Mesa area and 10.1 mgd (about 30 percent) from the Artesian area.

CHANGES IN WATER LEVELS

In 1903, the water levels were nearly representative of those before withdrawals from deep wells were begun in the Hueco bolson. A water-table map of the Hueco bolson for 1903 was constructed on the basis of data from maps and

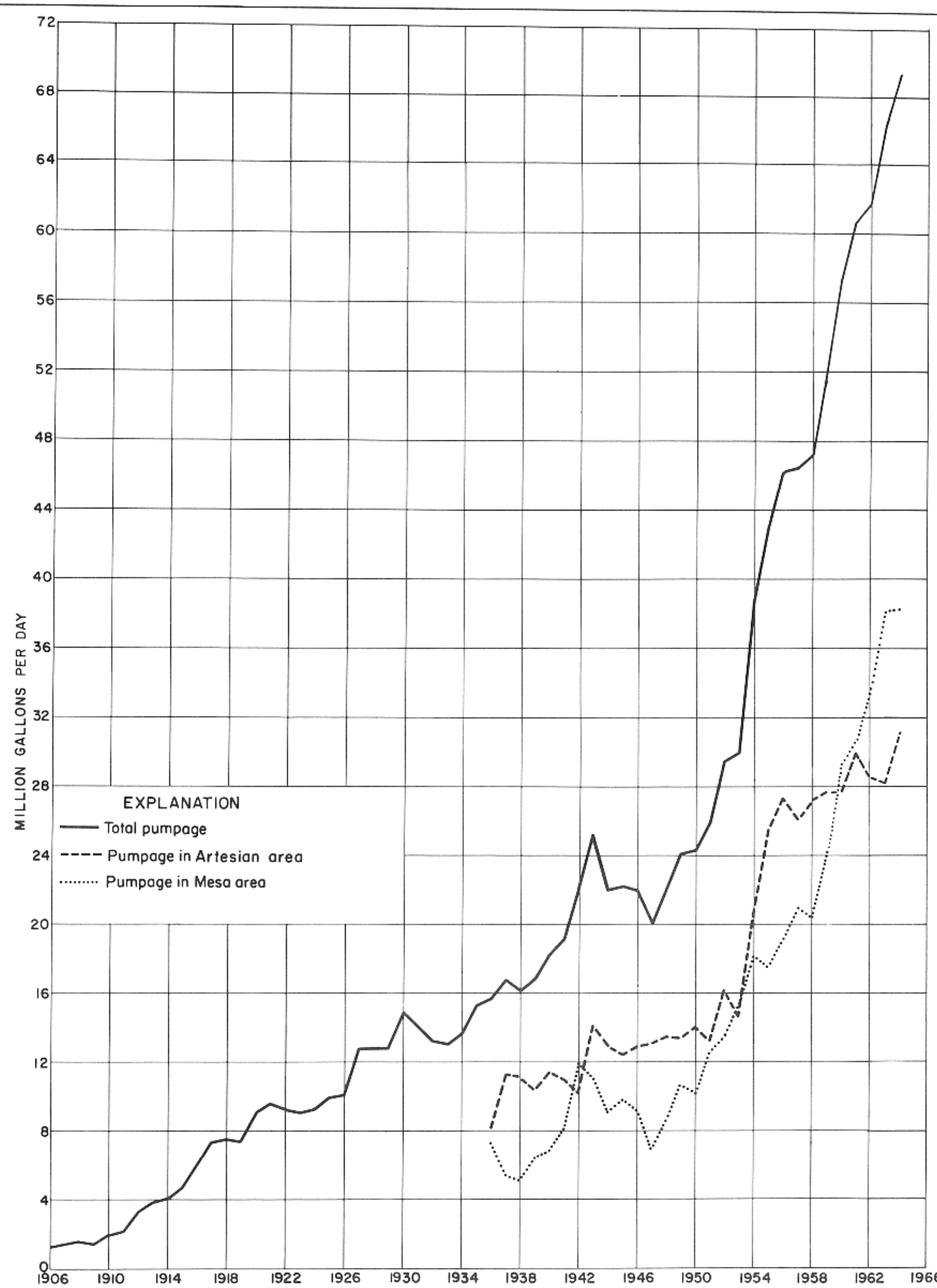

Figure 2

Estimated Average Daily Pumpage from Deep Wells in the Hueco Bolson, 1906-64

U.S. Geological Survey in cooperation with the Texas Water Development Board and the City of El Paso

well records published during the early 1900's. Water-table maps for the years 1953 and 1963 were likewise prepared from water-level measurements in a large network of observation wells in the El Paso area.

The approximate decline in water levels for the periods 1903-53 and 1903-63 (Figures 3 and 4) were prepared by superimposing the map showing the approximate altitude of the water table in 1903 (map not shown in this report) on the water-table maps for 1953 and 1963 (not shown in this report), and then drawing lines through points of equal decline as indicated by the intersections of the contours. Wells having long-term records of water levels also were used for supplementary control. The accuracy of these maps, of course, depends to a great extent on the quality and quantity of the control data available in the early 1900's. For some areas, particularly in that part of El Paso below the rimrock (the Artesian area), data were adequate; elsewhere, particularly in Ciudad Juarez, data were inadequate. Withdrawals of ground water during the 1903-63 period have lowered the water level as much as 50 feet in an area north of Fort Bliss (Figure 4).

Water levels in observation wells in the southern part of the Mesa area have declined steadily since 1936 because of the withdrawal of water in that area (Figure 5). Beginning about 1954, as the demands for water increased, well fields were developed south and north of the old Mesa field which was centered along the northern edge of Fort Bliss (Figure 1); and the increase in pumpage caused a more rapid decline in water levels in the vicinity of the well fields. As pumpage continued to increase, the cone of depression expanded northward and eastward, reaching wells relatively remote from pumping. By 1965, the area of decline due to pumping from the wells in the Mesa area extended northward several miles beyond the Texas-New Mexico State line and eastward probably to the eastern boundary of the Hueco bolson.

Water levels in wells in the Artesian area respond rapidly to changes in pumping rates in the area; however, a part of the change in water levels can be attributed to pumping from the Mesa area. The hydrographs of two observation wells (Figure 5) in the Artesian area show that the water levels have fluctuated over a wide range. During the period of record from 1937 to 1965, water levels generally declined except during brief periods when less water was pumped from the Artesian area by the city of El Paso; the levels reached record lows in 1965. Much of the decline in the Artesian area since about 1960 can be attributed to well fields recently added near the Rio Grande by Ciudad Juarez.

FRESH GROUND WATER IN STORAGE

The thickness of the bolson sediments that contain fresh water (less than 1,000 parts per million dissolved solids) is shown by means of isopachs in Figure 6. The isopachs were not extended into Mexico because the data were insufficient. On the basis of this map, the volume of saturated material containing fresh water is at least 50,000,000 acre-feet. If a coefficient of storage of 0.15 is assumed for the bolson deposits, approximately 7.5 million acre-feet of fresh water theoretically is recoverable. Although this volume of water is theoretically available for pumping from the bolson, the volume that can be withdrawn is contingent upon several factors--the principal one being the vertical and lateral movement of the salt water that everywhere underlies or adjoins the fresh-water body.

THE ELECTRICAL-ANALOG MODEL

Use and Construction

The theory, instrumentation, and use of electrical-analog models in the analysis of ground-water systems have been described by Skibitzke and Robinson (1954[1/]), Skibitzke (1960), and more recently by Patten (1965). In brief, the theory of the analog model is based upon an analogy between the flow of electricity and the flow of ground water. In an electrical system a resistor impedes the free flow of current, and in the ground-water system the water-bearing materials impede the free flow of fluid. Similarly, electrical energy is stored by the capacitor in a manner comparable to the storing of water by an aquifer. Likewise, voltage and amperage in an electrical system are the equivalents of head and the volume rate of flow in the aquifer system. Thus the two systems, electric and hydraulic, are analogous.

The model shown in Figure 7 consists of a network of electrical resistors and capacitors in which the electrical network functions as a scaled model of the aquifer system, an electric-pulse generator simulates the magnitude, duration, and areal distribution of pumping, and an oscilloscope displays the changes in water level as a time-drawdown graph.

The principal factors considered in constructing the model are: the areal extent, and boundaries, of the aquifer system; the hydraulic properties of the aquifer; the areal variations of these characteristics; the functions governing recharge to the system in terms of quantity, location, and time; and the pumping program. In the Hueco bolson, however, measurement of all these parameters in great detail or with a high degree of accuracy was impracticable. Nevertheless, sufficient records of ground-water withdrawals and water-level declines are available and the hydraulic characteristics have been fairly well established, so that the model probably can be constructed to represent the hydrologic system.

The area modeled is somewhat less than the extent of the Hueco bolson, as the area boundaries are based primarily on hydraulic rather than topographic or geologic criteria. The area extends from a short distance north of the Texas-New Mexico State line southward to Ciudad Juarez, and from the Franklin Mountains eastward about 17 miles (Figure 1). The Franklin Mountains form the western boundary; the other boundaries are rather arbitrary but, in general, are sufficiently remote from the pumping centers to reduce to a minimum any computational or model error. In effect, the area modeled includes nearly all the fresh water in that part of the Hueco bolson in Texas plus part of Mexico. The total area modeled was about 400 square miles, at a scale of 1 inch equalling 1/2 mile.

The coefficients of transmissibility and storage (the hydrologic properties of the aquifer) were simulated by the resistor-capacitor network. Each resistor

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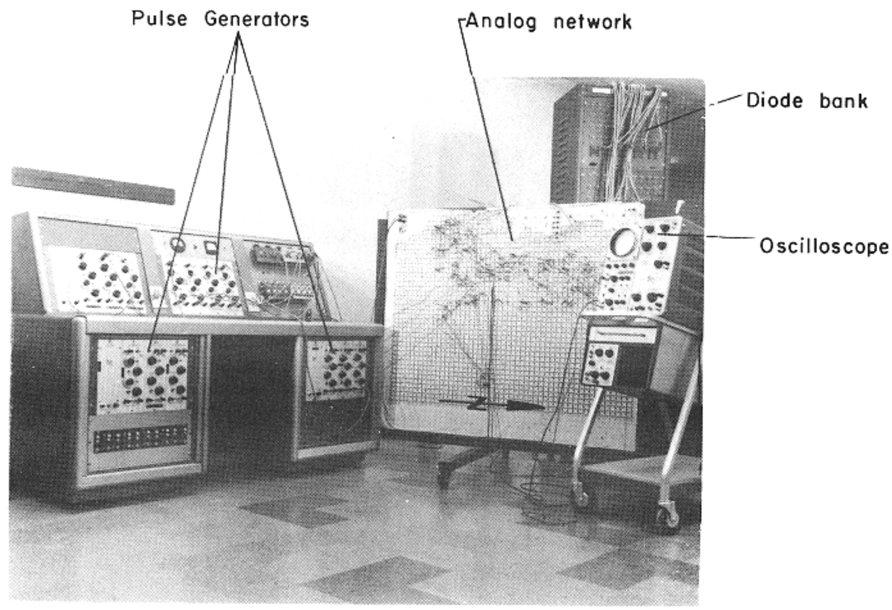
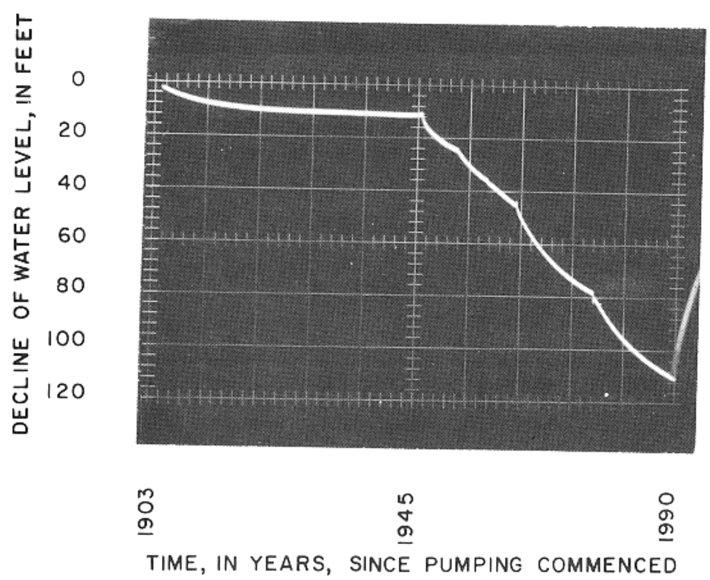
1/ Skibitzke, H. E., and Robinson, G. M., 1954, The use of numerical and electrical methods in solution of ground-water flow problems: Unpublished manuscript.



A. Electronic equipment used to excite element



B. Oscillogram obtained by measuring voltage drop as a function of time on the analog network

Figure 7

Electrical-Analog Model and Typical Oscillogram

U.S. Geological Survey in cooperation with the Texas Water Development Board and the City of El Paso

in the network represented the transmissibility of the particular segment of the aquifer beneath it, and each capacitor simulated the storage characteristic of 1 square mile of aquifer.

The transmissibility of the aquifer at each resistor was obtained by multiplying the coefficient of permeability by the thickness of the fresh-water section at that point. The permeability was obtained by dividing the coefficient of transmissibility, computed from pumping tests, by the thickness of the aquifer tapped by the well. Where pumping tests were not available, the coefficient of transmissibility was estimated from the specific capacity of the well. An isopachous map, on which was shown the total thickness of sand containing fresh water, was constructed principally from electric and drillers' logs of water wells (Figure 6). From this map and the coefficients of permeability, another map was drawn to show the areal distribution of transmissibility (Figure 8). A storage coefficient of 0.15 was used in the water-table part of the aquifer (Mesa area), and one of 0.001 in the artesian part.

Detailed records of pumpage from approximately 205 wells in the Texas part of the Hueco bolson and in Ciudad Juarez were available for the period 1903-62, except that some of the industrial pumpage was estimated for the period 1903-36. The average pumping rate of each well was distributed over four periods: 1903-46, 1947-52, 1953-57, and 1958-62. Where wells were closely spaced and the individual withdrawals were relatively small, it was sometimes necessary to combine two or more wells into one model well or "pumping center." The excessive drawdown resulting from this modeling introduced little error at distances of one or more node points away, although the delcine in the immediate vicinity of the pumping center was exaggerated. The number of pumping centers, which varied according to the pumping period, ranged from about 17 for the 1903-46 period to 63 for the 1958-62 period, and thus represented all the large-capacity wells in the bolson.

The pumpage, or excitation function, was imposed on the model by the use of an electronic function generator--one for each pumping period. The output of each function generator consisted of a voltage waveform whose duration was proportional to the number of days in the period and whose amplitude was constant. The constant amplitude voltage was connected through resistors to the analog network. Each resistor represented a pumping well, and the quantity of electricity flowing was proportional to the quantity of water pumped from the well.

The response of the model was sensed by an oscilloscope and displayed in the form of a graph whose ordinate was voltage and whose abscissa was time in microseconds--or in analogous terms, respectively, feet of water-level decline and time in years. The oscilloscope is connected to as many individual junctions in the model as are necessary to determine the response of the aquifer to changes in pumping.

Analysis

After construction of the model, the general procedure was to supply an external excitation--pumpage--and to observe or measure the response--change in water level. The accuracy and reliability of the model was assessed by comparing the 1903-53 and 1903-63 water-level changes computed by the model with those based on field data. To the degree that these changes could be duplicated on the analog system, the model could be considered as a valid representation of the hydrologic environment. Modification of the model, however, was necessary before the historical data on water-level declines in the bolson could be properly duplicated. Because the pumping history was known, the other parameters--transmissibility (permeability times thickness), storage, or recharge--were varied. However, modifications were made only for plausible hydrologic reasons.

The results of the early trial runs of the model showed excessive water-level declines along the western boundary of the bolson and, in general, throughout the Artesian area. The western boundary, or recharge area, was modeled at a constant head; and the Artesian area was assumed to receive induced leakage from the overlying clay or from the water table in the overlying alluvium.

Successive analyses of the model indicated that the quantity of water entering the model across the western boundary (assumed at constant head) was probably much too large, particularly during the 1958-62 period, when withdrawals were large. For this reason, and also because the potential for inducing recharge is limited by the sporadic nature of the rainfall on the Franklin Mountains, the maximum recharge that could flow into the bolson was limited to 13 mgd, as computed during the period prior to 1958.

In order to simulate vertical leakage to the artesian aquifer from the water table in the overlying alluvium, a one-dimensional flow system was added to the model to simulate the thickness and permeability of the confining beds. Because the water table was assumed to be at a constant head, leakage was a function only of the pumping program and the concommitant decline in the artesian head. The vertical permeability of the confining beds was not known; hence, the distributed value of that parameter could not be modeled. Consequently, the modeled equivalent was a constant ratio of bed thickness to vertical permeability. For a bed thickness of 100 feet, the vertical permeability was 0.1 gpd (gallons per day) per square foot.

Furthermore, the regional characteristics of the aquifer upon which the model design originally was based were not sufficient to duplicate the regional head change. Consequently, the ratio of storage to transmissibility (S/T) was arbitrarily changed until a suitable match was obtained. In fact, the S/T ratio ultimately was reduced by one half, indicating that the system was more diffusive than originally described. Although the reduction may be attributed either to higher transmissibilities or to lower storage coefficients, it is doubtless due to a combination of both.

After several trials and modifications, the model was considered an analogy of the physical system when its response to pumpage resulted in water-level decline maps (Figures 9 and 10) which duplicated reasonably well the field declines for those periods (Figures 3 and 4).

The magnitude of the maximum declines computed by the model and the configuration of the contours produced by the model closely approximate those based on field data. Superimposing the maps for the respective periods reveals, however, that in the Fort Bliss area the modeled cone of depression is offset to the south and east of that in the field decline map. This shift, which is also reflected in some of the decline contours, is due largely to inaccuracies in the field decline maps. In some heavily-pumped wells, water levels were not available; hence, the field decline map does not portray the actual water-table decline in the vicinity of the wells. In effect, the actual conditions are probably more accurately reflected in the model declines than in the field declines.

The most difficult cause-and-effect relation to reproduce was in and near Ciudad Juarez, where few reliable water-level data were available. Because of the similarity between the model and field declines in the downtown El Paso area, the model declines for the Ciudad Juarez area probably are correct at least in their order of magnitude.

PROJECTED INCREASE IN WITHDRAWALS AND THE EFFECT ON WATER LEVELS

On the basis of estimates furnished by the El Paso Public Service Board, the total water requirements of all users in the El Paso district, including Ciudad Juarez, will increase from 89.3 mgd in 1964 to 135 mgd by 1975 and to 190 mgd by 1990. Although the water supply for the district is obtained from three sources, the Hueco bolson, the La Mesa bolson west of the Franklin Mountains, and the Rio Grande, a substantial part of the expected needs will be pumped from the bolson. According to these estimates, 90 mgd will be withdrawn from the bolson in 1975 and 108 mgd in 1990.

The model was programmed to produce water-level changes from 1903 to 1975 and from 1903 to 1990 on the basis of known pumpage from 1903 to 1962 and of the pumping pattern suggested by the El Paso Public Service Board and industry for the periods 1963-75 and 1976-90. The declines computed by the model for these periods are shown in Figures 11 and 12.

Of the predicted increase in withdrawals during the period 1963-1975, about 65 percent would be for the municipal supply of El Paso and slightly less than 35 percent for that of Ciudad Juarez. Industrial use would increase less than 1 mgd.

The largest part of the increased withdrawals for El Paso would be from 19 additional wells in that part of the bolson bounded on the west by State Highway 213, on the east by U.S. Highway 54, on the north by the Texas-New Mexico State line, and on the south by a line through the intersection of the above highways. In 1965, wells in this area were at the corners of sections (a section is 640 acres or 1 square mile), or about 1 mile apart. During the latter part of the 1963-75 period, however, some wells will be located in the middle of the sections, resulting in a somewhat closer spacing of wells.

A comparison of the model decline maps for the periods 1903-63 (Figure 10) and 1903-75 (Figure 11) reflects the change in the distribution of pumping and spacing of wells. In general, the cone of depression formerly centered in the Fort Bliss area will have expanded northward; and the maximum decline, about 70 feet, will be centered in the northern part of the bolson. In the Ciudad Juarez area, the maximum decline will be about 25 feet as compared with 35 feet in the 1903-63 period. This decrease, as well as the slight shift eastward of the cone of depression, will be due to changes in centers of pumping.

In the period 1976-90, withdrawals from the Hueco bolson are expected to increase by 18 mgd, of which 15 mgd will be for the municipal supply of El Paso. According to the plan suggested by the Public Service Board, this increase would be from six additional wells in the same area of the bolson outlined above. In the model decline map for the period 1903-90 (Figure 12) is shown a maximum decline of 110 feet, or about 40 feet more than was computed for the period 1903-75 (Figure 11) in the same area. In Ciudad Juarez and in the El Paso Artesian area, where withdrawals would be increased only slightly, the declines are virtually unchanged.

Shown in Figure 13 is the computed decline in water levels resulting from a redistribution of the pumping pattern suggested by the Analog Model Unit for the period 1976-90. In this figure the maximum computed decline is about 100 feet, and the area enclosed by the 100- and 90-foot decline is much reduced compared to that shown in Figure 12. A comparison of these maps with the saturated thickness map (Figure 6) reveals that the cone of depression is more or less centered along the axis of the fresh-water trough.

The correspondence of the predicted water-level changes to actual water-level changes in the field depends directly on how closely future development conforms to the proposed pumping conditions, either in areal distribution or in the total for the bolson. Doubtlessly, the computed declines will be less if a part of the pumpage from the bolson is replaced by water from other sources. In 1965, El Paso, the largest single user of water in the district, obtained water from two other sources: the La Mesa bolson, west of the Franklin Mountains; and the Rio Grande. The middle and deep aquifers in La Mesa bolson are capable of a sustained yield of about 13 mgd. El Paso, by contract with the U.S. Bureau of Reclamation, can divert, when water is available in the river, a maximum of 3.5 acre-feet of water per acre of land acquired by the city, the maximum being 6,000 acres. On this basis, as much as 21,000 acre-feet can be diverted from the river, although since 1943, records reveal that seldom has an allotment of 3.5 acre-feet of water been available. In fact, the quantity of water diverted from the river by El Paso has ranged from slightly less than 0.5 mgd (560 acre-feet per year) to somewhat less than 8 mgd (about 8,700 acre-feet per year). In addition, the city can divert as much as 27,000 acre-feet a year (24 mgd) of "wild" water (water discharged from the land into the drains and river and water excess to irrigation needs).

THE SALT-WATER PROBLEM

A knowledge of the relation between the fresh water and salt water is important to the successful management of the ground-water resources in the Hueco bolson. A haphazard development of the supply available in the bolson might result in the isolation of an unduly large proportion of the fresh water by the salt water moving vertically or horizontally in response to pumping. However, in the proposed development, the problem of predicting the response of the aquifer system containing two fliuds of different mineralization cannot be solved solely by the electrical-analog model. The analog model, which is a two-dimensional idealization of the true three-dimensional system, is capable of predicting changes in the potential distribution in the aquifer systems. It cannot, however, predict the actual flow paths of the real system or the rate at which the transport of salt water will occur. In fact, such predictions would have to assume that the two fluids (fresh and salt water) are immiscible. The assumption that the contact of the two fluids can be represented by a sharp interface seemingly is untenable in view of the salinity gradients observed in the field.

The average vertical rate of salt-water movement could be estimated on the basis of the head change since 1903 and of the thickness and permeability of the sediments containing salt water. Such an approach, however, could be applied only to individual wells and only under steady-state conditions. Solving the problem by this technique is further complicated by the extreme complexities of the flow pattern, as indicated by the salinity gradients and the lenticularity of the beds; consequently, assuming an average permeability doubtlessly would result in large errors. This last factor is especially important because the ratio of the vertical to the horizontal permeabilities as well as the degree of heterogeneity will be at least as critical as the pumping stress in determining the migration of the interface. For example, even if computations indicate that the fresh water-salt water interface is at a safe distance from a well or well field, a thin but highly permeable bed could strongly affect the quality of the water pumped if that bed extended into the salt water.

NEED FOR ADDITIONAL STUDIES

The program of basic-data collection, including water-level measurements, data on new wells, pumpage records, and collecting and analyzing water samples for chemical quality should be continued in the Hueco bolson in order to evaluate the findings of the model study. Much more detailed data--for example, on permeabilities and storage coefficients, on salinity gradients in the salt-water part of the aquifer, and on the relation between the head in the alluvium and in the underlying artesian part of the aquifer--are necessary to refine and modify the present model. Also needed are considerably more basic data from the Ciudad Juarez area.

Because the salt water underlying the bolson is a potential source of contamination to the fresh water, special emphasis should be placed on the development of a non-steady two-dimensional model of a two-fluid (fresh and salt water) system. In the interim, a hydraulic model should be considered as a means of showing the movement of salt water resulting from patterns of pumping.

An annually increasing amount of ground water is withdrawn from La Mesa bolson (Lower Mesilla Valley), principally by the city of El Paso. The data available on the geohydrology of this bolson, however, are rather limited, the ground-water development being restricted to an area of less than 12 square miles in Texas. The scarcity of data necessarily imposes severe restrictions on adequately describing the flow system. Therefore more data--particularly concerning the extent of the reservoir or the position of the salt water-fresh water interface and vertical permeabilities--should be collected before the construction of a model of La Mesa bolson is attempted.

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