ANALOG MODEL STUDY OF GROUND WATER IN THE HOUSTON DISTRICT, TEXAS

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ANALOG MODEL STUDY OF GROUND WATER IN THE HOUSTON DISTRICT, TEXAS

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With a section on

Design, Construction, and Use of Electric Analog Models

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ANALOG MODEL STUDY OF GROUND WATER IN THE HOUSTON DISTRICT, TEXAS

ABSTRACT

Data on ground-water pumpage, water levels, aquifer coefficients, and geology in the Houston district, Texas, which have been collected since 1931 were used to construct an electrical analog model of the aquifer underlying the district. Water level decline maps for the periods 1890-1946, 1890-1953, and 1890-1961 were used to check the accuracy of the model. Adjustments were made by changing scale factors and electrical components to change the values of various parameters so that the model would respond in a manner similar to the aquifer when pumped. After reasonable maps of decline for those periods were prepared from data computed by the model, two decline maps for the period 1890-1970 were constructed. One map for the period 1890-1970 was based on extending the 1954-1960 pumpage rate from 1961 to 1970, which would cause 30 to 40 feet of additional drawdown in the Pasadena area between 1960 and 1970. The other map was based on a predicted increase in pumpage of 67 mgd (million gallons per day) between 1961 and 1970. The predicted increase would cause about 100 feet of additional drawdown in the western part of Houston between 1961 and 1970. Although the predicted declines of water level are not exact, the model is useful in determining the order of magnitude of future water levels, which is necessary for the proper management of the Houston district's water resources.

ANALOG MODEL STUDY OF GROUND WATER IN THE HOUSTON DISTRICT, TEXAS

INTRODUCTION

Data on ground-water pumpage, water levels in wells, geology, wells, aquifer coefficients, and water quality have been collected systematically in the Houston district from 1931 to the present time by the U.S. Geological Survey in cooperation with the city of Houston and the Texas Water Commission. In 1959, the U.S. Geological Survey and its cooperators agreed to a study of these data with the objective of forecasting water levels. Because of the complex hydro-geologic conditions in the Houston district, the only economically feasible method of making such a forecast was decided to be the analog model of the aquifer underlying the district. This report is devoted chiefly to the method of approach and the results obtained from analysis of the analog model.

The Houston district, as defined in this report, consists of all of Harris County and parts of Galveston, Brazoria, Fort Bend, Austin, Waller, Montgomery, Liberty, and Chambers Counties (Figure 1). The district is in the West Gulf Coastal Plain of Texas and contains about 5,000 square miles.

In 1960, about 1,430,000 persons lived in the Houston district; of these, nearly 1,250,000 were in the Houston metropolitan area in Harris County and about 140,000 in Galveston County.

The Houston district is one of the leading oil-producing and refining areas in the Nation and is an important petrochemical center. The Port of Houston handles either the second or third largest tonnage each year among United States ports. Besides a large diversified manufacturing industry, the Houston district has a strong agricultural industry; rice, cotton, and beef cattle are its most important products. The economy of the district is oriented toward water because its industries use large amounts for cooling and irrigation, and depend to a great extent on water for transportation.

The Houston district is in the West Gulf Coastal Plain, and the land surface slopes toward the Gulf at a very low angle. The slope from the northern part of the district to Houston is about 5 feet per mile, and from Houston to Galveston Island, the slope is about 1 foot per mile. Except for the part of the district in Montgomery and northern Waller Counties, the district is nearly flat and featureless; the only relief is provided by the youthful valleys of the smaller streams. The larger streams, the Trinity River in the eastern part of the district, the Brazos River in the western part of the district, and the San Jacinto River below Lake Houston, have wide valleys. The district generally is treeless except along the borders of streams, in the river bottoms, and in Montgomery County and northeastern Harris County. Galveston Bay, which is very shallow, is separated from the Gulf of Mexico by Galveston Island and Bolivar Peninsula. which are barrier-island deposits.

The normal annual precipitation at Houston is 45.26 inches, which generally is distributed evenly throughout the year. Potential annual evaporation is about equal to the precipitation, but the rate is higher in the warmer months than during the winter. The mean annual temperature is 70°F; the warmest month is August with a mean temperature of 84.1°F, and the coldest month is January with a mean temperature of 54.6°F.

Many reports have been written on the ground-water resources of the Houston district. Among the most comprehensive is the report by Lang and others (1950). Petitt and Winslow (1957) summarized the geology and ground-water resources of Galveston County. The relation of salt water to fresh ground water in Harris County was discussed by Winslow and others (1957). Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region was first reported by Winslow and Doyel (1954a). The most recent progress reports, which contain data on pumpage and water levels in Harris County through 1960 and Galveston County through 1961, were those by Anders and Naftel (1962 and 1963). Selected references concerning the Houston district are in the list at the end of the report.

Most of the data upon which the report is based were available in reports or in the files of the U.S. Geological Survey. The well inventory was updated in 1961 and 1962 by the addition of more complete information obtained from well drillers and by on-the-site inspection and interviews with well owners. During this period, about 150 new large-capacity wells were inventoried. In addition, electric logs of oil and gas tests were obtained to supplement the electric logs in the files of the Geological Survey and the Texas Water Commission.

The base of the heavily pumped layer in the aquifer underlying the Houston district was mapped by correlating lithology as interpreted from electric logs. Although many drillers' logs of water wells in the vicinity of Houston were used, the sand-thickness and the clay-thickness maps also were prepared largely by interpretation of electric logs. The data were organized, compiled, and synthesized in the office of the Geological Survey in Houston. The completed maps and tabulations were then sent to the Analog Model Unit at Phoenix, Arizona, where personnel designed, constructed, and interpreted the model. The Analog Model Unit also prepared the section of the report dealing with the design, construction, and use of analog models of aquifers.

The authors wish to express their appreciation to B. J. Bermes, R. W. Stallman, and H. E. Skibitzke of the Geological Survey for assistance and advice in conceiving and implementing the analog model study. Thanks are especially due to R. W. Stallman of the Geological Survey who assisted in the planning of the study and devoted considerable time to constructive review of the manuscript, and the staff of the Analog Model Unit in Phoenix, Arizona, for their many suggestions concerning the preparation of the data and for their willingness to modify the model, which was often necessary because some of the aquifer properties were only approximated. Messrs. D. E. Van Buskirk and Noah Hull of the city of Houston furnished data on predicted increases and decreases of pumpage in the Houston area for the period 1961-70. Mr. John Focht, Jr., of McClelland Engineers, and Mr. H. P. Carothers of Lockwood, Andrews, and Newnam, gave valuable time and data to the authors. Well owners and drillers supplied electric logs and other data on recently drilled water wells; the Layne-Texas Co., Texas Water Wells, Inc., and Katy Drilling Co. were especially helpful.

GEOLOGY OF THE HOUSTON DISTRICT

The formations from which the Houston district obtains its water supply are composed of sediments derived from older Tertiary and Cretaceous formations and consist of sand, gravel, silt, and clay. The formations were built up by rivers as coalescing fans on and near the continent and as marine and lagoonal deposits along the coast.

The water-bearing formations in the Houston district are as follows, from oldest to youngest: The Catahoula Sandstone of Miocene(?) age, the Oakville Sandstone of Miocene age, the Lagarto Clay of Miocene(?) age, the Goliad Sand of Pliocene age, the Willis Sand of Pliocene(?) age, the Lissie Formation and Beaumont Clay of Pleistocene age, and the alluvium of Recent age (Table 1). The formations crop out in belts roughly parallel to the coast, the oldest formation farthest inland and each younger formation cropping out successively nearer the coast (Figure 2). The estimated dip of the older beds is from 50 to 60 feet per mile and of the younger beds 15 to 20 feet per mile. All the formations thicken downdip so that the older formations dip more steeply than the younger ones. Localized structures, such as faults and salt domes, cause reversals of dip or thickening or thinning of beds. The faults may have several hundred feet of displacement in the older Tertiary formations, but the displacement tends to decrease toward the surface so that faulting generally is not apparent at the surface, and the fresh-water-bearing beds generally are not displaced enough to disrupt hydraulic connections.

The salt domes are structures resulting from the upward movement of a salt mass and generally are circular in plan. The source of the salt is very deep and probably of Mesozoic age. In many domes, the salt mass pierces the overlying strata and nearly reaches the surface. Several salt domes approach the surface in the Houston district, but they have only local effect on ground water becasue of their small size ($1\frac{1}{2}$ to 4 miles in diameter), and for this reason, they were ignored in the construction of the model.

Sand and clay beds in the Houston district are not persistent in lithology or thickness because of their origin and method of deposition. The predominantly sandy zones are made up of lenticular beds of sand, gravel, silt, or clay. The predominantly clayey zones contain many thin beds of sand. Sand and gravel grade laterally into clay beds and clayey zones may grade into silt or sand in very short distances. The similarity of sediments and the lack of continuity of the beds make differentiation of geologic formations in drillers' and electric logs virtually impossible. However, White and others (1944, p. 146-147) and Lang and others (1950, p. 37) delineated the aquifer into zones based on the amount of sand and clay present as interpreted from electric logs (Figure 3). The dashed lines between logs on the cross section do not indicate formation boundaries; they separate the predominantly sand zones from the predominantly clay zones. Zones 5 and 7 include the most productive water-bearing beds in the Houston, Pasadena, and Katy areas, although some wells in the district tap sands in 1 or more of all 7 zones. Even though the clay zones appear to persist across the district in the cross section, none of the individual beds of clay within zones 3, 4, 5, 6, and 7 are continuous. Zone 2, a clay zone, underlies the heavily pumped part of the aquifer and contains the most continuous beds in the area, but it probably is not everywhere a perfect confining layer.

Table 1.--Stratigraphy and water-bearing properties of geologic formations in the Houston district

System	Series	Formation	Approximate thickness (feet)	Lithology	Water-bearing properties
Quaternary	Recent	Alluvium	0- 100+	Fluviatile deposits of brown, red, or black sand, gravel, clay, and silt in stream valleys and deltas. Also lagoonal and near-shore marine deposits.	Important water supplies developed only in valley of Brazos River. Small supplies in other areas.
	Pleistocene	Beaumont Clay	0-1,300	Calcareous bluish, yellowish, or pinkish-gray, purple, and red clay containing calcareous nodules. Light or bluish-gray sand, medium to fine grained, occurs as lenses in the clay. Buried logs, peat, plants, and shell beds are common. Basal (Alta Loma) sand 100-350 feet thick occurs in southeastern part of district. The Alta Loma sand has not been identified in the outcrop.	Yields small to large supplies of fresh water in southeastern Harris County, central and northern Galveston County, and southeastern Brazoria County to municipal, industrial, irrigation, domestic, and livestock wells. Yields slightly to moderately saline water to wells in southern Galveston and Brazoria Counties. Principal aquifer in southeastern Harris County and Galveston County.
		Lissie Formation	0-1,100+	Alternating thin to thick beds of fine to coarse, pink to gray, sand interbedded with sandy clay and clay. Contains lentils of gravel. Largely fluviatile and deltaic deposits with some layers of marine clays near the coast.	Yields small to large supplies of fresh water to municipal, industrial, irrigation, domestic, and livestock wells where present in the district except in extreme southeastern Harris County, southern Brazoria County, and Galveston County where it contains saline water.
Tertiary(?)	Pliocene(?)	Willis Sand	0- 350	Ferruginous fine to coarse sand and gravel, pink to red in surface exposures. Bentonitic gray clay interbedded and disseminated in varying amounts.	Yields small to large supplies of fresh water to municipal, industrial, irrigation, domestic, and livestock wells.
Tertiary	Pliocene	Goliad Sand	0- 250	Whitish or pinkish-gray sand cemented with calcium carbonate and interbedded with white to red gravel and greenish-gray clay. Occurs only in the subsurface in the Houston district as the Willis Sand overlaps the Goliad east of the Brazos River.	Yields small to large supplies of fresh, soft water to very deep multiple-screened municipal and industrial wells in the Houston and Pasadena areas. Most of the large-capacity wells in the Houston and Pasadena areas are screened in several of the sand beds in the Lissie Formation, Willis Sand, Goliad Sand, and the Lagarto Clay.
	Miocene(?)	Lagarto Clay	1,100-2,200	Principally yellow, gray, and green massive to laminated clay, interbedded with lenses of brown to gray, cross-bedded, medium to coarse, friable sand.	Yields fresh soft water to very deep multiple-screened wells in the Houston and Pasadena areas. Yields fresh water to domestic, livestock, municipal, and industrial wells in Montgomery County and northern Waller County.
	Miocene	Oakville Sandstone	200- 500	Crossbedded light-gray massive sand interbedded with gray or yellow calcareous clay. Continental deposits in outcrop grading into marine sediments toward the present coast. Contains reworked Cretaceous fossils and volcanic ash. Not differentiated in outcrop from Lagarto Clay, east of Brazos River.	Yields small to moderate quantities of fresh water to wells in northern part of Houston district.
	Miocene(?)	Catahoula Sandstone	700-1,200	Massive dark-brown, blue, and gray clay and silt, tuffaceous silt, and sand, and sandstone. Sandstone beds are gray, brownish-gray, and bluish-gray and are medium-grained and cross-bedded; they consist of quartz grains with opaline cement. Conglomerate bed at base in some places.	Electric logs indicate thick beds of sand containing fresh water in Montgomery County and northern Waller County. Tests in Houston indicate that the sand beds there contain saline water.

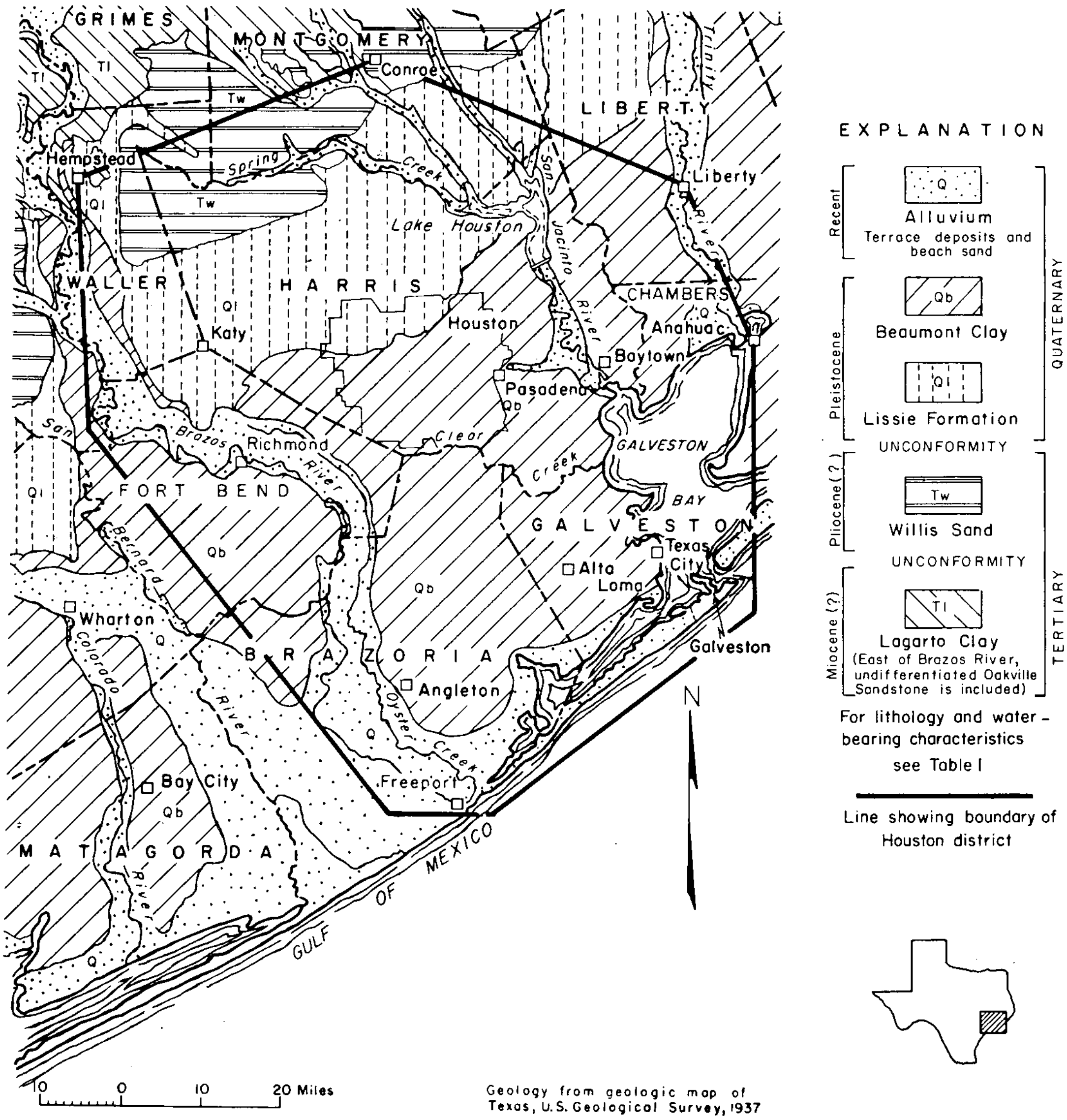

Figure 2

Geologic Map of the Houston District

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The heavily pumped part of the aquifer makes up the most important layer; it includes zones 3, 4, 5, 6, and part of 7 (Figure 3). The heavily pumped layer is defined as that part of the aquifer lying above zone 2 (Figure 4) and below the base of the "confining" layer (Figure 31) or, in areas where the Alta Loma Sand of Rose (1943) is present, below the base of the Alta Loma. Downdip from Houston, the confining layer is principally the Beaumont Clay exclusive of the Alta Loma Sand. In Houston and updip from Houston to the point where the heavily pumped layer crops out, the confining layer consists of the Beaumont Clay or part of the Lissie Formation. The confining layer is made up of alternating beds of clay and sand; it contains more clay than sand where it is the Beaumont Clay and slightly more sand than clay where it is the near surface part of the Lissie Formation. The confining layer yields water to many small to moderate capacity wells; however, the large multiple-screened public supply, industrial, and irrigation wells, which pump most of the water in the Katy, Houston, and Pasadena areas, are screened beneath the confining layer in the heavily pumped layer.

Figure 4 is a structural map of the top of zone 2. The contoured horizon does not represent a formation boundary or even a perfect hydraulic boundary, but was arbitrarily chosen to represent the base of the heavily pumped layer in the Houston district.

The Alta Loma Sand of Rose (1943) is a persistent massive sand bed at the base of the Beaumont Clay; it occurs in southeastern Harris County, southeastern Brazoria County, Galveston County, underlies parts of Galveston Bay, Chambers County, and the counties east of Chambers County. The Alta Loma Sand does not crop out, but breaks up into smaller beds of sand, and loses its identity in the vicinity of the Houston Ship Channel in Harris County. Laterally, the Alta Loma Sand can be traced eastward into Louisiana, but westward only into southeastern Brazoria County.

HYDROLOGY OF THE HOUSTON DISTRICT

Of the approximately 45 inches of precipitation that falls annually on the district, about 11 inches runs off in streams; much of the rest is evaporated or transpired or retained temporarily as soil moisture for later evapotranspiration. Some of the precipitation percolates vertically through the soil and subsoil to the ground-water body or zone of saturation. The quantity of water per unit area that reaches the water table is greater in the outcrop area of the Lissie Formation and the Willis Sand than in the outcrop of the Beaumont Clay. However, measurements of water levels in wells tapping shallow thin beds of sand in the Beaumont in downtown Houston show that precipitation from major storms causes rises in water levels within a few hours after precipitation begins. In the outcrop of the Lissie and Willis, more water is added to the ground-water body than is transmitted downdip to the discharge areas. The water table is intersected by the land surface in many places, and water is discharged by evaporation, transpiration, and by seeps and springs. The base flow of many of the streams in the San Jacinto Basin is rejected recharge.

Some of the water used for rice irrigation is returned to the heavily pumped layer. The rice is partly submerged throughout most of the growing season of 100 to 120 days, and the water not lost by evapotranspiration and runoff percolates down to the water table.

Ground water in the outcrop of an aquifer generally is unconfined and the water surface is under atmospheric pressure only. The unconfined water is said to be under water-table conditions. Downdip where the water-bearing bed is overlain by less permeable material, which transmits water very slowly, the water is confined under pressure and will rise in wells above the top of the bed in which it occurs. The confined water is said to be under artesian conditions. Before withdrawals begin, the hydraulic head of the water in the bed is controlled by the elevation of the surface of the ground-water body in the outcrop, the elevation of the natural discharge area, and the permeability. Originally, water in any sand bed in the Houston district had a higher head than the water in the overlying sand bed because the deeper sand bed crops out at a higher elevation. Because of the head differential with depth, some water moved upward through the upper confining bed, or through coarser material where the confining bed is absent, into the overlying sand bed, and eventually to the surface where the water was discharged by evapotranspiration, seepage into streams, or directly into the Gulf of Mexico. As water was discharged upward, water was added at the outcrop. The velocity of lateral movement through the aquifer became progressively less downdip as water was dissipated by loss to the overlying beds and by resistance to movement within the aquifer. The lateral movement ceased at the point where the dynamic head of the fresh water equaled the head of the sea water. In this manner, the aquifers in the Houston district were flushed of saline water several miles downdip from their outcrop. A more complete discussion of the relation of fresh to salty ground water in the Houston district is given by Winslow and others (1957).

In a large part of the Houston district, heavy withdrawals of ground water from wells tapping sand beds between about 500 and 2,000 feet, or deeper, have changed the natural conditions which were probably in equilibrium before pumping began (C. V. Theis, personal communication, 1939). In areas where more water is being withdrawn from the deep sand beds than from the shallow sand beds, the pressure differential has been reversed from the natural state, and water now moves downward from the shallow sediments to the more heavily pumped deep sediments. Also, the lowering of the pressure head in the Houston area has reversed the coastward hydraulic gradient so that the interface between fresh and salty ground water is moving updip toward centers of pumping. However, the movement of the interface is slow; the rate was estimated to be only a few hundred feet per year by Winslow and others (1957, p. 395-397).

All granular sediments contain pore spaces or interstices which are filled with water (or other fluids such as oil and gas) below the zone of saturation. The ratio of the aggregate volume of interstices in a rock or soil to its total volume is called porosity and usually is expressed as a percentage. The porosity of a granular material determines the amount of water per unit volume that it may store; whereas, the ability of the material to transmit water or to yield it from storage is governed principally by the size and arrangement of the pore spaces. The coefficient of transmissibility, which is a measure of the ability of a formation to transmit water, is defined as the number of gallons of water that will move in 1 day through a vertical strip of the aquifer 1 foot wide and having the height of the aquifer when the hydraulic gradient is 1 foot per foot. The coefficient of transmissibility can be measured in the field by means of pumping tests. The coefficient of permeability, defined as the rate of flow in gallons a day through a cross section of 1 square foot under a unit hydraulic gradient at 60°F may be determined from disturbed samples using a permeameter in a laboratory. The field coefficient of permeability has the same definition but is generally computed by dividing the coefficient of transmissibility by the thickness of the aquifer tapped by the well except that the field coefficient is at the prevailing temperature in the aquifer. The coefficients of transmissibility measured by pumping tests in municipal, industrial, and irrigation wells in the Houston district generally are in the range of 75,000 to 150,000 gallons per day per foot for the part of the aquifer screened by a particular well.

As water is pumped from an aquifer, the artesian pressure is lowered, and the weight of the overlying sediments (part of which is supported by the artesian pressure) compresses the water-bearing material, causing water to be released from storage. The coefficient of storage of an aquifer is 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. The coefficient of storage determined in the heavily pumped layer by pumping tests of a few hours to a few days duration in the typical large-capacity industrial or municipal multiple-screened well is about 0.001 to 0.002.

A small part of the water released from storage is due to the expansion of the water, but more is due to the elastic compression of the aquifer skeleton as the pressure head is reduced. With time, a larger part of the water released from storage is water that drains from the finer-grained materials either in the confining layer or interbedded in the aquifer. As water is withdrawn from a sand bed, the hydrostatic pressure in the sand is reduced and a pressure difference is established between the sand and the associated clay beds, causing water to move from the clay into the sand and the clay to be compressed. Only part of the resulting reduction in volume of the clay is elastic and reversible. Some of the clay particles are permenently rearranged and the clay is compacted. As compression and compaction of the beds occur, the land surface subsides. The ratio of subsidence to the decline of artesian pressure, expressed in feet, is about 1 to 100 in the Houston area. The ratio is smaller in the outcrop of the Lissie Formation where more sand is present, and larger in the Texas City area where the water is withdrawn from younger sediments, principally clay.

The quantity of water derived from compaction of the clay beds is many times greater than the water released from artesian storage in the sand beds. The effect of the water draining from the clay is to increase the storage coefficient from about 0.001 as measured in short-term pumping tests to about 0.01 as in inferred from subsidence data in the Houston area and larger in the southern part of the district. Winslow and Wood (1959, p. 1034) computed that about one-fifth of the water pumped from wells in the Katy-Houston-Pasadena-Baytown areas between 1954 and 1959 was water of compaction. Figure 5 shows the amount of subsidence (and the amount of water released from compaction) in the Houston area between 1943 and 1959.

The coefficients of transmissibility and storage of an aquifer are not the only factors that determine the effect of withdrawing water from or adding water to the aquifer. The effective vertical permeability governs the interchange of water between layers; this factor is difficult or impossible to measure in the field. A significant but undetermined quantity of water withdrawn from the area within the cone of depression is water that was stored in the clay or shallow beds.

The quantity of water contributed by vertical leakage from sediments overlying the heavily pumped layer also is probably greater than the quantity of water released from artesian storage within the heavily pumped layer as determined from short-term tests. The amount of water stored in the deposits above the heavily pumped layer plus the amount recharged to those deposits is many times as great as the annual withdrawals, The rate that the water moves downward to

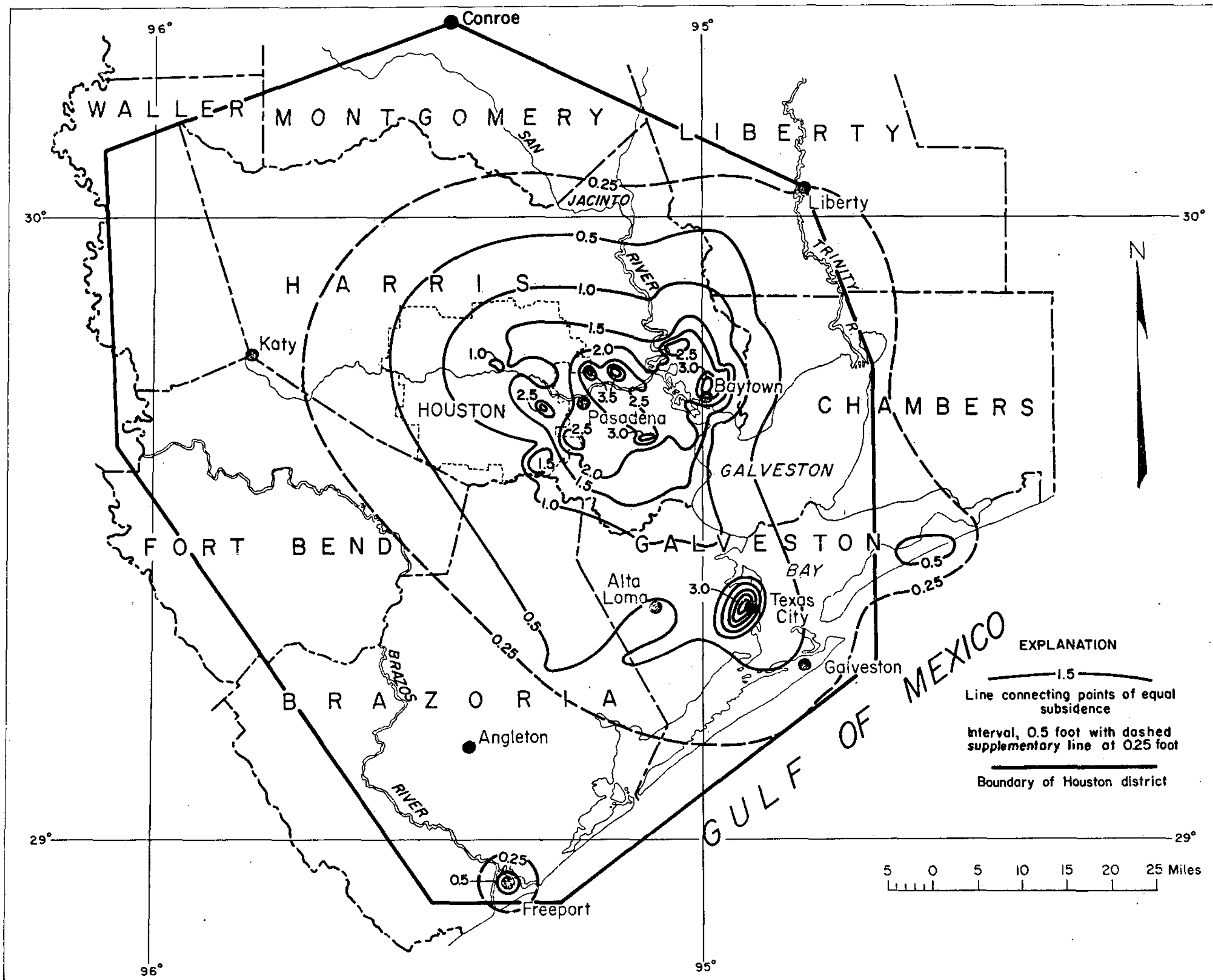

Figure 5

Approximate Subsidence of the Land Surface in the Houston District During the Period 1943-1959

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the heavily pumped layer is proportional to the head difference between the layers and the effective vertical permeability. Even though the vertical permeability of a typical bed of clay is very small, the clay beds are not persistent and each sand bed probably is connected to both the overlying and underlying sand beds at some points by material of higher permeability than clay, either silt or sand.

Disregarding the devious paths that water may move vertically, a large volume of water can move directly through the beds of low permeability. For example, the volume of water that would move through 150 feet of material having an effective coefficient of permeability of only 0.002 gallons per day per square foot under a head differential of 100 feet, would be almost 40,000 gpd (gallons per day) per square mile, or 20,000,000 gpd in an area of 500 square miles. Assuming a specific yield of 16 percent and no recharge, the removal of 20,000,000 gpd from storage would result in lowering the water table a little more than 0.4 foot per year. These figures are not necessarily correct for the Houston area, but are intended to show the possible order of magnitude of vertical leakage. Local recharge replaces some if not all of the water lost from the shallow beds by vertical leakage; however, data are lacking to determine the annual replenishment.

The contribution of water from compaction and vertical leakage to areas of concentrated withdrawals has prevented the water levels from declining as much as they would have if all the water, except the relatively small amount released from artesian storage, had moved laterally into the Houston area. The cone of depression would not only have been much deeper but also much larger than it is.

DEVELOPMENT OF GROUND WATER IN THE HOUSTON DISTRICT

The principal areas of pumpage in the Houston district are the Houston, Pasadena, Katy, Baytown-La Porte, Texas City, and the Alta Loma areas (Figure 1). Records of pumpage in the city of Houston, Alta Loma, and Texas City areas date back to the late 19th century and records of pumpage in the Baytown-La Porte area date back to 1918. Records of pumpage for the rest of the district (including the Katy area are incomplete, but, except for the Katy area, indicate that this pumpage constituted less than 20 percent of the total.

Figure 6 shows the total average daily pumpage of ground water from the modeled layers in the Houston district for the period 1890-1960.

Figures 7 and 8 show a breakdown of the major pumpage for each of the layers by areas for the same period. No attempt was made to distinguish the pumpage from the confining layer prior to 1940 because of the lack of data. Pumpage from the confining layer was very small and probably had insignificant effects on water levels in the heavily pumped layer. Small changes in water levels in the heavily pumped layer caused by the inclusion of confining layer pumpage before 1940 has since been overshadowed by later withdrawals and subsequent declines in water levels.

The pumpage rates shown in Figure 6 are totals of the detailed pumpage used in the analog model to reproduce the past history of water levels. Lesser amounts of water are being pumped from the upper confining layer, but because the pumpage constitutes probably less than 8 percent of total pumpage in the Houston district, it was not incorporated in the analog model.

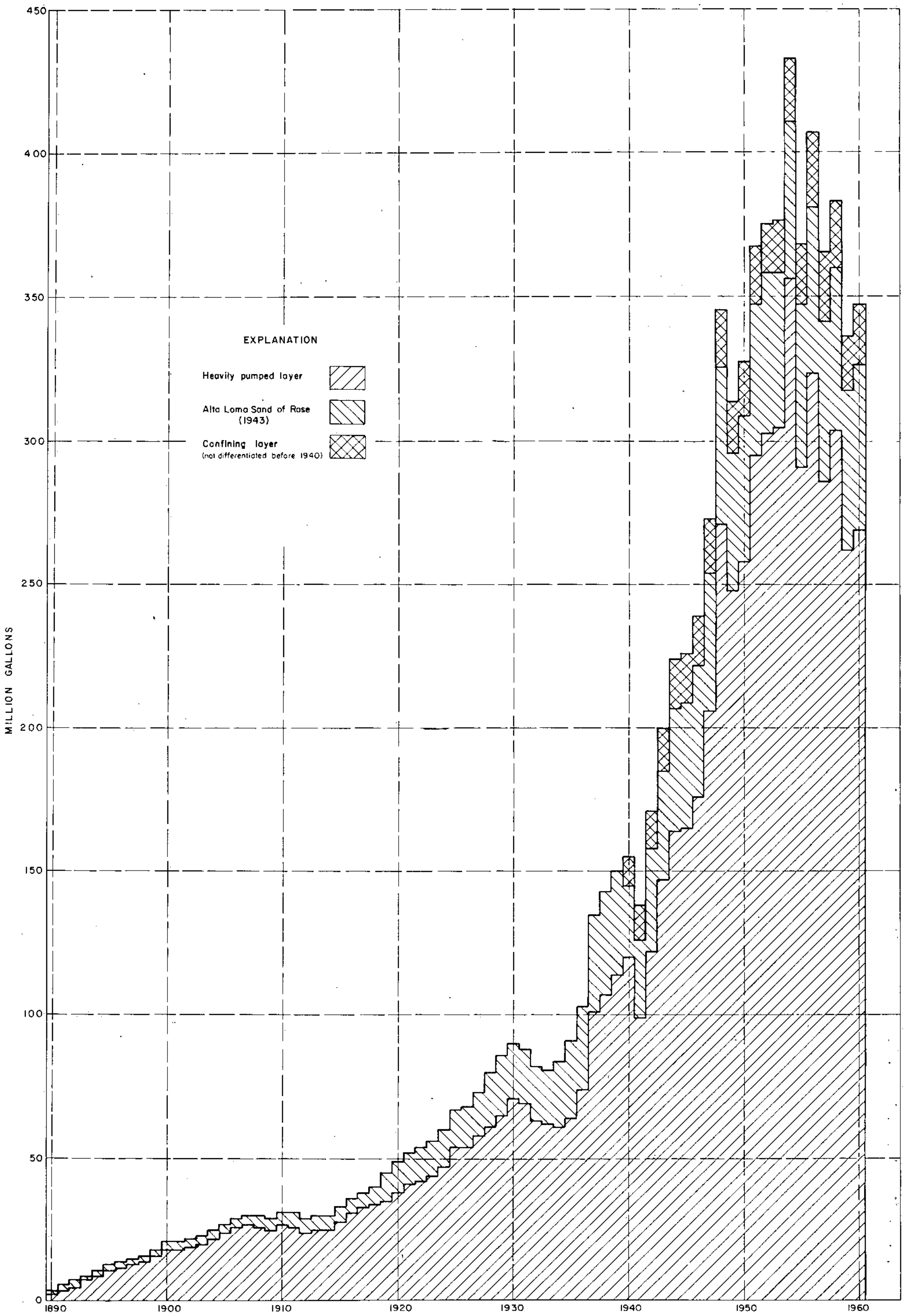

Figure 6

Average Daily Pumpage of Ground Water in the Houston District, 1890-1960

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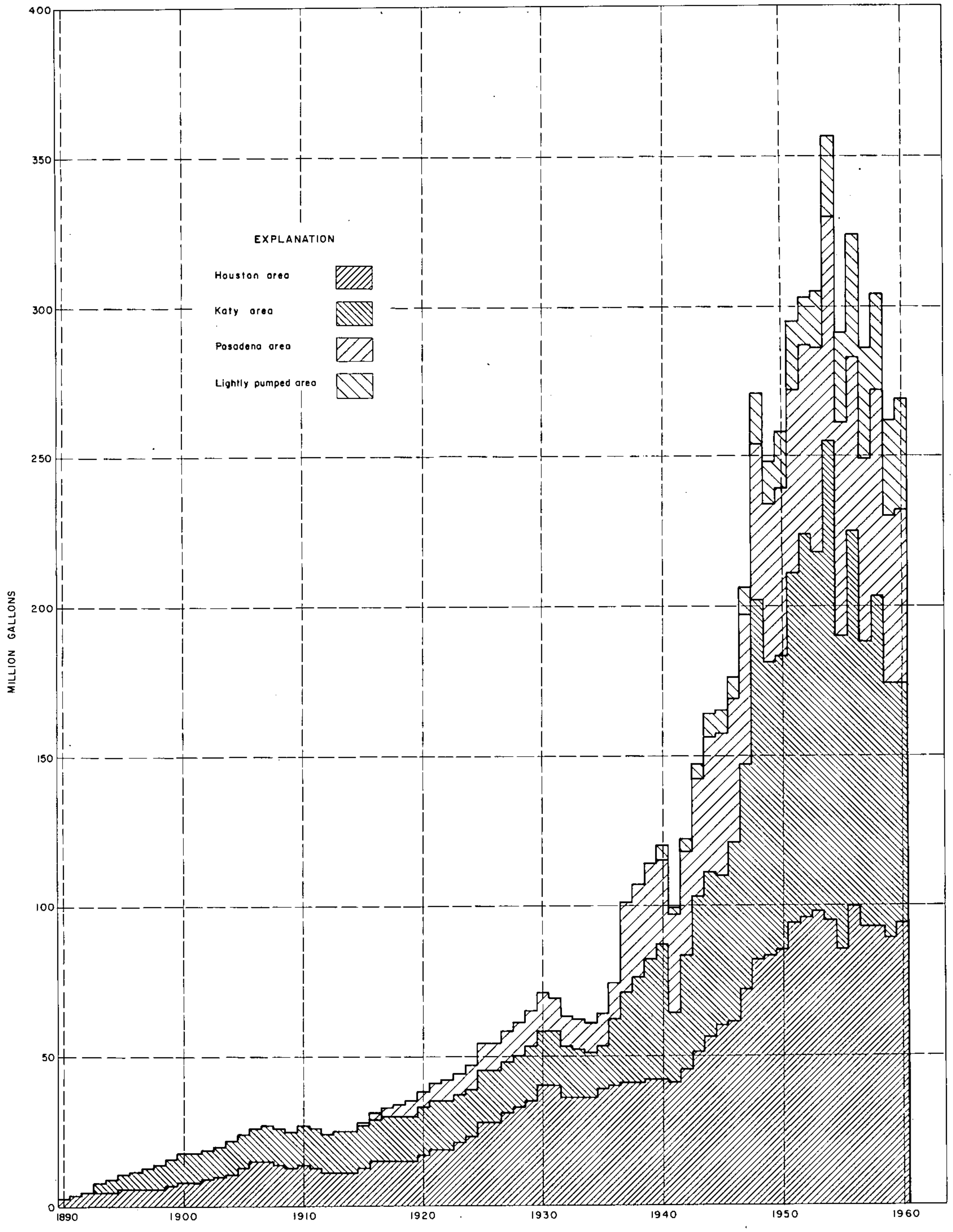

Figure 7

Average Daily Pumpage of Ground Water From the Heavily Pumped Layer in the Houston District, 1890-1960

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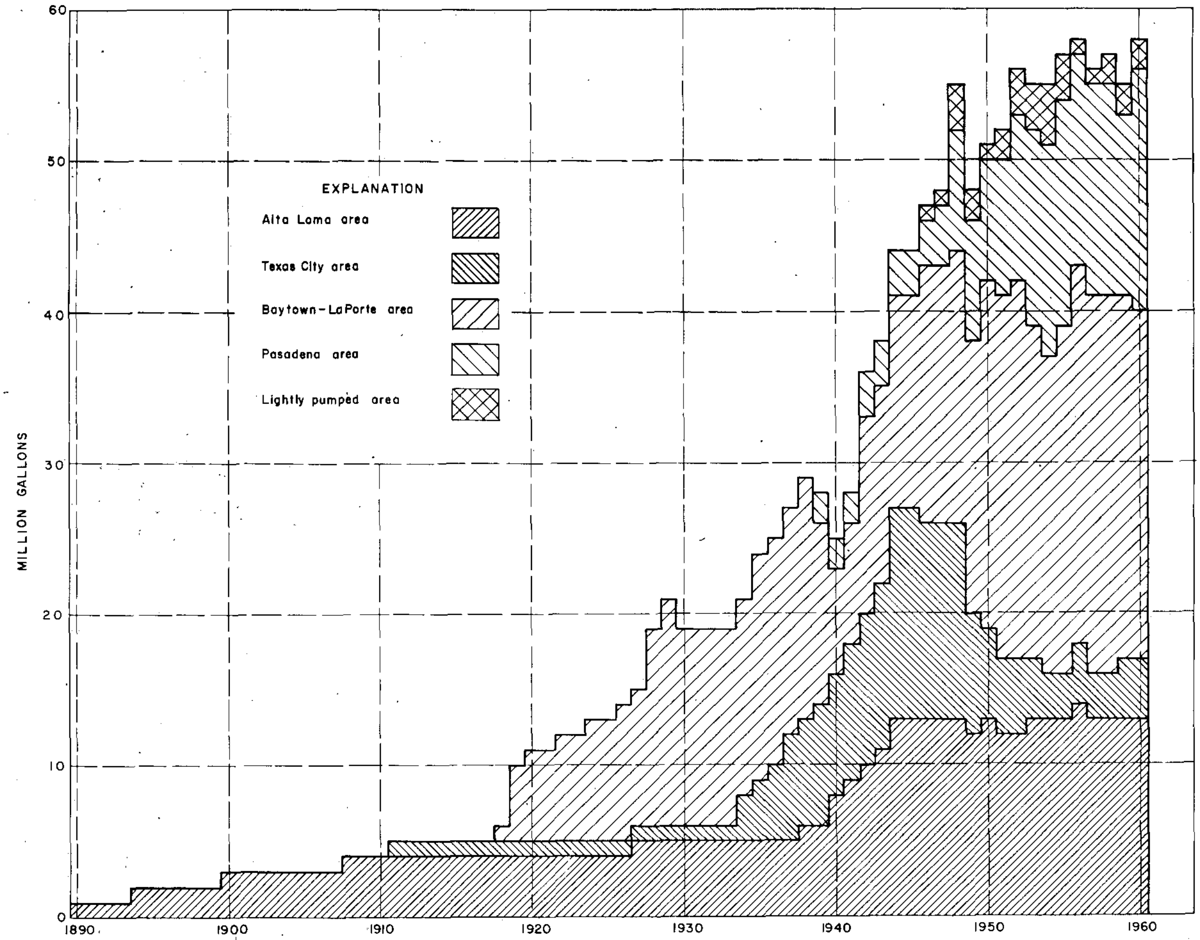

Figure 8

Average Daily Pumpage of Ground Water From the Alta Loma Sand of Rose (1943) in the Houston District, 1890-1960

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Houston Area

In 1887, when the city purchased a private water-supply company, Houston's demand for water was about 1 to 2 mgd (million gallons per day). The demand grew steadily, and in 1960, the Houston Water Department used 78 mgd of ground water and about 25 mgd of treated surface water. Until 1954, at which time ground water was supplemented by surface water from Lake Houston, the total public supply was from ground water. Public supply is the largest use of ground water in the Houston area; in 1960, only 16 mgd of a total of 94 mgd of withdrawals in the Houston area from the heavily pumped layer was for use other than public supply.

The total daily rate of pumpage from the heavily pumped layer in the area (Figure 7) shows a somewhat small but steady increase from 1890 to 1941 and then an accelerated rate of increase until 1953. The introduction of treated surface water in 1954 caused the ground-water withdrawal rate to remain comparatively stable from 1955 to 1960; increases in demand during that period were met by increases in use of the surface water.

Pasadena Area

Industrial pumpage in the Pasadena area began near the end of World War I and grew slowly until 1936 when about 12 mgd was pumped. In 1937, the construction of a paper mill increased the pumpage rate to 30 mgd. The pumpage rate increased rapidly during and following World War II; the peak year was 1953 when 87 mgd was pumped. Surface water from Lake Sheldon and the San Jacinto River was brought into the area in 1942, but the amount of surface water used was less than 20 mgd until Lake Houston was completed in 1954. In 1960, 74 mgd of ground water and 53 mgd of surface water was used in the area. Most of the pumpage in the Pasadena area is for industrial use along the Houston Ship Channel, and most of the pumpage is from the heavily pumped layer. In 1960, about 58 mgd was pumped from the heavily pumped layer and 16 mgd was pumped from the Alta Loma Sand (Figures 7 and 8).

Katy Area

All water used in the Katy area is pumped from the ground, and more than 95 percent of the water is used for the irrigation of rice. Rice irrigation in the Katy area began in the 1890's, increased gradually until about 1935, then increased rapidly until 1954 when 64,600 acres was irrigated. Acreage limitations imposed under a price-support program instituted by the U.S. Department of Agriculture caused a decline in the acreage of rice planted in 1955 and 1956, but allotment transfers from other coastal areas caused an increase in acreage planted in the Katy area from a 10-year low of 40,700 acres in 1956 to 52,000 acres in 1960. Total pumpage of water used for rice irrigation is related not only to acreage planted but also to precipitation, seepage, evaporation, and other losses, and to individual farm practices. Withdrawals of water for irrigation are made during approximately 5 months and daily rates during this period greatly exceed rates shown which, for tabulation purposes, are an average daily rate based on a full year. All major ground-water withdrawals in the Katy area are from the heavily pumped layer. The area experienced a small steady increase in pumpage from about 1 mgd in 1893 to about 60 mgd in 1946, and then a rapid increase to about 160 mgd in 1954 (Figure 7). The decreased acreage and increased rainfall caused a decline in pumpage from 1954 to 1960.

Baytown-La Porte Area

Withdrawals from large-capacity industrial wells began in the Baytown-La Porte area about the end of World War I. The pumpage rate increased from about 5 mgd in 1919 to about 9 mgd in 1927, averaged about 15 mgd from 1928 to 1946, then gradually increased to about 28 mgd in 1960. Most of the withdrawals in the area are from wells tapping the Alta Loma Sand.

Alta Loma Area

Pumping from a well field in the Alta Loma area by the city of Galveston was begun in 1894, and withdrawals gradually increased from about 2 mgd in 1896 to nearly 5 mgd in 1937 (Figure 8). Between 1937 and 1944, the withdrawals increased to about 12 mgd, and have remained at about that rate to 1960. All of the withdrawals in the Alta Loma area are from the Alta Loma Sand.

Texas City Area

Withdrawals from the Alta Loma Sand and the confining layer in the Texas City area increased from less than 2 mgd in 1930 to about 12 mgd in 1940, then rapidly increased to about 24 mgd in 1944 and 1945. Withdrawals decreased slightly at the end of World War II, then rapidly after 1948 when surface water from the Brazos River was brought into the area. Ground-water withdrawals averaged about 10 mgd from 1950 to 1960. During the peak years of withdrawal, about 70 percent was from the Alta Loma Sand; after 1950, 50 percent or more was from the confining layer.

WELL CONSTRUCTION

Practically all large-capacity wells in the Houston district, except those tapping the Alta Loma Sand, withdraw water from more than one sand bed. Public supply and industrial wells may be screened opposite as many as 20 different sand beds, and the casing in irrigation wells normally is slotted from the bottom of the surface casing or "pump pit" to the bottom of the well. The typical public supply well has 300 to 400 feet of wire-wrapped screen installed in 10- to 40-foot sections opposite the sand beds between 500 and 1,800 feet below the surface.

Fawcett (1963, p. 16) has given a complete discussion of the methods used in constructing the large-capacity wells in the Houston district. A test hole generally is drilled and logged as the first step in construction. Public supply and industrial wells then are reamed to 300-600 feet, and the large-diameter pump pit is installed and cemented in place. Pump pits range from 14 to 30 inches in diameter, but generally are 18 to 24 inches. After the cement has set for 24 hours or more, the plug is drilled out and the test hole reamed to a diameter slightly smaller than the pump pit to the bottom and underreamed to 30 to 36 inches in the sections to be screened to increase the effective diameter of the well. Then, 8- to 12-inch diameter screen and blank casing are installed, and the annular space around the screen and blank casing is packed with gravel to stabilize the wall of the hole. Even though all sand beds are not screened, the gravel packing in the wells provides a medium through which water is interchanged between sand beds and permits all sand beds between the bottom of the pump pit and the bottom of the well to furnish water to the well.

An irrigation well generally differs from municipal or industrial wells in construction. A single string of casing is set; the bottom of the pump pit is reduced to the diameter of the screen and welded to the screen, requiring the screen to be lowered in place before the pump pit. The "screen" in irrigation wells generally is slotted casing. Usually the sand beds between the surface and 100 to 400 feet in depth in the section opposite the pump pit are not screened because water (and entrained air) cascading into the well above the pump bowls would decrease the efficiency of the pump. The gravel pack is placed opposite the screen through the annular space around the uncemented pump pit; the gravel envelope extends through the entire depth of the well, and water from the shallow sand beds can flow down to the screen in the gravel envelope around the casing.

Some municipal and industrial wells are single screened, especially those that draw water from the Alta Loma Sand. Construction of the single-screened wells follows the same general procedure as construction of multiple-screen wells.

CHANGES IN WATER LEVELS

Before the beginning of heavy withdrawals in the Houston district, the water level in the heavily pumped layer generally was much higher than the land surface--that is, water would flow from wells tapping the aquifer. In 1890, the water levels were nearly representative of those before withdrawals from wells were begun in the district. Withdrawals have lowered the water level as much as 310 feet; in 1961, water levels were more than 260 feet below sea level in part of the Pasadena area. Figure 9 shows the approximate altitude of water levels in the Houston-Pasadena-Katy area in 1961, and Figure 10 shows the estimated decline in water level between 1890 and 1961. Data for the 1890 water levels are scarce, and a detailed water-level map could not be constructed, but a gradient across the area could be estimated. Figures 11 and 12 show the estimated water-level declines for the periods 1890-1946 and 1890-1953, respectively. Figures 10, 11, and 12 represent estimates of the total declines.

The water-level map for the Houston district (Figure 9) does not reflect water levels in a particular sand bed but rather in the heavily pumped layer. Most observation wells have multiple screens, and the water levels are a composite of the water levels of the sand beds tapped. No single observation well completely penetrates and screens the heavily pumped layer; thus, the water level measured in a particular well represents only a part of the heavily pumped layer. Closely spaced wells that are screened at different depths in the heavily pumped layer generally have slightly different water levels. However, in some wells that are only a few tens of feet apart but that are screened in different parts of the heavily pumped layer, the water levels differ by as much as 25 or 30 feet. Because of these conditions, maps showing water levels in the heavily pumped layer in the Houston district are regional approximations and may not be correct at any particular location or particular depth.

The water-level decline in the Katy area has been the smallest of all the declines in the areas of heavy withdrawals. Figure 13 shows a decline of about 42 feet in Harris County well 186 during the 31-year period 1931-61, or less than 1.5 feet per year. The rate of decline is small because the wells are widely spaced and close to the outcrop of the heavily pumped layer.

In the Pasadena area, the rate of decline varies markedly with changes in pumpage rates. A composite hydrograph (Figure 14) shows little net change in water levels from 1931 to 1937; the water levels declined about 14 feet per year from 1937 to 1953, rose about 5 feet per year during the period 1953-56, and then declined about 4 feet per year from 1956 to 1961. Figure 15 contains hydrographs of two single-screen wells in the southern part of the Pasadena area, which show approximately the same pattern of decline. The rate of decline from 1939 to 1953 in the southern part of the area was about the same in well 1230 as in the wells near the Houston Ship Channel (Figure 14), but was slightly less in well 1229. Water levels recovered during the period 1953-1957, but in 1957 they began to decline again; the water level in well 1230 reached a new low in 1958 and again in 1960. The water level is lower in the well screened from 1,399 to 1,414 feet than in the well screened from 1,661 to 1,676 feet (Figure 15). The upward hydraulic gradient between the sand beds, although probably lesser in magnitude than it was originally, is a reflection of the original gradient.

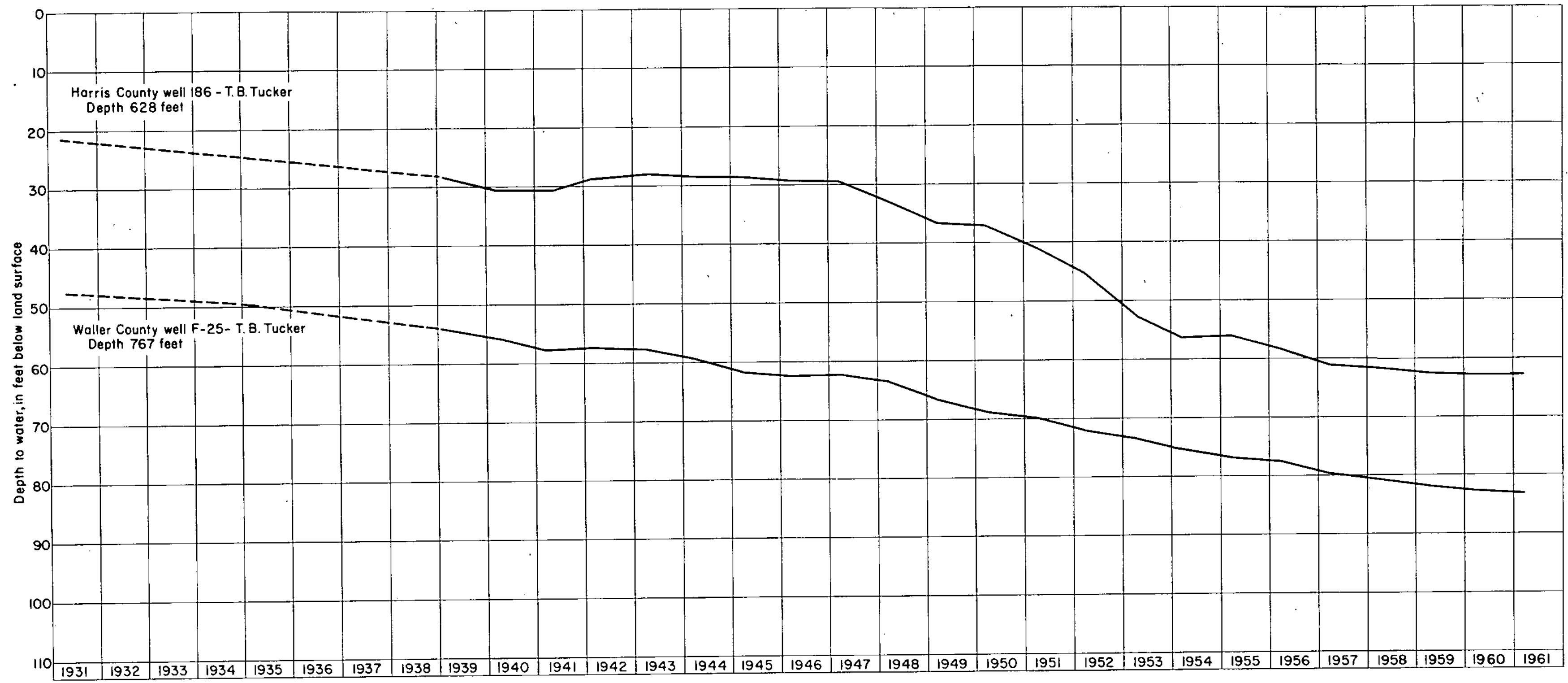
In the northern part of the Pasadena area, hydrographs (Figure 16) show a smaller decline rate, about 9 feet per year, in the heavily pumped layer (well 933) between 1938 and 1953. Only seasonal fluctuations were recorded between 1954 and 1961. Most of the decline shown in well 934 is probably due to vertical leakage downward into the heavily pumped layer.

Hydrographs of two wells (Figure 17) in the eastern part of the Katy area (Figure 1) show the downward gradient between two sand beds in the heavily pumped layer. The rate of decline in the deeper well was about 5 feet per year from 1939 to 1961 and about 3 feet per year in the shallow well for the same period. The deeper well reflects the pumpage from municipal wells in the Houston area and the shallow well is more typical of the irrigation wells in the eastern part of the Katy area.

Figure 18 shows hydrographs of two wells in central and western Houston. The pattern of decline is the same here as elsewhere in the region affected, but the rate from 1931 to 1954 was about 7 feet per year as compared to about 13 feet per year in the Pasadena area.

The difference in water level and rate of decline in different parts of the heavily pumped layer in wells that are relatively close together are shown very well by Figures 15 and 17.

Changes in water levels in the Alta Loma Sand in the Baytown-La Porte area are shown by hydrographs of three wells in Figure 19.



(After Anders and Naftel, 1962, Figure 13)

Figure 13

Hydrographs Showing Water Levels in Wells in the Katy Area

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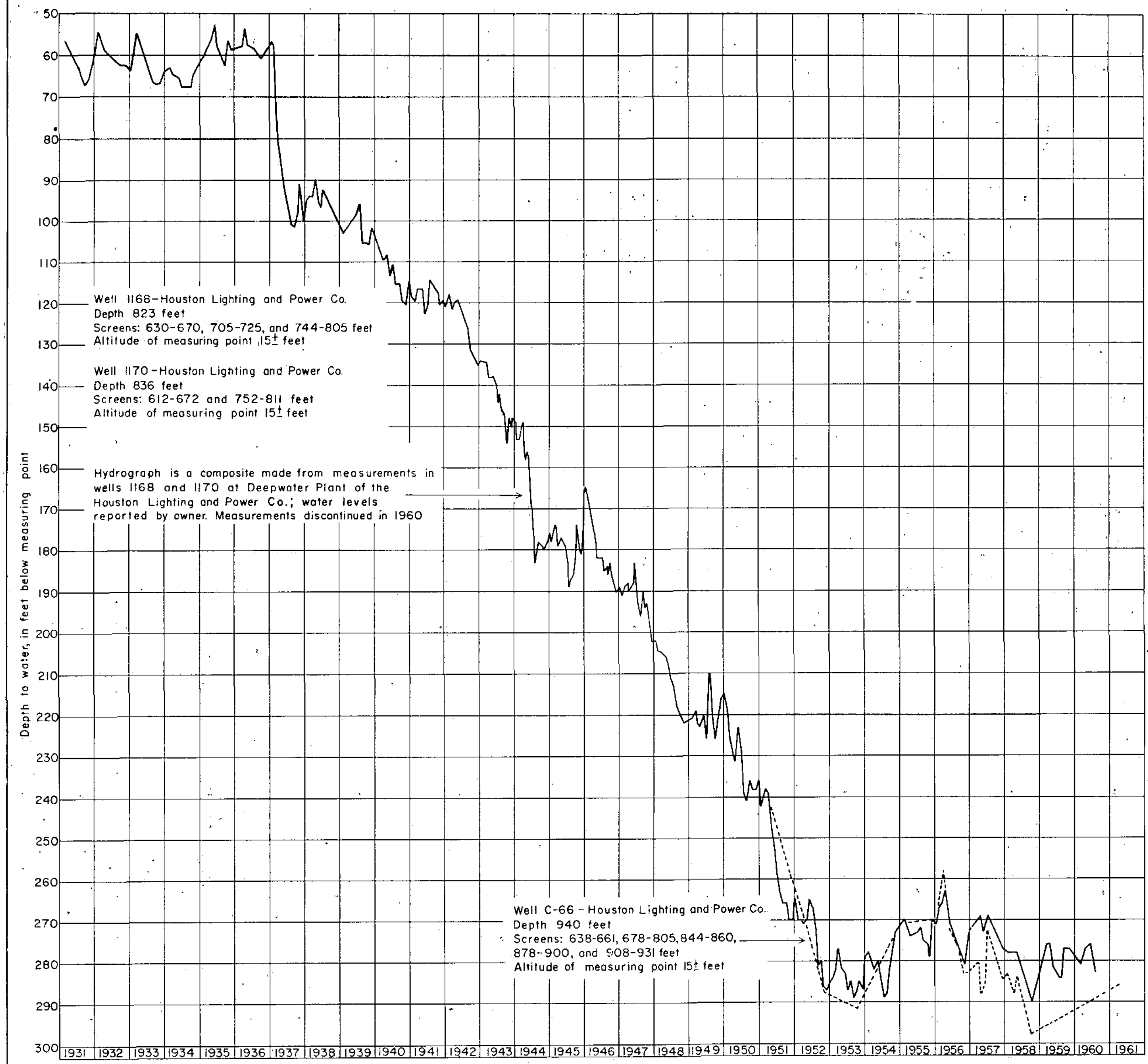

(After Anders and Naftel, 1962, Figure 14)

Figure 14

Hydrographs Showing Water Levels in Harris County Wells 1168, 1170, and C-66 in the Pasadena Area

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(After Anders and Naftel, 1962, Figure 17)

Figure 15

Hydrographs Showing Water Levels in Two Single-Screened Deep Wells in the Southern Part of the Pasadena Area

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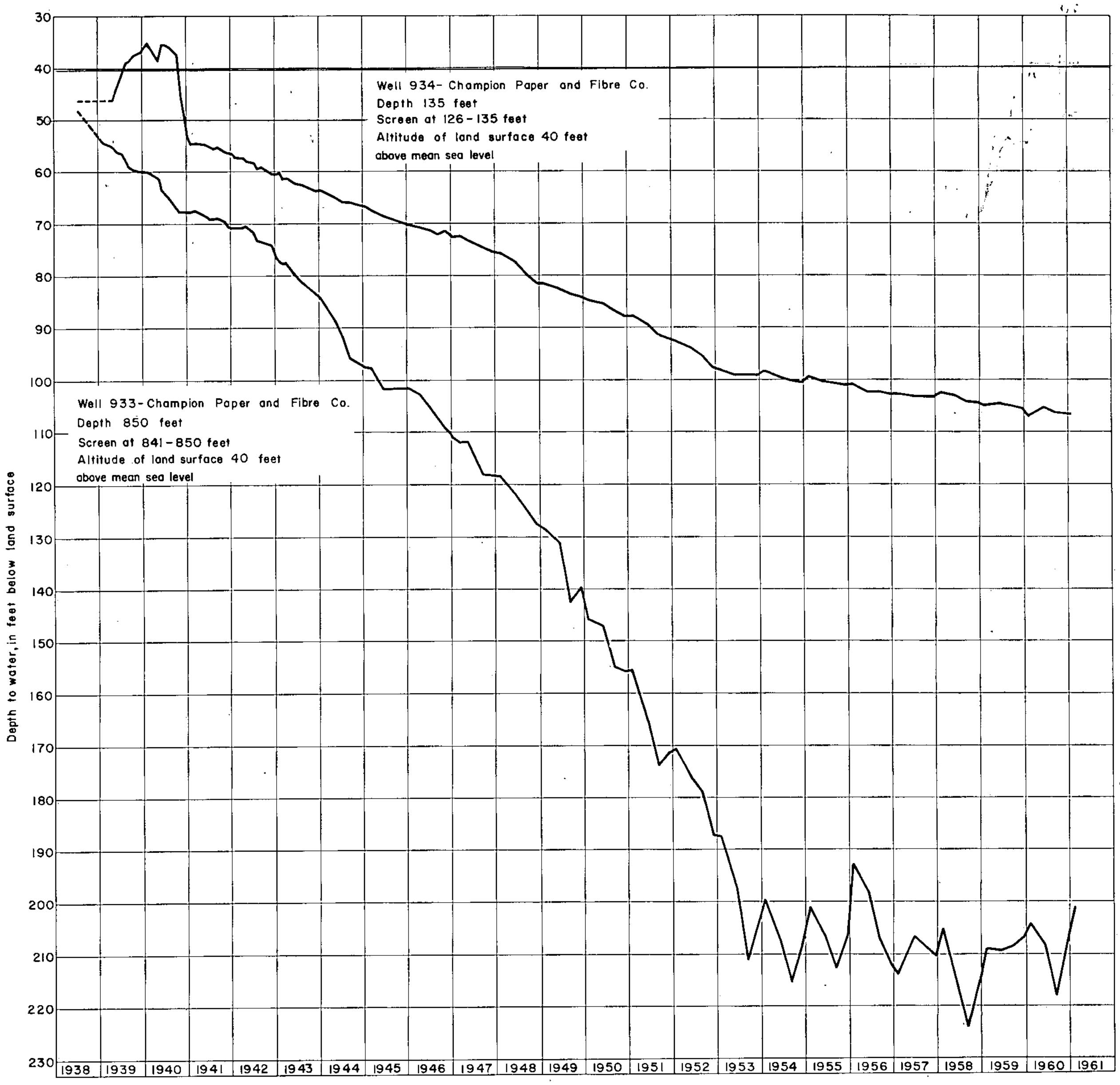

(After Anders and Naftel, 1962, Figure 15)

Figure 16

Hydrographs Showing Water Levels in a Very Shallow Well and a Moderately Deep Well in the Northern Part of the Pasadena Area

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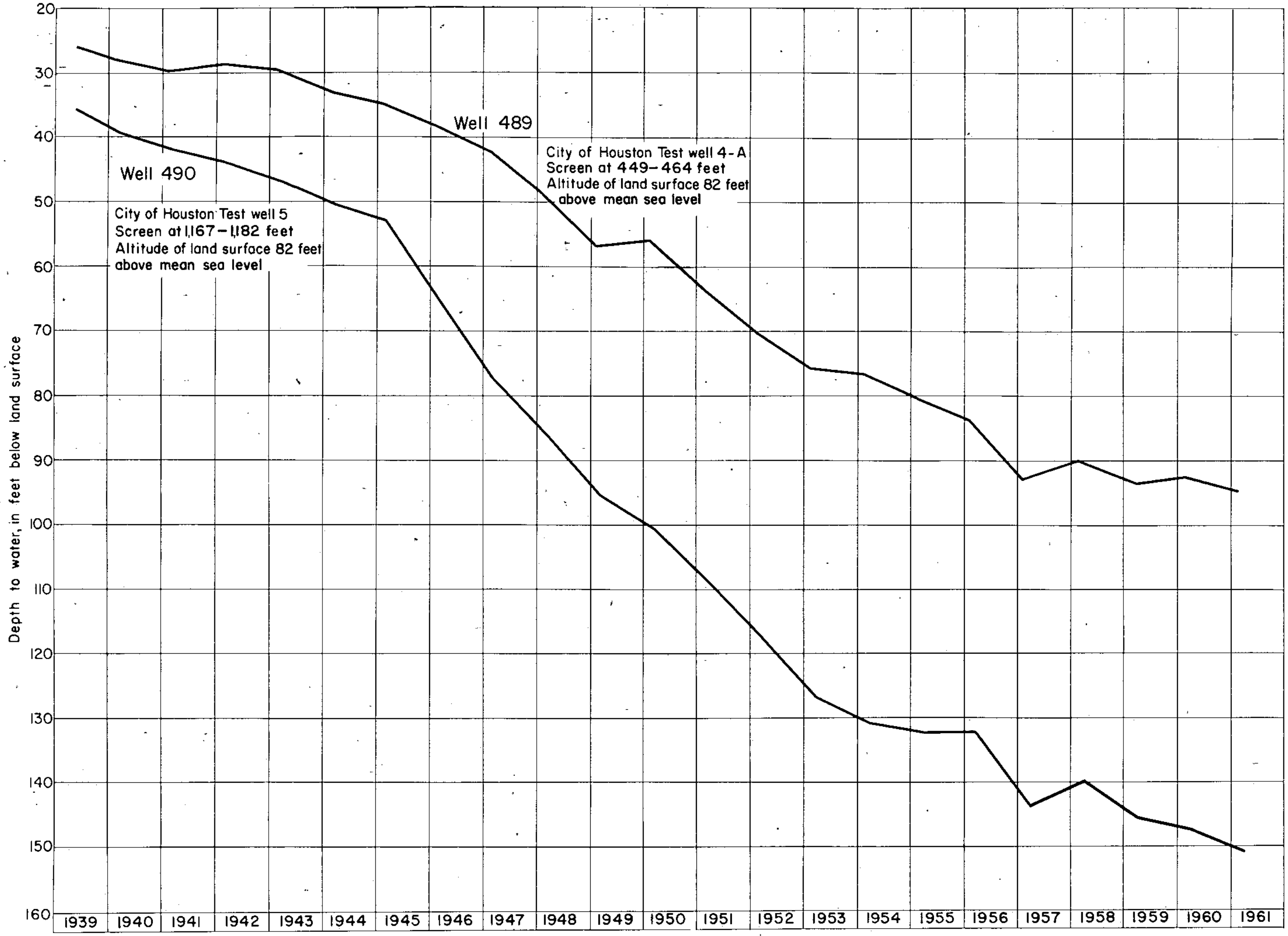

(After Anders and Naftel, 1962, Figure 18)

Figure 17

Hydrographs Showing Water Levels in Two Single-Screened Wells of Different Depths in the Eastern Part of the Katy Area

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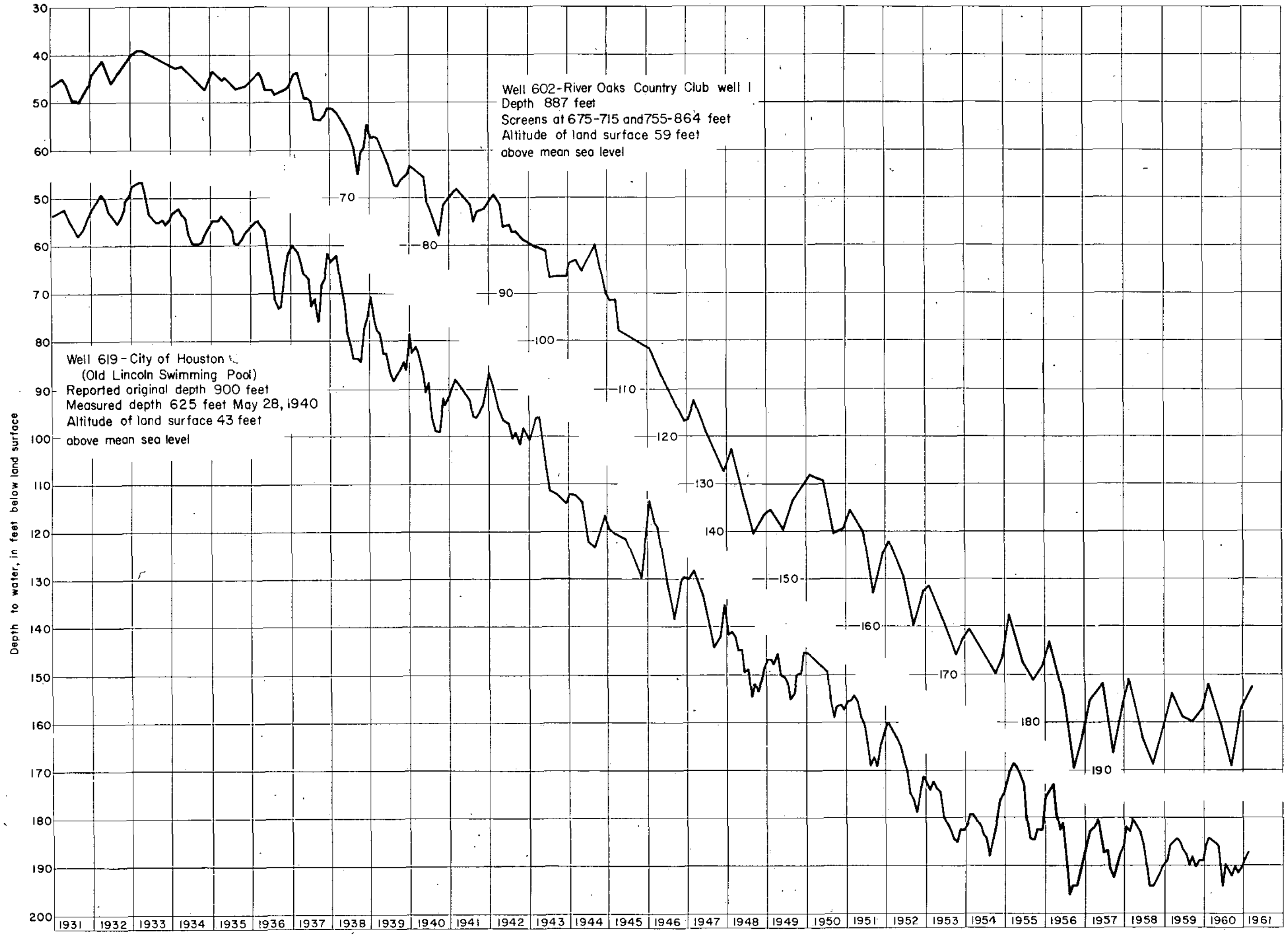

(After Anders and Naftel, 1962, Figure 21)

Figure 18

Hydrographs Showing Water Levels in Wells in Central and Western Houston

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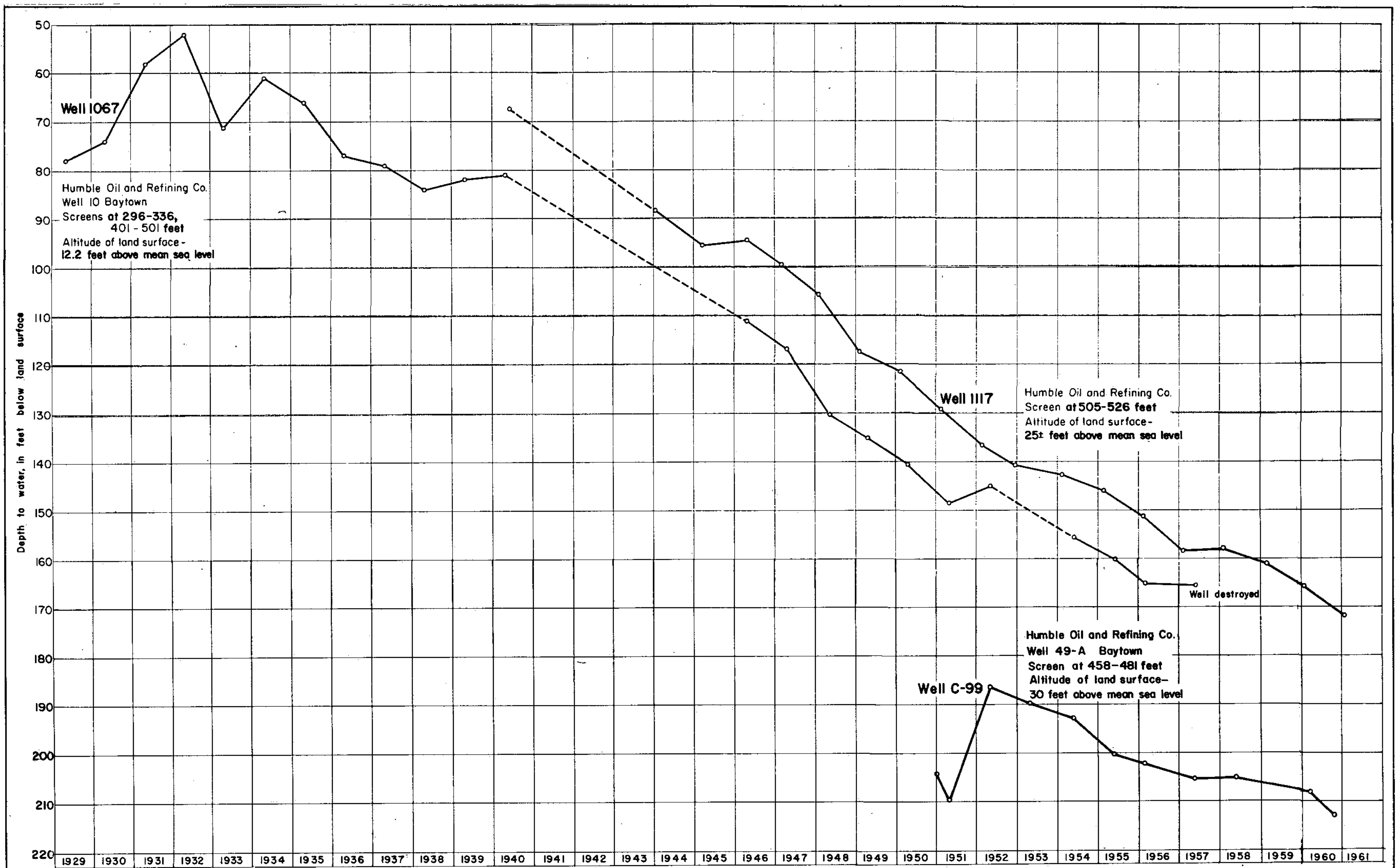

(After Anders and Naftel, 1962, Figure 26)

Figure 19

Hydrographs Showing Water Levels in the Alta Loma Sand of Rose (1943) in the Baytown-La Porte Area

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DESIGN, CONSTRUCTION, AND USE OF ELECTRIC ANALOG MODELS

By

Eugene P. Patten, Jr.

Introduction

The use of electric analog techniques for the solution of hydrologic problems was described by Skibitzke and Robinson (1954 [1]). Since that time, the use of electric analog methods has come to be regarded as one of the more powerful computing tools available to the hydrologist. Recognition of the value of analogs, and wide-spread interest in their application to study of regional ground-water flow problems led to the establishment in 1960 of the Hydrologic Analog Model Unit as an operational service unit within the Ground Water Branch of the U.S. Geological Survey. The general function of the unit is to provide facilities, equipment, and the necessary technical skills to design and construct analog models for analyzing problems of water movement.

The application of analog modeling techniques to the study of the Houston district was warranted for three reasons: (1) The hydrologic system could not be described adequately by conventional quantitative methods owing to the system's complexity; (2) quantitative interpretations of local hydrologic information--such as pumping tests--require extrapolation beyond the small areas of observation; and (3) predictions of future water levels require definition of the cause and effect relations governing the response of the regional hydrologic system.

The analog model is basically a computing device which enables the hydrologist to estimate the changes in water occurrence resulting from patterns of water use. In the Houston district, the patterns of water use are known from pumpage records and predictions. The principal change in water occurrence has been and will be the decline of water levels. The relation between pumpage and water levels is dependent chiefly on the shape and boundaries of the aquifer system, the ability of the aquifer to transmit and store water, the areal variations of aquifer coefficients, and the factors governing recharge to the system in terms of both time and location. Ground-water studies should be oriented to quantitatively define these parameters so as to facilitate sound management of the water resources.

In complex aquifer systems, it is impractical to measure all these parameters in great detail or with high accuracy. If, however, sufficient records of pumpage and water levels are available and the aquifer coefficients are known approximately, the system characteristics on a regional basis can be determined by successively changing the model design until the water-level changes computed by the model agree with observed changes.

Analog models are used in many branches of science where it is more convenient to use or measure the parameters of another physical system rather than

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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.

the one of direct interest. The electrical analogy, while not the only analogy in common use, is the most versatile and most easily adapted to the solution of hydrologic problems. The validity of such analog models depends on the rigorous definition of a one-to-one correspondence between the elements of the two physical systems--that is, every quantity which appears in the hydraulic system must be represented by an analogous quantity in the electrical system.

Skibitzke and Robinson [2] discussed the concept of the aquifer as a passive element within the hydrologic cycle. The stimulus to the passive aquifer was represented by discharge and recharge, and the response was the observed change in water levels. This concept is particularly useful to the hydrologist. It separates the non-changing geologic environment from the variable hydrologic parameters; it enables the hydrologist to modify complicated hydrologic factors with relative ease; and he can observe the effects within the constant environment of those modifications.

Direct simulation of the hydraulic environment simplifies the computational process; the hydrologic parameters may be converted directly into their electrical equivalents according to the modeling and scaling of the problem. One of the greatest benefits derived from the direct simulation technique is that all electrical phenomena observed on the model have a direct hydrologic significance, and hence, it guides the hydrologist in his evaluation of model changes and enables him to reach a better understanding of the flow system. Figure 20 shows schematically the repetitive process of comparing the model response to the observed response and the subsequent modification of the model until a sufficiently accurate correspondence has been obtained.

Theory

The partial differential equation describing the unsteady confined flow of water in a uniform porous medium was given by Jacob (1950, p. 333, equation 17):

$$\nabla^2 h = \frac{S'}{P}\frac{\partial h}{\partial t}, \tag{1}$$

where S' is the storage coefficient per unit volume of the medium, in feet^{-1}, and is defined as the quantity of water released from or taken into storage instantaneously per unit change in head per unit volume.

P is the permeability of the aquifer in feet per day.

h is the hydraulic head in feet.

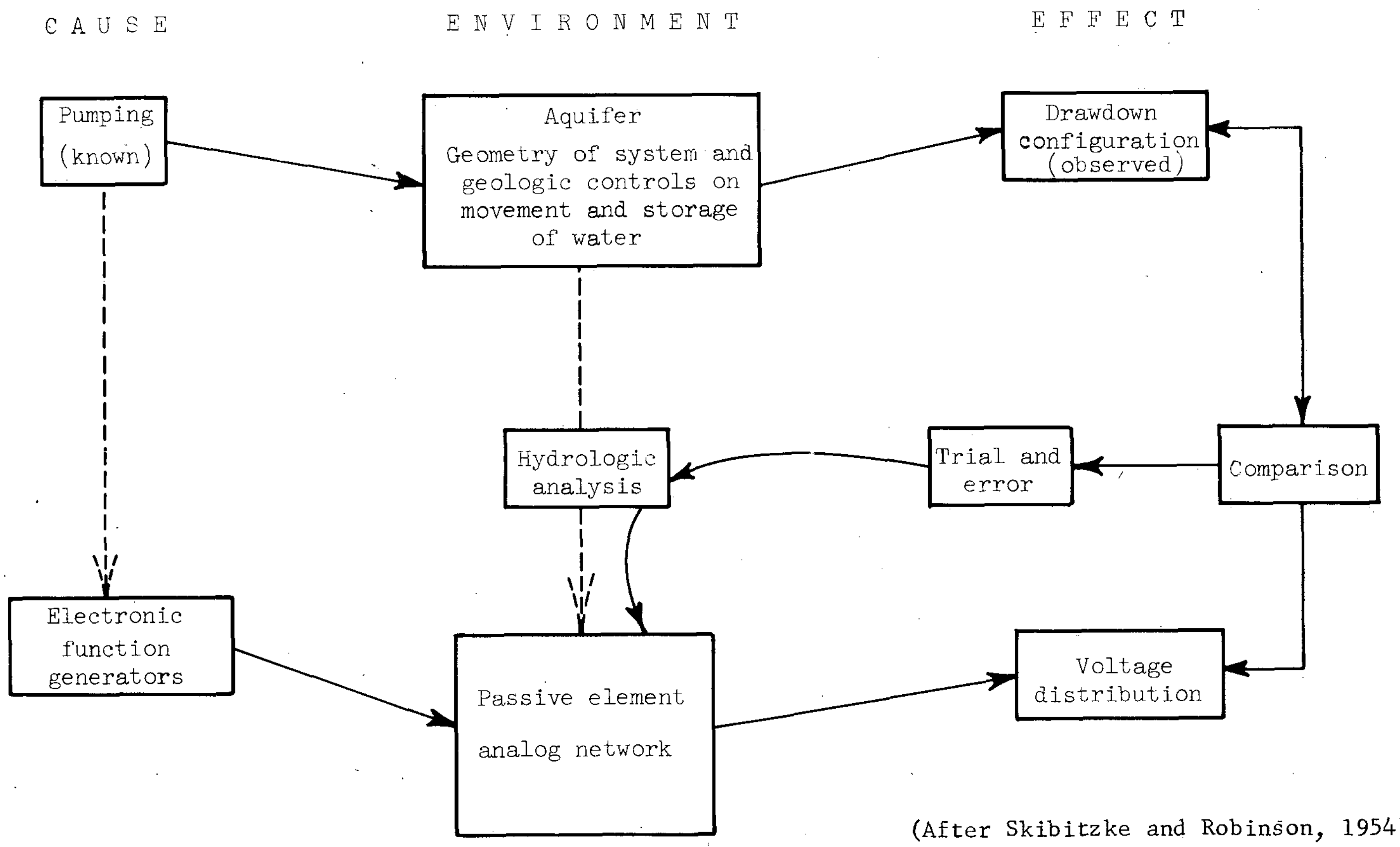
t is time in days.

∇^2 is the Laplacian operator $\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$.

The equivalent equation for a three-dimensional diffusion field in electricity is given by Karplus (1958, p. 34),

$$\nabla^2 V = RC\frac{\partial V}{\partial t} \tag{2}$$

2/ Ibid.



(After Skibitzke and Robinson, 1954)

Figure 20

Schematic Diagram of Trial and Error Method of Duplicating Aquifer Response on the Analog Model

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and can be derived directly from Maxwell's field equations (Robinson, 1963) where V = electrical potential, in volts

R = electrical resistance, in ohms

C = electrical capacitance, in farads

The similarity between the systems described by equations 1 and 2 is apparent, and these are the basic equations upon which the analog model is designed. However, inasmuch as it is difficult to construct a continous field model which simulates areal variations in transmissibility, it is necessary to resort to a finite-difference approximation of the left sides of equations 1 and 2. The analogy between the two systems is dependent on the formal similarity between the node equation of the model expressed by Kirchhoff's current law and the finite-difference equation for the aquifer segment represented by the model node (Karplus, 1958, p. 80).

The finite-difference network can be considered as a continous field composed of many unit volumes, $\Delta x \Delta y \Delta z$, of aquifer material. Each unit will then have the ability to transmit water through any of its six faces according to its permeability in the x, y, z directions. Figure 21 shows such a unit volume and its equivalent hydraulic representation by six pipes joined at a common node point. Each pipe can then be envisioned as conducting the quantity of water from one node to another and passing through one face of the cube. The potentials (hydraulic head) existing at the pipe ends, at nodes spaced Δx, Δy, Δz from the common junction, 0, can be considered h_1, h_2, etc. The average gradient in each pipe can then be expressed as a difference in head divided by the unit length of each of the pipes as follows. (After Karplus, 1958, p. 92.)

$$\left(\frac{\partial h}{\partial x}\right)_{0-1} \approx \frac{h_1 - h_0}{\Delta x} \qquad (3)$$

$$\left(\frac{\partial h}{\partial x}\right)_{2-0} \approx \frac{h_0 - h_2}{\Delta x} \qquad (4)$$

$$\left(\frac{\partial h}{\partial y}\right)_{4-0} \approx \frac{h_0 - h_4}{\Delta y} \qquad (5)$$

$$\left(\frac{\partial h}{\partial y}\right)_{0-3} \approx \frac{h_3 - h_0}{\Delta y} \qquad (6)$$

$$\left(\frac{\partial h}{\partial z}\right)_{0-5} \approx \frac{h_5 - h_0}{\Delta z} \qquad (7)$$

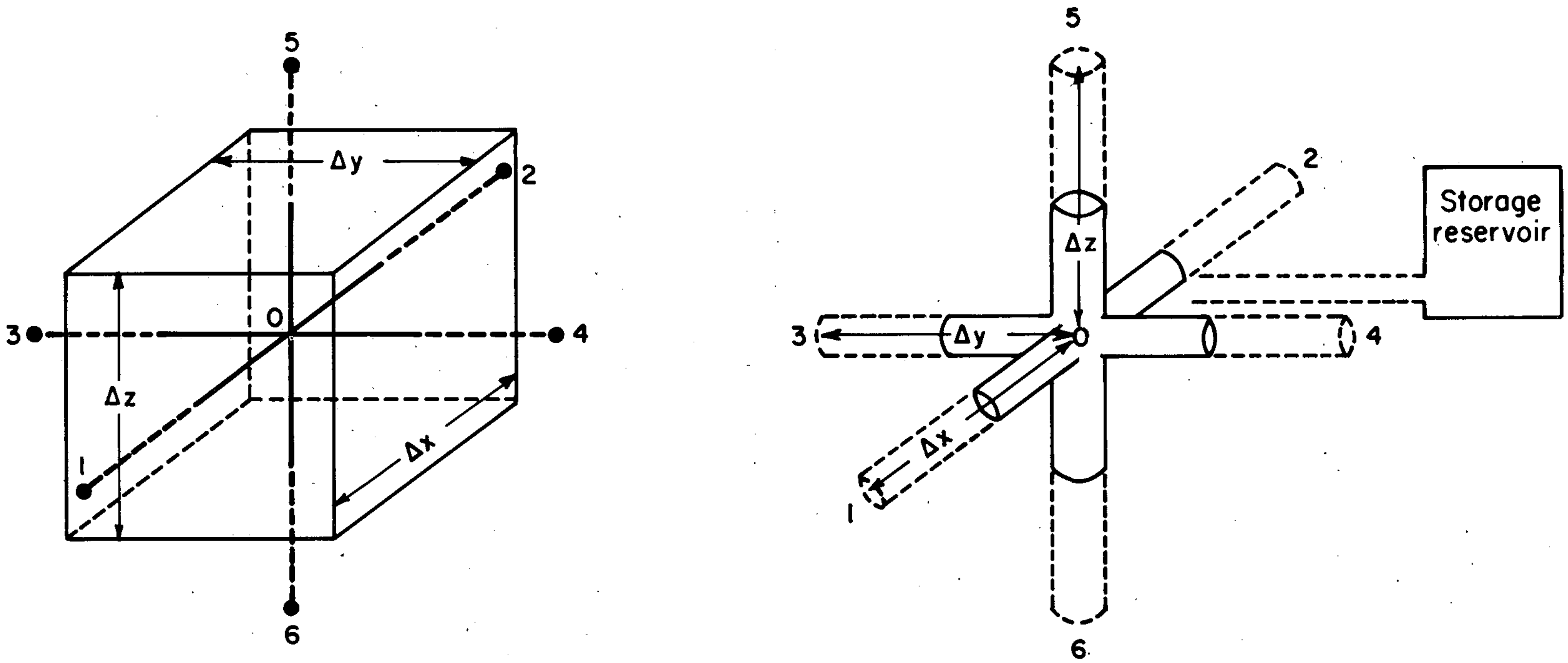
$$\left(\frac{\partial h}{\partial z}\right)_{6-0} \approx \frac{h_0 - h_6}{\Delta z} \qquad (8)$$

The second derivative with respect to x can then be obtained as follows:

$$\left(\frac{\partial^2 h}{\partial x^2}\right)_0 \approx \frac{\left(\frac{\partial h}{\partial x}\right)_{0-1} - \left(\frac{\partial h}{\partial x}\right)_{2-0}}{\Delta x}, \qquad (9)$$

and substituting equations 3 and 4 in equation 9,

$$\left(\frac{\partial^2 h}{\partial x^2}\right)_0 \approx \frac{1}{\Delta x^2}\,(h_1 + h_2 - 2h_0). \qquad (10)$$



A

Elemental cube of aquifer showing coordinate axes.

(Numbers explained in text)

B

If all flow through any face of the cube is assumed to be along these axes, a system of pipes will represent flow through the aquifer element. The storage reservoir represents the compressibility of water contained within the aquifer element.

Figure 21

Schematic Representation of Flow Through a Three-Dimensional Aquifer Element

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Similarly, the second derivatives with respect to y and z can be obtained.

$$\left(\frac{\partial^2 h}{\partial y^2}\right)_o \approx \frac{1}{\overline{\Delta y}^2}(h_3 + h_4 - 2h_o) \tag{11}$$

$$\left(\frac{\partial^2 h}{\partial z^2}\right)_o \approx \frac{1}{\overline{\Delta z}^2}(h_5 + h_6 - 2h_o). \tag{12}$$

The finite-difference expression for $\nabla^2 h$ is then

$$\nabla^2 h \approx \frac{1}{\overline{\Delta x}^2}(h_1 + h_2 - 2h_o) + \frac{1}{\overline{\Delta y}^2}(h_3 + h_4 - 2h_o) + \frac{1}{\overline{\Delta z}^2}(h_5 + h_6 - 2h_o) = \frac{S'}{P}\frac{\partial h}{\partial t}. \tag{13}$$

If $\overline{\Delta x} = \overline{\Delta y} = \overline{\Delta z} = L$, equation 13 can be written

$$\nabla^2 h \approx \frac{1}{L^2}(h_1 + h_2 + h_3 + h_4 + h_5 + h_6 - 6h_o) = \frac{S'}{P}\frac{\partial h}{\partial t} \tag{14}$$

or

$$\nabla^2 h \approx \frac{1}{L^2}\left[\left(\sum_{n=1}^{6} h_n\right) - 6h_o\right] = \frac{S'}{P}\frac{\partial h}{\partial t}. \tag{15}$$

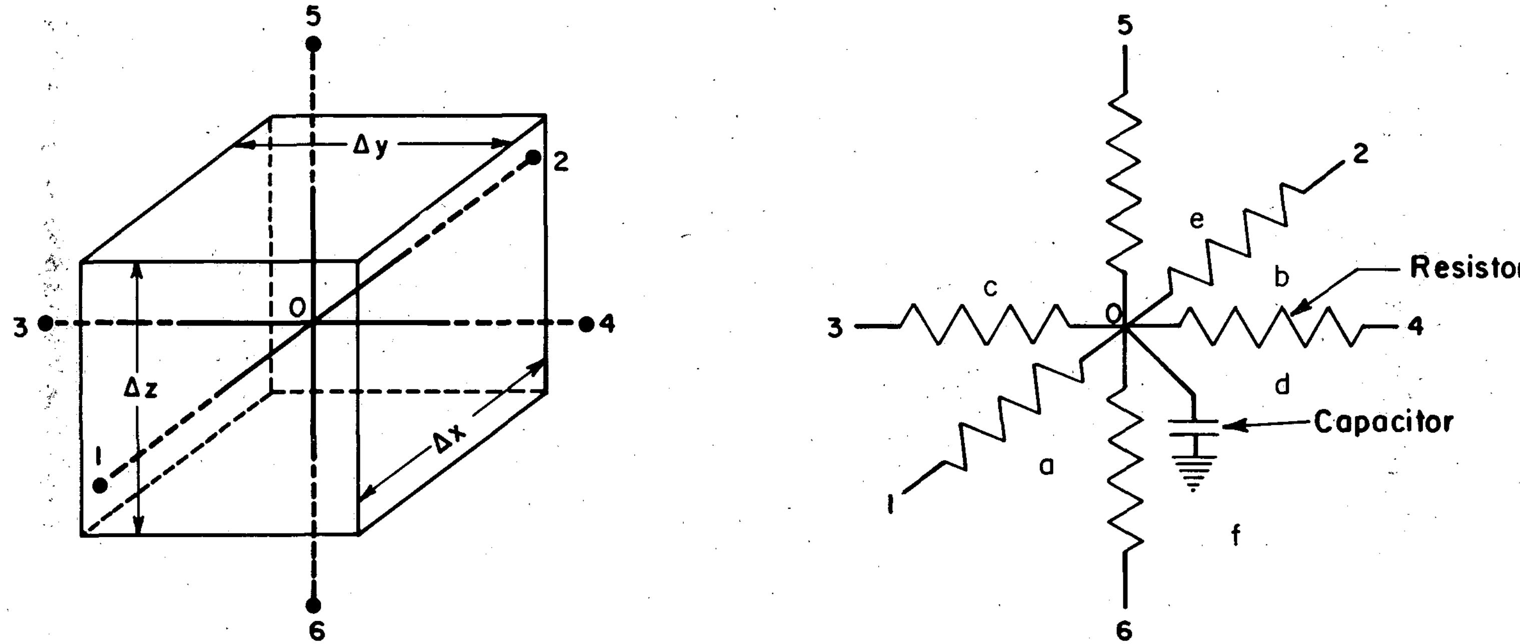
If the storage reservoir in Figure 21 is assumed to represent the unit storage coefficient of the elemental aquifer volume $\Delta x\ \Delta y\ \Delta z$, equation 15 can be modified slightly

$$L^3 P \nabla^2 h \approx LP\left[\left(\sum_{n=1}^{6} h_n\right) - 6h_o\right] = L^3 S' \frac{\partial h}{\partial t}. \tag{16}$$

The quantity LP may now by considered directly proportional to the hydraulic conductivity if it is assumed that the permeabilities in the x, y, and z directions are equal.

The node equation obtained by Kirchhoff's current law is given by Skibitzke (1961) who considered the electrical network shown in Figure 22. Each resistor represents resistance to flow of water between centers of adjacent elemental volumes of the aquifer. A capacitor connected to ground represents the storage of the elemental volume. The total current entering node 0 is

$$(V_1 - V_o)\frac{1}{R_a} + (V_2 - V_o)\frac{1}{R_b} + (V_3 - V_o)\frac{1}{R_c} + (V_4 - V_o)\frac{1}{R_d} + (V_5 - V_o)\frac{1}{R_e} + (V_6 - V_o)\frac{1}{R_f} = -\epsilon\ , \tag{17}$$



Elemental cube of aquifer

Representation of current flow by analogous resistor network. The capacitor represents the storage coefficient of the elemental aquifer cube.

(After Skibitzke, 1960)

Figure 22
Schematic Representation of Current Flow in a Three-Dimensional Analog of an Aquifer Element

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where V_0, V_1, V_2, etc. = the electrical potential at nodes 0, 1, 2 . . . ,

R_a, R_b, etc. = the electrical resistance of resistors a, b . . . ,

ϵ = the current flow from the capacitor to the node.

The rate at which a capacitor at node 0 will store a charge is given by

$$-\epsilon = C \frac{\partial V_0}{\partial t} \tag{18}$$

Substituting equation 18 into equation 17,

$$C \frac{\partial V_0}{\partial t} = (V_1 - V_0)\frac{1}{R_a} + (V_2 - V_0)\frac{1}{R_b} + (V_3 - V_0)\frac{1}{R_c} +$$

$$(V_4 - V_0)\frac{1}{R_d} + (V_5 - V_0)\frac{1}{R_e} + (V_6 - V_0)\frac{1}{R_f}. \tag{19}$$

If the resistances R_a, R_b, R_c ... are each equal to R, equation 19 may be written

$$C \frac{\partial V_0}{\partial t} = [\ (V_1 + V_2 + V_3 + V_4 + V_5 + V_6) - 6V_0\ ]\frac{1}{R} \tag{20}$$

or

$$\frac{1}{R}\left[\left(\sum_{n=1}^{6} V_n\right) - 6V_0\right] = C \frac{\partial V_0}{\partial t}. \tag{21}$$

Rewriting equation 16 as follows, the formal analogy may be seen by comparing with equation 21.

$$LP \sum_{n=1}^{6} h_n - 6h_0 = L^3 S' \frac{\partial h}{\partial t}$$

It should be noted that the storage coefficient per unit volume used in analog modeling is the storage of a unit volume of aquifer material, L^3S. The direct analogic proportionality between head and voltage, time in the two systems, storage and capacitance, and permeability and reciprocal of resistance permits the direct use of equations 16 and 21 for designing analog models.

Although equation 16 is derived from consideration of altitudes of water levels, an identical form describes drawdowns or recovery due to change in pumping rates or other boundary conditions. The equations used for the model study are obtained by simply substituting the symbol s, generally used to indicate a drawdown in water level, for h. The Houston study is chiefly concerned with changes in the system due to pumping and, therefore, the equations used for analsis were derived from the drawdown form of equation 16. Model scaling factors, described briefly in the following paragraphs, are the same for both equations of head or drawdown.

Scaling

Equations 16 and 21 show the formal analogy between the electrical and hydraulic systems, and each parameter or variable in the equation governing the flow of water has an equivalent term in the corresponding electrical equation. In order to construct an analog model of a hydraulic system, it is necessary to make these analogous quantities proportional through the use of constants of proportionality or scale factors.

Although the selection of the values of the scale factors is arbitrary, the useful values are limited by operating ranges of electronic equipment used to impose voltages, to provide current, and to measure time and voltage. Also, there must be an internal consistency among the scale factors. The table below summarizes the analogous quantities of the two systems.

Hydraulic		Electric	
length, in feet	ℓ_w	length, in feet	ℓ_e
potential, head in feet	h	potential, volts	V
mass, in pounds	M	energy, in coulombs	Q_e
time, in days	t_w	time, in seconds	t_e
discharge, in feet^3 per day	q_w	current, in amperes	q_e
permeability, in feet per day	P	resistance, in ohms	R
storage coefficient per unit volume, in feet^{-1}	S'	capacitance, in farads	C

It can be seen that length, mass, time, and potential are the four fundamental dimensions involved in flow through the aquifer. The fundamental dimensions of the flow of electricity in the model are length, energy, time, and potential. By selecting values of scale factors between the pairs prototype length and model length, mass and energy, prototype time and model time, and prototype potential and model potential, the analogy between flow of water and electricity is completely defined. The fundamental units as shown in the above table are seldom applied directly in the analog analysis because the working units generally applied to water are not consistent with those of the fundamentals, except for time. The four basic scale factors, K_ℓ, K_e, K_t, and K_v, may be defined as follows:

Length : $\ell_w = K_\ell f_e$; $\frac{\text{feet}}{\text{feet}} = K_\ell$

Mass and Energy: $Q_w = K_q Q_e$; $\frac{\text{gallons}}{\text{coulomb}} = K_e$

Time : $t_w = K_t t_e$; $\frac{\text{days}}{\text{seconds}} = K_t$

Potential : $V = K_v h$; $\frac{\text{volts}}{\text{feet}} = K_v$

The odd assortment of units given for the mass and energy relation results directly from the adoption of the gallon as a common measure of water. The four basic scale factors listed can be used to derive the scale relations between other analogous properties. For example, by algebraic comparison of Ohm's law and Darcy's law, it can be shown that the product PR equals $K_v K_\ell K_q / K_t$.

Construction

The transmissibilities and storage characteristics of the heavily pumped layer were simulated by a resistor-capacitor network constructed for convenience in two sections (Figures 23 and 24). The transmissibilities and storage coefficients of the Alta Loma Sand were simulated by a second network (Figures 23 and 24) of resistors and capacitors.

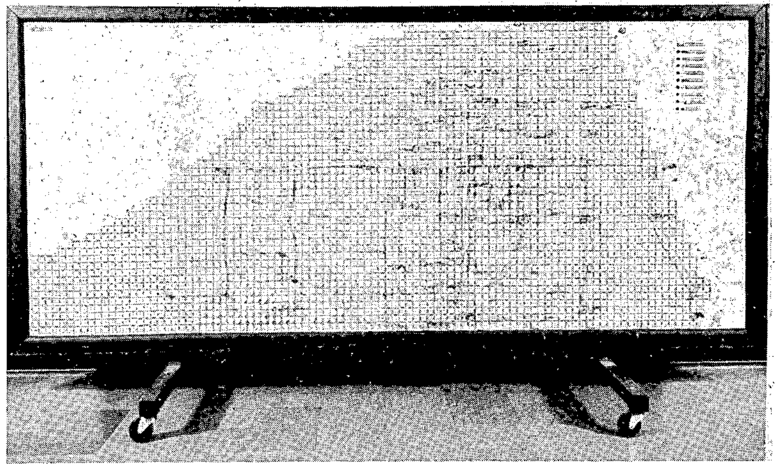
Each network was constructed over a 1-inch = 1-mile base map of the Houston district, and each resistor in the network represented the transmissibility of the particular segment of the aquifer mapped beneath it. Capacitors connected between electrical ground and each node simulate the storage characteristic of one square mile of aquifer.

The equivalent node points on each network were connected by wires. Because the effective vertical permeabilities between the Alta Loma Sand and the heavily pumped layer are unknown, a variable resistor was placed in each of the leads connecting the two networks. The variable resistor facilitated model design by allowing convenient trial and error adjustment of vertical permeability. Once the observed potential patterns were duplicated by the model, the value of the variable resistor could be measured and those values converted to effective vertical permeability by use of the scaling factors.

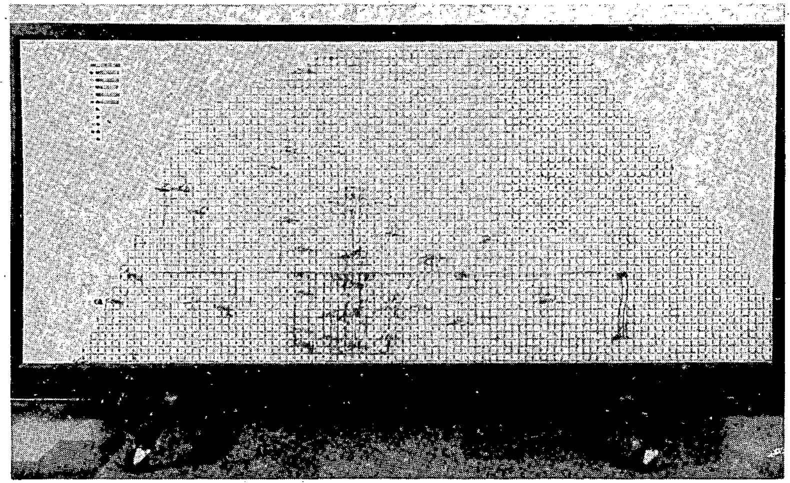
Only the storage contributed by vertical leakage from the confining layer to the underlying layers was modeled because the pumpage from the confining layer is insignificant.

Because the heavily pumped layer is thick and vertical flow conponents have been observed, several networks representing the transmissibility and storage coefficients of zones within the layer would have improved the aquifer representation. However, the construction of such a model would have required detailed identification of the transmissibility and storage coefficients, as well as the vertical permeability, of each zone. Such detail cannot be extracted from the basic data presently available in the Houston district. The model of the heavily pumped layer as completed for this study represents the effective hydraulic characteristics of that part of the aquifer system most directly influenced by the pumping wells. Adoption of such a hypothetical aquifer leads to computation of average or hypothetical water levels by the analog model.

The dominant storage characteristic of the aquifer system is the release of water owing to compaction of clay in response to reduced water pressures, the water being released to the sand beds; storage of the aquifer was computed on the basis of feet of land subsidence per 100 feet of water-level decline. The values assigned ranged from less than 0.01 in the Katy area to 0.03 in the southern part of the Houston district. The artesian storage coefficient of the heavily pumped layer is relatively insignificant and, consequently, it was not included in the model design. Because the major storage component of the aquifer was derived from the clays, the release of water is time dependent and a function of the thickness and vertical permeability of the clays. Storage

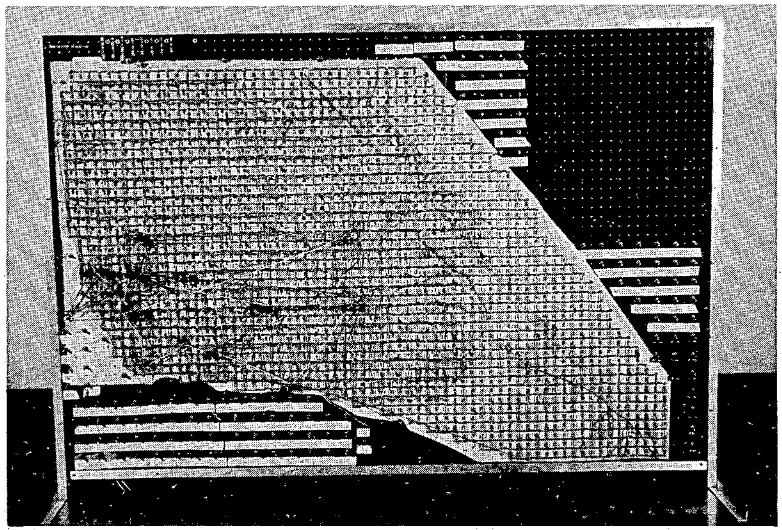


West half



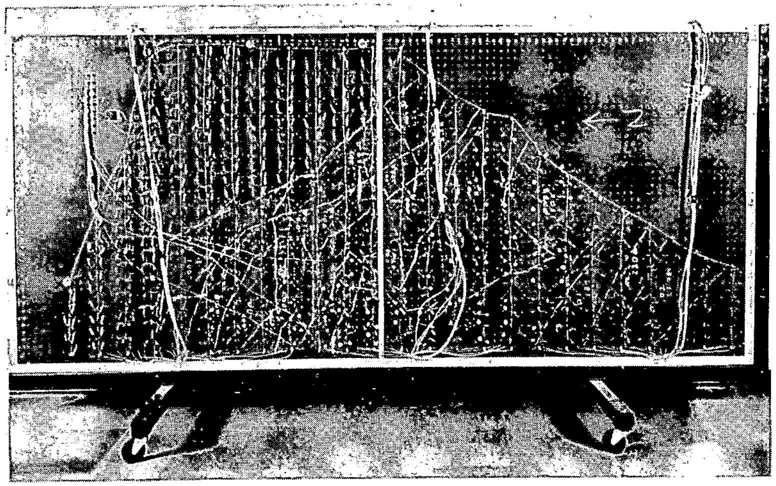
East half

A.--Heavily pumped layer

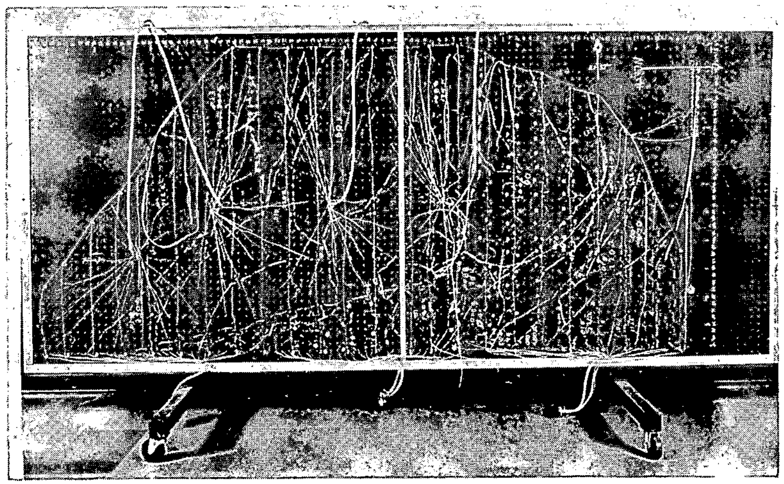


B.--Alta Loma Sand of Rose (1943)

Figure 23.--Analog network (front views) showing resistors, pumping centers, and electrical input connections

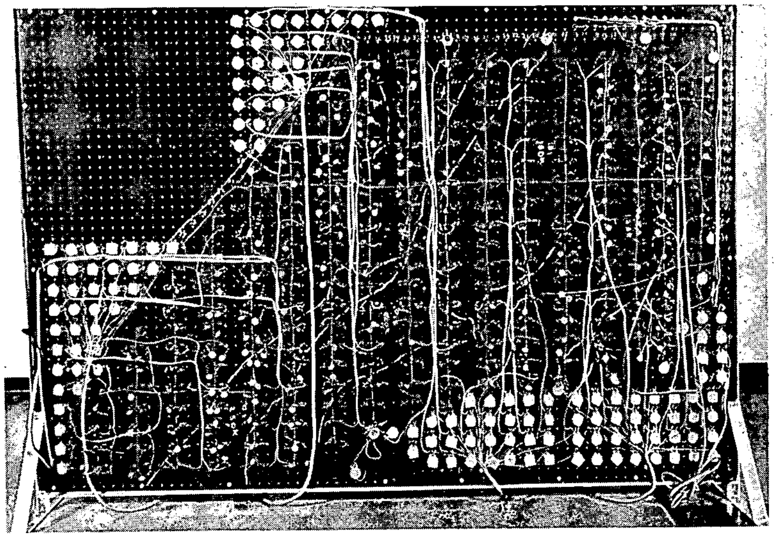


West half



East half

A.--Heavily pumped layer



B.--Alta Loma Sand of Rose (1943)

Figure 24.--Analog network (back views) showing storage capacitors and cabling

capacitors, which were scaled according to the storage coefficients computed from the subsidence data, were connected in series with appropriate resistors and connected to electrical ground. The amount of water released from storage by the clay is proportional to the total clay thickness, but the rate of release is dependent on the vertical permeability and thickness of the individual beds. Complicating the problem of estimating the value of storage is the unknown relative proportion of subsidence in the confining layer to subsidence in the heavily pumped layer. Total storage was arbitrarily divided between the upper and lower clays. The younger clays in the confining layer are undoubtedly more porous and less compact than the older clays in the heavily pumped layer. However, the thickness of the clay in the confining layer is considerably less than that in the heavily pumped layer. Because the relative contribution from storage yielded by the different clay layers was unknown, the values of the storage parameters entered in the initial model design were estimated. However, the areal distribution of storage as computed from data on clay thickness is probably in the correct proportion, so it is possible to synthesize their values by changing other model parameters so as to duplicate the observed relation between pumpage and water level response.

Boundary Conditions

The outcrop of the heavily pumped layer is a recharge area for the aquifer, and it also supports local withdrawals for irrigation. The discharge-recharge relations could not be identified in the field because of inadequate original water-level data, unknown irrigation return and recharge from precipitation, and rough estimates of amount and distribution of pumpage. In order to approximate these conditions, a bank of thermionic diodes was used on the model to provide a constant current which simulated the net recharge to the outcrop area; the amount of current was determined by trial and error approximation of the recharge necessary to duplicate the water-level decline (Figure 25).

The other physical boundaries of the model of the heavily pumped layer were constructed sufficiently remote from the Houston-Pasadena area so as to have negligible effect on computed water-level declines.

The Alta Loma Sand, at its northern and western boundary, interfingers with sand beds in the unmodeled confining layer, and water-level contour maps show a regional hydraulic gradient which indicates that a significant volume of water flows across the boundary. The flow of water was simulated by current flow through a resistor connected between electrical ground and the boundary. The current flowing in the resistor was proportional to the potential existing at the boundary.

The southern boundary of the Alta Loma network was sufficiently remote from the pumping centers to minimize computational error.

Pumping Program

About 150 model wells or pumping centers were used on the model to represent approximately 1,100 industrial, municipal, and irrigation wells. In general, each model well represented the composite pumpage from an area of 3 to 5 square miles. The coarseness of this modeling did not introduce serious errors in the computed water-level declines regionally, although the decline in the immediate vicinity of each well was exaggerated. Theoretically, decline near

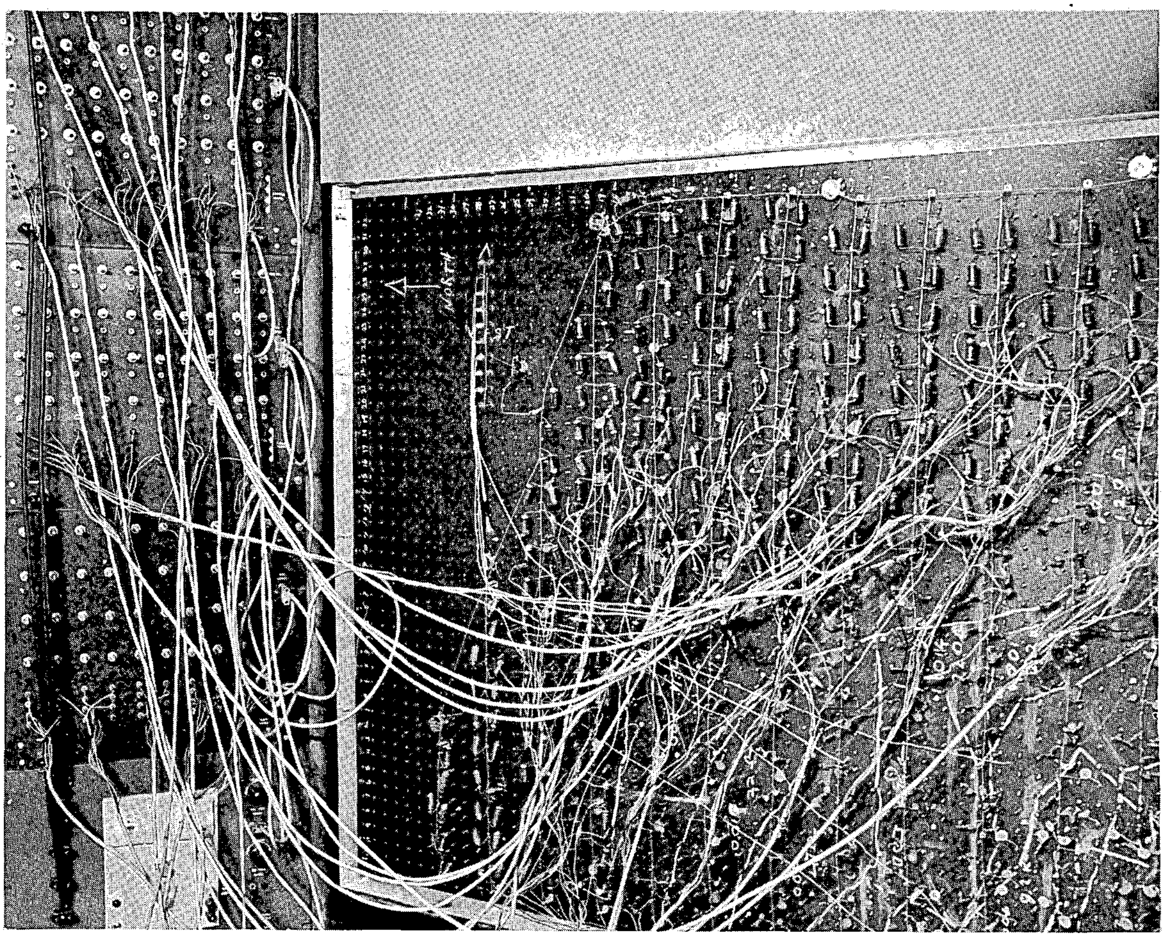


Figure 25.--Diode bank and west half of heavily pumped layer showing connection of individual diode leads to the passive element network

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the wells could be computed more accurately if the density of the model wells were increased.

Five pumping periods were used to approximate pumpage from 1890 to 1960. These periods were 1890-1930, 1931-1940, 1941-1947, 1948-1953, and 1954-1960. An electronic function generator was used for each pumping period. The generator's output consisted of a square wave pulse having a constant amplitude, and duration of the pulse was proportional to the number of days in the pumping period. The output terminal of each pulse generator was connected to a group of resistors, each of which represents model wells. The value of each resistor was inversely proportional to the average pumpage from the well represented by the resistor during a pumping period. If a well was pumped continuously, but at different rates each period, the model well had five resistors, one for each period, and pulsed by separate generators.

In some locations pumpage was significantly reduced at various times. In order to approximate the net discharge at these locations, it was necessary to superimpose recharge. Three pulse generators were used as recharge wells during the last two periods and for predictions. The approximation of the pumping history resulted in a complex wave-form, which was applied to the model about once every three seconds.

The time interval between pulses was needed to let the network capacitors return to zero voltage (and zero drawdown) before the pumping sequence was repeated.

Analysis

The electronic equipment used to excite the model is shown in Figures 26 and 27. The pulse generators and the operational amplifiers used for voltage amplification and to provide positive polarity pulses for the recharging wells are shown in Figure 26; the diode bank, and the oscilloscope used to measure voltage levels on the net, are shown in Figure 27.

The output of the function generators was distributed to the wells and voltage drop was measured at each node (Figure 27).

Figure 28 is an oscillogram showing a typical time-drawdown curve obtained from the model. Time in microseconds (model time) and years (prototype time) is shown on the abscissa, and potential in volts and feet of drawdown is shown on the ordinate.

Analysis consisted of measuring the decline computed by the model for the periods 1890-1947, 1890-1953, and 1890-1960 and preparing decline contour maps for each interval. These maps were compared to field decline maps for the same periods based on observed water-level data.

When an acceptable match was made between maps of the model decline and the field decline for each period, the model was considered as an analogy of the physical system. The matching process was the major task in the modeling study; because the pumping history was known, it was never changed (except when errors were noted), but other parameters were varied until both the time response of the system and the distribution and magnitude of the water-level declines were duplicated. Modifications of the model were made only for plausible hydrologic reasons and not because they were electronically possible.

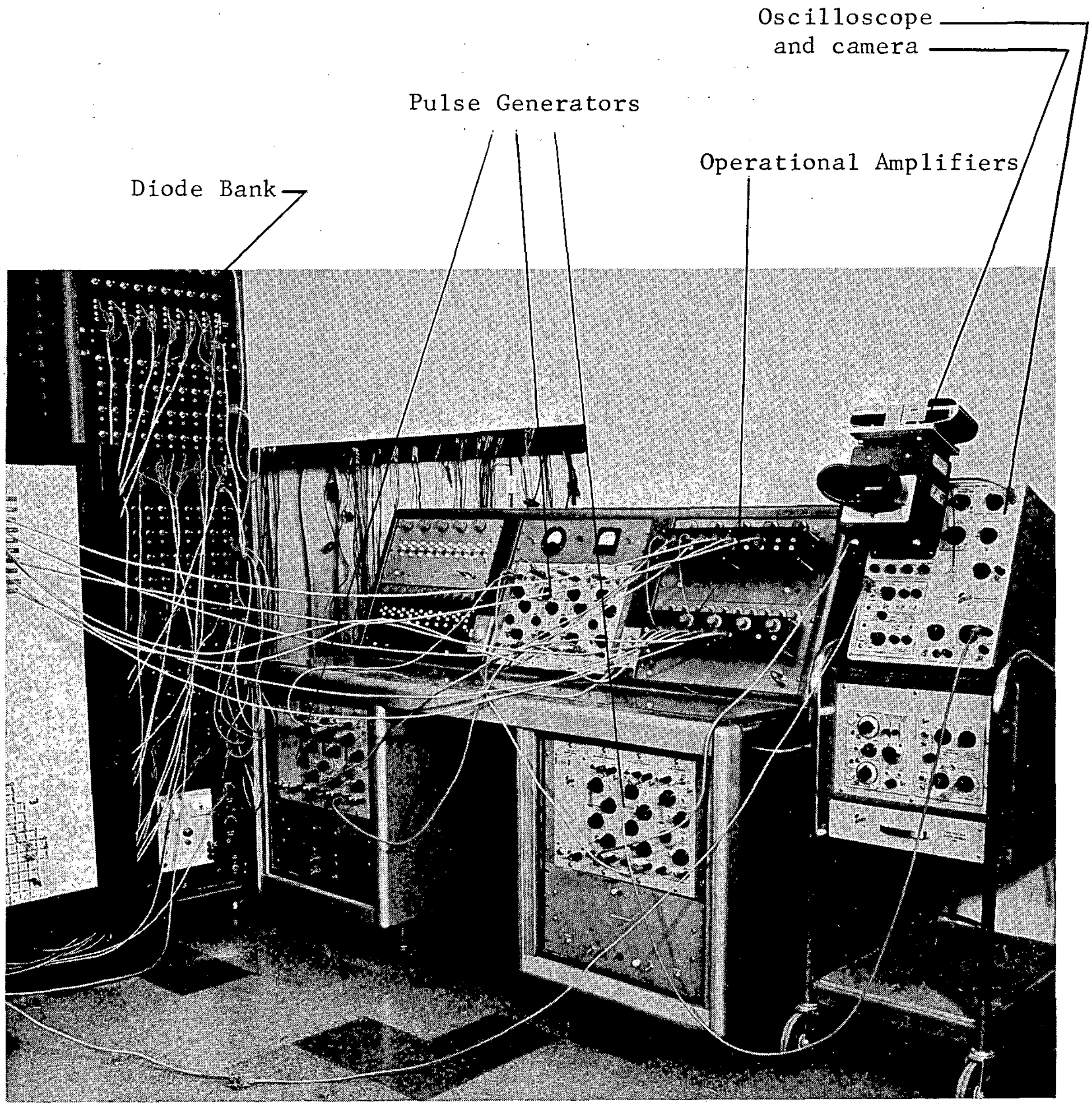

Figure 26.--Electronic equipment used to excite the passive element network

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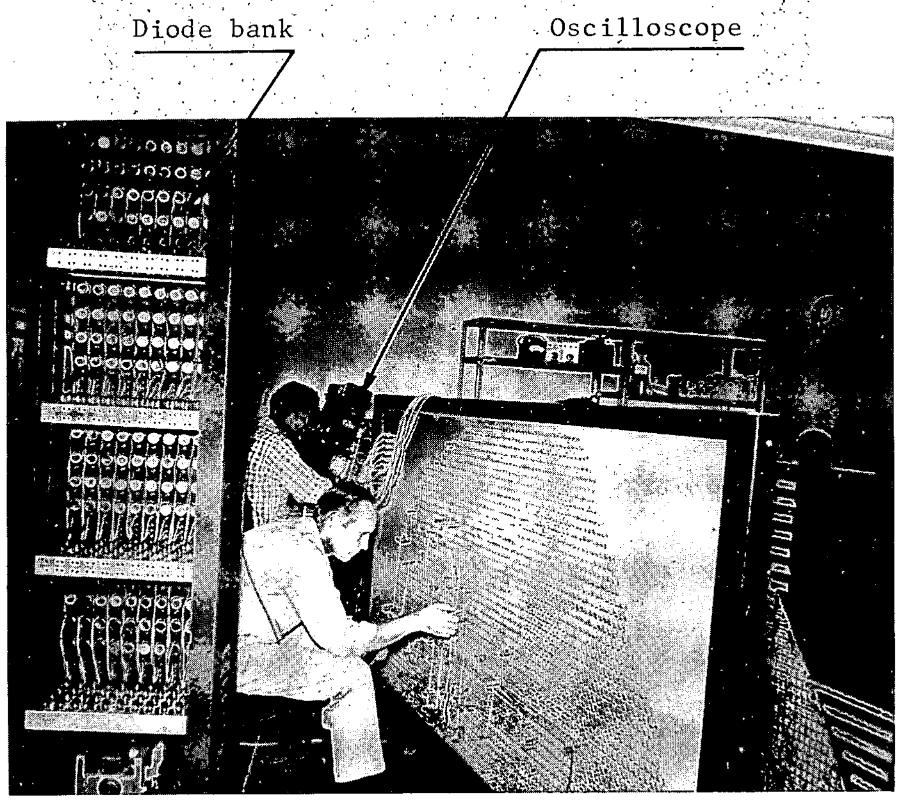

Figure 27.--Measuring the response of the analog model.

Voltage drop on the resistor-capacitor network as a function of time is portrayed on the oscilloscope

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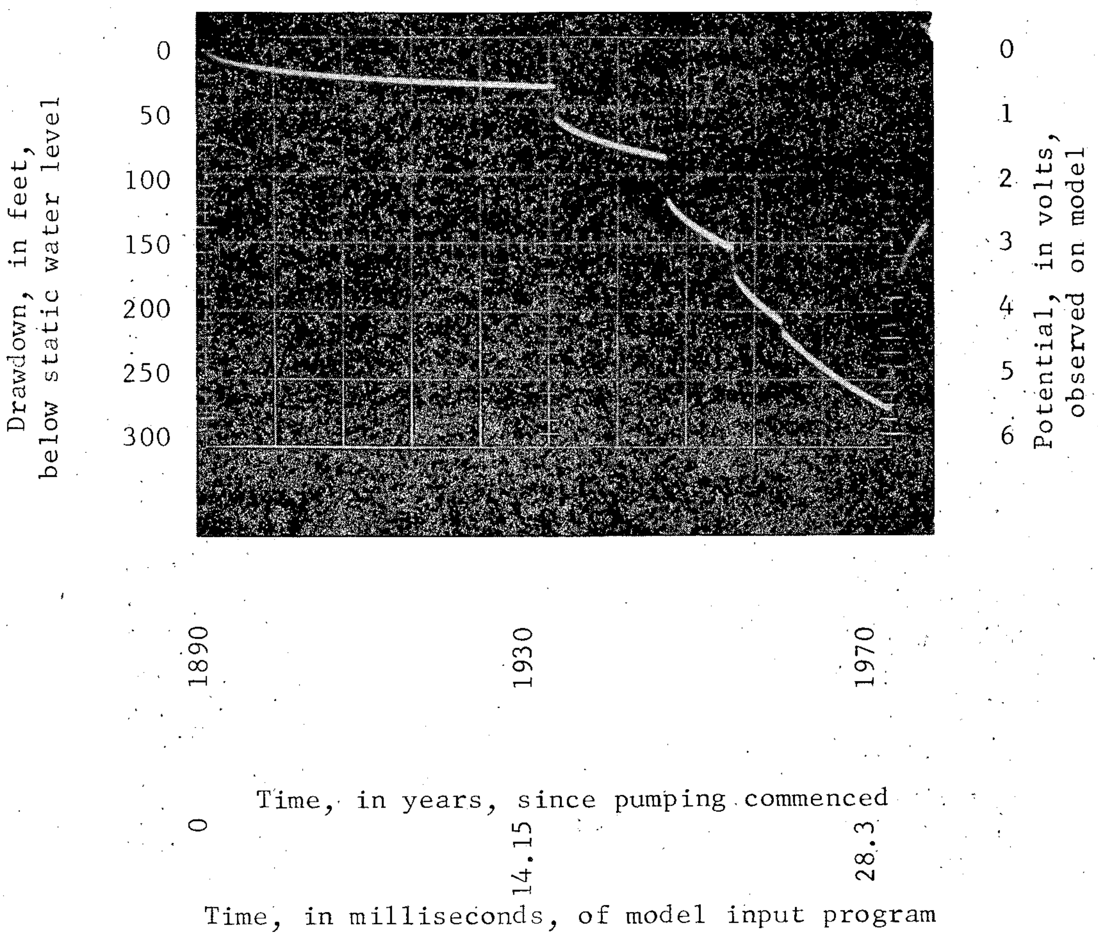

Figure 28.--Typical oscillogram obtained by measuring voltage drop as a function of time on the analog network

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Modifications of the model were of two basic types--changes in the S'/P ratio achieved by rescaling the model and physical changes on the resistor-capacitor network.

Adjustments of S'/P

During the course of the model analysis, it became apparent that the shape and size of the model decline did not match the field decline. The parameter that governs the shape and size of the decline is the S'/P ratio, which appears in both equation (1) and its analogous electrical form in equation (2). Because $S' \propto C$ and $P \propto 1/R$, changes in S'/P could be accomplished by changing resistance and capacitance of the net. Obviously, that would be a time consuming task and one which would preclude any trial and error methods. However, that is not necessary when S'/P is to be changed proportionally everywhere on the model.

Because S'/P is directly proportional to RC, and the node voltage is a function of time (equations 1 and 2), and because the choice of the scale factor relating prototype time to model time is arbitrary, the S'/P ratio may be changed by changing the time scale factor. For example, one microsecond can be made equal to two days rather than one day, thereby increasing the S'/P ratio by a factor of two, and modifying the rate of decline and areal extent of the resultant drawdown cone.

Network Changes

As mentioned above, changes in S'/P by rescaling must apply to the entire network. Where it is necessary to modify parts of the net, the resistors or capacitors must be replaced.

Three major changes were made on the Houston model. The storage parameter of the eastern part of the heavily pumped layer was reduced by 50 percent. Hydrologically, the change was reasonable because too much storage was originally apportioned on the basis of the total clay in the heavily pumped layer. Deformation of clay at depths below the zone of heavy pumpage was negligible in the southeastern part of the district where the heavily pumped layer increases in thickness. In order to account for the total storage, however, the capacitors which were removed from the heavily pumped layer were incorporated in the confining layer in the same area.

Excessive model decline in the western part of the Houston area was corrected by increasing the transmissibility of the aquifer in the outcrop, thereby increasing the rate of movement of water towards the center of pumping near Bellaire. The change in transmissibility was about 25 percent of the original and was well within the range of error of the modeled estimate.

The largest physical change of components was on the model of the Alta Loma Sand, where it was necessary to install an entirely new resistor network. That change was made after the equivalent S'/P ratio for the heavily pumped layer was reduced by rescaling. Rescaling was not desirable for the Alta Loma, and the only alternative was to change the Alta Loma resistor network.

Summary and Evaluation

The stage at which a model of an aquifer becomes an actual analog of the physical system is very difficult to define. Usually, it is where the range of error of the model response is approaching the range of error in estimating the controlling hydrologic parameters. When that stage is reached, further refinement has no hydrologic significance. The Houston model, however, is amenable to additional refinement should the data warrant. The original objectives--to model the heavily pumped layer in terms of cause and effect and to extrapolate pumpage data to predict future water levels to 1970--have been accomplished. If predictions much beyond 1970, or predictions in areas nearer the edge of the model, or more nearly accurate predictions in local areas are required, further refinement of the model may be desirable. If water-level predictions are required for the Alta Loma Sand, further work should be done to define more closely the effective vertical permeability between the Alta Loma and the heavily pumped layer. In addition, refinement would be warranted in the Katy area, but such work would require additional field data.

PREPARATION OF DATA FOR THE ANALOG MODEL OF THE HOUSTON DISTRICT

The construction of the model of the Houston district required simplification of the complex aquifer system. Obviously, it is not possible to portray each individual sand and clay bed because even their areal distribution is unknown despite the abundance of electric logs and other descriptive information. Nor was it practical to model each of the separate zones shown in Figure 3 because of the following reasons: The aquifer coefficients for the different zones are unknown because most wells are completed in more than one zone and coefficients of transmissibility and storage obtained from pumping tests are composite coefficients; and insufficient water levels are available for each zone to permit construction of a more complex model.

Figure 29 shows the generalizations incorporated into the model. The model contains two layers in most of the district, three layers in part of the district, and one layer where the principal aquifer crops out. The layers were not defined solely according to geology but by the vertical distribution of withdrawals from the aquifer system. The vertical distribution of pumping, however, is determined to a large extent by the geology.

The Alta Loma Sand was modeled separately from the heavily pumped layer because it is easily defined and has a relatively high coefficient of transmissibility (100,000 to 250,000 gpd per foot) for its thickness; its coefficient of transmissibility is nearly as large as the underlying heavily pumped layer which contains several times the thickness of sand. The massive Alta Loma Sand with its high transmissibility and relative freedom from lensing has a profound influence on the heavily pumped layer. In the part of the Pasadena area where the head in the heavily pumped layer is below the head in the Alta Loma, the Alta Loma loses water to the heavily pumped layer; elsewhere it gains water from the heavily pumped layer (Figures 9 and 30).

Basic Assumptions

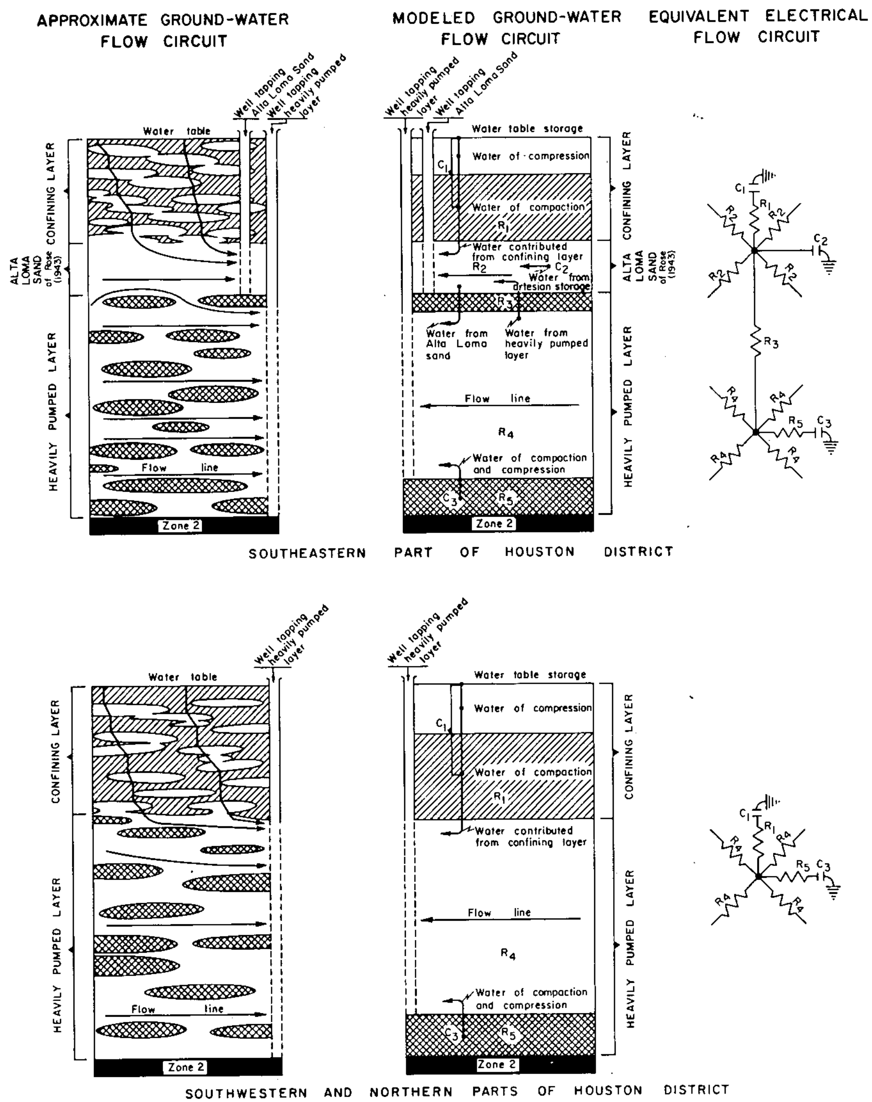
In preparing data for the model, a basic assumption was made that the heavily pumped layer could be simulated by one layer even though vertical hydrualic gradients of differing magnitude and direction exist in the layer at different places. The vertical gradients differ from place to place because the horizontal and vertical distribution of pumpage differs and the lenses of clay retard the vertical equalization of pressures. Other assumptions are as follows:

1. Zone 2 is an impermeable boundary marking the bottom of the flow field.

2. Wells tapping the heavily pumped layer fully penetrate the layer so that all the pumpage from the layer may be considered as a unit. This statement is generally true for the Alta Loma Sand.

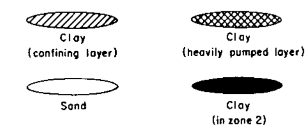
3. True three-dimensional flow can be approximated by purely horizontal flow through the sand and purely vertical flow through the clay.

4. The leakage from and through the confining layer and the long-term storage coefficient of the heavily pumped layer are related to the clay thickness in each layer and to the ratio of land-surface subsidence to head decline.



EXPLANATION

ELEMENT	DESIGNATION	FUNCTION
Capacitor	C_1	Water contributed from storage in confining layer (from water table, compaction, and compression)
Resistor	R_1	Effective vertical permeability between confining layer and Alta Loma Sand or heavily pumped layer
Resistor	R_2	Transmissibility of Alta Loma Sand
Capacitor	C_2	Water contributed from artesian storage in the Alta Loma Sand
Resistor	R_3	Effective vertical permeability between the Alta Loma Sand and heavily pumped layer
Resistor	R_4	Transmissibility of heavily pumped layer
Capacitor	C_3	Water contributed from storage in heavily pumped layer (from compaction and compression)
Resistor	R_5	Permeability of clay in heavily pumped layer



NOT TO SCALE

BASIC MODELING ASSUMPTIONS

1. Zone 2 is an impermeable boundary marking the bottom of the flow field.
2. Wells tapping the heavily pumped layer fully penetrate the layer so that all pumpage from the layer may be combined. (Statement is generally true for Alta Loma Sand.)
3. True three-dimensional flow can be approximated by purely horizontal flow through the sand and purely vertical flow through the clay.
4. The leakage from the confining layer and the long-term storage coefficient of the heavily pumped layer are related to the clay thickness in each layer and to the ratio of land-surface subsidence to head decline.
5. The water yielded by plastic deformation of clay is released slowly at a rate inversely proportional to the thickness of the clay assuming that the clay permeability and thickness are not time dependent.

Figure 29

Diagram Showing the Relation Between Ground-Water Flow and Electrical Flow in the Model of the Houston District

U.S. Geological Survey in cooperation with the Texas Water Commission and the city of Houston

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The leakage and long-term storage coefficients are proportional to the effective vertical permeability of the confining layer and the vertical permeability of the clay in the heavily pumped layer.

5. The water yielded by plastic deformation of clay is released slowly at a rate inversely proportional to the thickness of the clay, assuming that the clay permeability and thickness are not time dependent.

The heavily pumped layer is represented in the model by a resistor net which simulates the transmissibility (R_4, Figure 29) and by capacitors (C_3, Figure 29) which simulate storage in the clay beds. Each capacitor is connected to the resistor net by a resistor (R_5, Figure 29) which has a value proportional to the permeability and thickness of the clay. Recharge directly to the heavily pumped layer in the northwestern part of the district is fed as electric current into the net by a diode bank connected to the resistor net in that area. The heavily pumped layer is connected to either the overlying confining bed or the Alta Loma Sand by resistors (R_1 or R_3, Figure 29) which are proportional to the effective vertical permeability between the two layers. The artesian storage in the heavily pumped layer was not modeled because it is considered to be insignificant compared to the storage release caused by compaction of the clay.

The Alta Loma Sand is modeled by a resistor net (R_2, Figure 29) which simulates the transmissibility and by capacitors (C_2, Figure 29) that release electric current in the same manner as water from artesian storage is released from the sand as pressure head declines. The resistor net representing the Alta Loma is connected vertically to the overlying and underlying layers by resistance (R_1 and R_3, Figure 29) proportional to the effective vertical permeability between each layer. The underflow that moves into the Alta Loma Sand laterally from the confining layer was simulated by feeding current at the appropriate points from a source external from the model.

The confining layer was not completely modeled; only the storage (in sand and clay) that is contributed by vertical leakage to the underlying layers was represented. Capacitors (C_1, Figure 29) depicting storage were connected either to the heavily pumped layer or the Alta Loma Sand by resistance proportional to the effective vertical permeability and thickness of the confining bed between the confining layer and the underlying layers.

Portrayal of Data

In preparing the data in a form suitable for building the model (maps, tables, and hydrographs), considerable use was made of electric logs of oil and gas tests in addition to electric and drillers' logs of water wells; more than 1,200 electric logs of wells were used. The first step was to prepare a map of the top of zone 2 (Figure 4), which is the base of the heavily pumped layer. Maps showing the top of the heavily pumped layer and the top of the Alta Loma Sand also were prepared (Figures 31 and 32). After the top and bottom of the heavily pumped layer had been mapped, an isopach map showing the total thickness of sand in the heavily pumped layer was constructed (Figure 33). From this and a study of the field permeabilities obtained in about 150 pumping tests in the district, a map showing the transmissibility was prepared (Figure 34). Even though permeability decreases downdip, the transmissibility in the southern part of the district was estimated to be as great or greater than that nearer the outcrop because of greater sand thickness. The average field coefficient of permeability is about 250 gallons per day per square foot in the heavily pumped layer. An isopach map of the clay in the heavily pumped layer also was prepared (Figure 35). The clay thickness and the results of a study of the ratio of subsidence of land surface to decline of water level in different parts of the aquifer system at several locations in the district were used in estimating the gross storage coefficient.

The isopach map of the Alta Loma Sand (Figure 36) and field coefficients of permeability estimated from pumping-test results were used to construct Figure 37, which shows the approximate transmissibility of the Alta Loma Sand. The average field coefficient of permeability was about 600 gpd per square foot.

The next step was to prepare in isopach map of the clay in the confining layer (Figure 38). The isopach map of the clay and the rates of subsidence of land surface to decline of water level were used to estimate the gross storage coefficient. The transmissibility of the confining layer and the pumpage from it were not modeled.

The most difficult coefficients to estimate were the effective vertical permeability between the confining layer and the heavily pumped layer, between the confining layer and the Alta Loma Sand, and between the Alta Loma Sand and the heavily pumped layer. The estimates were based on very limited core analysis data and on water balance calculations made in a part of the Houston-Pasadena area. The withdrawals from a part of the area in excess of the inflow to the area (based on gradient and transmissibility) plus the water removed from storage (based on artesian storage and compaction water derived from the heavily pumped layer) is water that is transmitted vertically from the confining layer. The coefficient of vertical permeability obtained in this manner was not accurate but served as a basis for making preliminary estimates.

All the coefficients that were estimated from field data were subject to modification as the model was built and refined. The response of water levels in wells based upon withdrawals of ground water were the criteria upon which the coefficients were judged because the water level and pumpage data are the most reliable of all the data. The coefficients shown on Figures 34, 35, 37, and 38 are the original estimates. They do not correspond with the modifications made to the model because some of the modifications were changes in the ratio of storage to transmissibility and not to the individual coefficients.

Detailed records of pumpage from individual wells were not available for the period 1890-1930. However, public supply, industrial, and irrigation pumpage was estimated for the period from published reports and was assigned to the respective areas which were restricted to localized areas before 1930.

The average pumping rate, in million gallons a day for each year from 1931 through 1960, was tabulated for each well in the Houston district except in the Katy area where the annual pumpage was prorated over the area. In 1930, rice irrigation was limited to an area surrounding Katy, but the area expanded gradually to its present size before 1954; since that time, it has remained about static. The pumpage rate was assigned equally to each square mile during each arbitrarily defined growth period.

The base map of the Houston district was subdivided by a grid of east-west and north-south lines at 1-mile intervals. Each intersection represented 1 square mile--that is, the area one-half mile north, one-half mile south, one-half mile east, and one-half mile west of the intersection. Each well in the district was located on the map and assigned the grid-intersection designation nearest to it. Yearly pumpage from wells having a common grid junction were added together. The pumpage was further grouped together according to magnitude and time into the five arbitrary periods. Changes in pumping rates (either additions or reductions) were also grouped according to magnitude and time. In some cases, pumpage at several grid intersections was represented by a composite well.

COMPARISON OF MODEL DECLINE TO FIELD DECLINE

Figures 39, 40, and 41 show the decline in water level in the Houston district as calculated by the analog model for the periods 1890-1947, 1890-1953, and 1890-1960 based on final model design. Generally, the magnitude and location of maximum decline computed by the model (model decline) closely approximates the decline based on field data (field decline). (See Figures 11, 12, and 10.) The greatest departures between the field decline and the model decline are for the 1890-1947 period (Figures 11 and 39) when the model decline was about 240 feet in the Pasadena area, and the field decline was about 190 feet. Part of the difference is because the field decline (Figure 11) used for comparison is based on 1946 data (Lang and Sundstrom, 1946, Figure 11), and the model decline is based on pumpage from 1890-1947. Also, the early pumpage data are more coarsely lumped than the later data so that the model response is less accurate in the early period. The effect of coarsely lumping the early pumpage decreased with time so that the magnitude of error is lessened in the later maps.

In the Pasadena area in the 1890-1953 period, the maximum field decline and model decline were both approximately 310 feet, and in the 1890-1961 period, the declines were both between 310 and 320 feet except at the model well where decline is exaggerated. The configuration of the contours of model decline (Figures 39, 40, and 41) closely parallel those of field decline (Figures 11, 12, and 10) throughout the region, but the model decline contours cannot be superimposed on the field decline contours for each respective period. Irregularities in aquifer characteristics that are reflected in the decline contours were dampened by the model because of the regularity in the characteristics that were built into the model. Differences between field decline and model decline in some areas are due partly to observations in wells that do not completely penetrate the heavily pumped layer. In these areas, the model decline may be more representative of actual conditions than the field declines. These differences, however, are small. Much larger differences between field and model decline are apparent in and immediately around the model wells because several wells in the field are represented by a single well in the model. Regionally, the model decline maps are correct in order of magnitude; at specific locations, the maps are in error. The error (except at the model wells) is but a small percentage of the total decline.

PREDICTED WITHDRAWAL RATES AND WATER-LEVEL CHANGES

Several projects, some of which have already begun and others which are planned, will affect the rates of withdrawal of ground water in different parts of the Houston district. Many other factors, which cannot be predicted, may have great bearing on future rates of withdrawal.

One of the projects either under construction or planned for construction by 1970 is the installation of additional large-diameter water mains that will connect the city of Houston water-treatment plant on the north side of the Ship Channel to southeastern, southern, and southwestern Houston. The use of treated surface water from these mains will cause a reduction in pumping from the East End well field by 1966 and will slow down the rate of increase in ground-water withdrawal in southern and southeastern Houston. Also under construction in 1963 are additional raw water lines extending from the end of the canal at the treatment plant to industries south of the Ship Channel. These will reduce the withdrawal rate experienced in 1954-60 from industrial wells along the Ship Channel and will absorb some of the increased demand for water in the area.

The construction of Lake Livingston on the Trinity River, which is being planned by the city of Houston, will have a great effect on withdrawals in eastern Harris County. Large quantities of surface water for industry from Lake Livingston are anticipated by 1970.

The addition of an industry using large quantities of ground water, a prolonged drought similar to the one in the early 1950's, the unlimited planting of rice, or any of several other circumstances could substantially change the ground-water withdrawal rate in any part or throughout the district.

Because of the foregoing reasons and because long-range predictions will require refinement of the model, it was believed unwise to make predictions of water levels beyond 1970.

For comparative purposes, two maps for the period 1890-1970 were constructed. Figure 42 is a contour map of model decline for the period 1890-1970, assuming that the 1954-1960 pumpage rate would continue unchanged until 1970. Comparing this map with Figure 41, the contour map of model decline for the 1890-1960 period, about 30 to 40 feet of additional decline was computed for the 1961-70 period in the Pasadena area; probably about 50 feet of decline near the intersection of the north boundary of the city of Houston and U.S. Highway 75; about 40 feet additional decline west of Houston near Alief; about 30 feet additional decline southwest of Houston near Almeda; and probably not more than about 10 feet on the west side of Baytown. The principal reason for the greatest additional declines being to the north, west, and south of Houston rather than to the east is that pumpage increased in northern, western, and southern Houston during the 1954-60 period and decreased in the Pasadena area.

The other map (Figure 43) is based on the estimates of increased and decreased pumpage rates suggested by officials of the city of Houston and on other estimates of demands for irrigation and industry. It was estimated that the rate of ground-water withdrawal from the heavily pumped layer would increase from 270 mgd in 1960 to 337 mgd in 1970, an increase of 67 mgd, the weighted average of which would be 38 mgd over the 10-year period. This increase would be due principally to increased use for public supply. Minor adjustments were made in the withdrawal rates from industrial wells near the Ship Channel, but predictions of changes in rates from other industrial wells or from irrigation wells cannot be made.

The largest increases in pumpage rates are for the west side of Houston because of the anticipated residential growth of the city in that direction. Weighted average increases in pumpage between 1960 and 1970 were outlined as follows: About 6.8 mgd in the southwestern part of the city, about 17.5 mgd on the west side, about 2.8 mgd on the south side, about 5.9 mgd in the east-central part, and about 5.2 mgd in the northeastern part of the city. It also was anticipated that pumpage would decrease 8.5 mgd in the Pasadena area.

It was estimated that the rate of ground-water withdrawal from the Alta Loma Sand would increase from 58 mgd in 1960 to 98 mgd in 1970, or about 40 mgd in the vicinity of the National Aeronautic and Space Administration (NASA) installation in the southeastern part of Harris County. The weighted average increase would be about 16 mgd for the 10-year period from 1961 to 1970. Most of the predicted increase was from proposed industrial wells, although increases in withdrawals for public supply were anticipated. A decrease in pumpage of 8.7 mgd from the Alta Loma Sand in the Ship Channel area also was anticipated.

The predicted rate of increase of ground-water withdrawals in the Houston-Pasadena area for the period 1961-70 closely parallels the rate of increase experienced between 1941 and 1954. The increase was temporarily halted between 1954 and 1961 by the increased availability of surface water as the result of the construction of Lake Houston, the city of Houston's treatment plant, and the necessary canals and distribution lines. However, all the water in Lake Houston was committed in 1963, and the ground-water withdrawal rate had begun to increase again.

Withdrawals from the irrigation wells in the Katy area and the other parts of the district fluctuate with the number of acres planted and the amount of precipitation during each growing season. The total number of acres irrigated probably will not change greatly in the 1961-70 period, and, accordingly, the withdrawal rate for 1961-70 was estimated to be the same as for the 1954-60 period.

Comparing Figure 43 with Figure 41, the additional decline computed in the western part of the city of Houston between 1961 and 1970 would be about 100 feet. Additional declines would be smaller in other parts of the district. For example, about 40 feet of additional decline was computed in the Pasadena area; about 80 feet near the intersection of the north boundary of the city of Houston and U.S. Highway 75; about 80 feet west of Houston near Alief; about 60 feet southwest of Houston near Almeda; and about 30 feet on the west side of Baytown. Comparing Figures 43 and 42, the predicted increase in pumpage would cause much larger declines throughout the Houston area than would the 1954-60 pumpage rate if continued from 1961-70.

In the Pasadena area, pumpage was predicted to decrease between 1960 and 1970 by 8.5 mgd; however, declines would continue. West of Baytown, where no increase in pumpage was predicted, as much as 20 feet of additional drawdown was computed.

SHORTCOMINGS OF THE MODEL

It has been stressed in this report that the nature of the aquifer in the Houston district and the data available required lumping of aquifer properties and pumpage. An increase in quantity of certain kinds of data would aid in making a closer estimate of the properties and the response of the aquifer. The system can by modeled with as much detail as the field data justify. Because of the very rough estimates of some properties of the aquifer, some of the detail furnished by the field data was not incorporated into the model. The detail, if built in, would only be overshadowed by some of the rough estimates.

Based on the overall quantity and quality of the data available, the model of the Houston district was designed and built to obtain a best possible estimate. For example, no measurements of vertical leakage from the confining layer or transmissibility values of the full thickness of the heavily pumped layer were available, and only estimates of storage characteristics and compaction-time relationships could be made. Also, the amount of change in recharge conditions accompanying withdrawals at any particular location is not known.

The pulse generators and other equipment used in operating the model are capable of greater accuracy than was inherent in the hydrologic data. The improvement in model response by reworking available pumpage data--that is, breaking the pumpage down into more periods and distributing the model wells to correspond more nearly to the actual well distribution, would be worthwhile if more equipment were available. Additional pulse generators (which are costly items) would be required, but extensive changes of equipment cannot be justified without better estimates of hydrologic characteristics that are based on additional data.

Although the model could be improved, much was learned about the aquifer system, more, in fact, than is included in this summary report.

DATA NEEDED TO REFINE MODEL

The program of basic-data collection, including the gathering of information on new and existing wells, water-level measurements, collecting and analyzing water samples for chemical quality, and collection of subsidence data should be continued in order to evaluate the findings of this study and to provide data for refinement of the model. Refinement and modification of the model would be desirable in order to make predictions much beyond 1970, or to make predictions nearer the edge of the model, or to make more accurate predictions in local areas. The program of data collection in the heavily pumped layer and the Alta Loma Sand should be expanded to include water-level measurements in shallow wells in the confining layer in order to provide data for studies of recharge to the water table and downward movement to the heavily pumped layer. More detailed pumpage data from wells of all depths should be collected, especially in the Katy rice-growing area, to more clearly define the cause and effect relations in the aquifer system. Many more vertical gradients and permeability and storage coefficients of individual beds of sand and clay must be measured, especially for the deeper part of the heavily pumped layer, in order to evaluate the part each plays in the aquifer system.

Special studies on salt-water movement, infiltration rates, compaction, and rainfall and evapotranspiration should be initiated. These studies will provide part of the data necessary for proper economic management of all the water resources in the Houston district.

The data that are most easily obtainable and that offer the most gain in the ability of the model to predict short-term (10 years or less) changes in water level are the pumpage and water-level data. Improving the accuracy of pumpage records, both in quantity pumped and the distribution of the pumpage in space and time, would improve the accuracy of forecasts.

These data must be obtained when they are available. Although pumpage data can be compiled for some types of uses for past years (municipalities and certain industries keep excellent records), most irrigators and many smaller users cannot estimate their pumpage for more than a year or two before the present year. Water-level data will be scarce unless a scheduled program of measurements in carefully selected wells is made by some responsible organization. It is difficult to go back in time for water levels unless such a program of periodic measurements has been instituted and maintained.

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Year	Water-Supply Paper No.	Year	Water-Supply Paper No.	Year	Water-Supply Paper No.
1935	777	1944	1019	1951	1194
1937	840	1945	1026	1952	1224
1939	886	1946	1074	1953	1268
1940	909	1947	1099	1954	1324
1941	939	1948	1129	1955	1407
1942	947	1949	1159	1956-59	1549
1943	989	1950	1168		