Salt Water and Its Relation to Fresh Ground Water in Harris County, Texas

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1360-F

Prepared in cooperation with the Texas Board of Water Engineers and the city of Houston

Winslow and others SALT WATER AND ITS RELATION TO FRESH GROUND WATER, HARRIS COUNTY, TEX.—Geological Survey Water-Supply Paper 1360-F

Salt Water and Its Relation to Fresh Ground Water in Harris County, Texas

By ALLEN G. WINSLOW, WILLIAM W. DOYEL, *and* LEONARD A. WOOD

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1360-F

Large withdrawals of fresh ground water in the Houston area have reversed the direction of the hydraulic gradient and salt water has begun to move slowly toward the center of pumping; continuous observation in existing wells and wells that should be drilled is suggested.—Prepared in cooperation with the Texas Board of Water Engineers and the city of Houston

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SALT WATER AND ITS RELATION TO FRESH GROUND WATER IN HARRIS COUNTY, TEXAS

By Allen G. Winslow, William W. Doyel, and Leonard A. Wood

ABSTRACT

Harris County, in the West Gulf Coastal Plain in southeastern Texas, has one of the heaviest concentrations of ground-water withdrawal in the United States. Large quantities of water are pumped to meet the requirements of the rapidly growing population, for industry, and for rice irrigation. The water is pumped from artesian wells which tap a thick series of sands ranging in age from Miocene (?) to Pleistocene.

The water-bearing sands, many of which contained slightly saline water, are interbedded with clays. Subsequent artesian circulation has flushed the sands, probably to the limit determined by the Ghyben-Herzberg principle. The base of the fresh-water sands ranges in depth from about 100 feet over the salt dome near Hockley to more than 3,000 feet in the northeastern part of the county.

Before large-scale ground-water withdrawals were begun, the hydraulic gradient sloped gently toward the coast. Then, as large quantities of water were withdrawn a large cone of depression was established, the hydraulic gradient was reversed, and salt water began to move slowly toward the centers of pumping. The rate of movement of the salt water is very slow and the closest salt water is probably 5 miles from centers of pumping in the deeper sands. However, the threat of salt-water intrusion is present and the rate of advance of the salt water should be watched by means of strategically placed observation wells.

Other less probable potential sources of salt-water contamination which are discussed include upward movement of salt water from below, vertical movement around salt domes or along faults, downward seepage from surface sources, and contamination through leaking wells.

INTRODUCTION

PURPOSE OF THE REPORT

The purpose of this report is to present the available information regarding the occurrence of salt water and its relation to fresh water in aquifers in Harris County, Tex. The report directs attention to the possibility of contamination of the fresh-water sands by salt water and points to critical areas where additional data are needed.

The danger of salt-water encroachment was recognized in the early part of the ground-water investigation in the Houston district (Turner and Foster, 1934). White, Turner, and Livingston (1937, p. 25) referred to the problem as follows:

The possibility that a further large decline in the artesian pressures may result in the encroachment of salt water is to be feared. Salty water occurs below the Houston-Pasadena area at depths of 3,000 to 3,500 feet, but this water is rather effectively confined by the thick clays of the Lagarto formation, and is not likely to rise into the wells. But chlorides in objectionable quantities probably occur only a few miles down dip in the deep horizons from which the largest supplies in the Houston-Pasadena area are now being pumped, and this water may move up the dip to this area. The recent extension of the cone of depression down the dip to the southeast of Houston adds to the apprehension on this score.

If, following over-pumping, salt water does move into the locality of greatest artesian depression, its movement, fortunately, is likely to be slow, and the movement can be watched. The contact, down the dip, between the fresh water and salt water in all probability is not abrupt, but is in the form of a zone of brackish water with a gradual gradation from fresh water to salt water. Moreover, further pronounced deepening of the cone of depression at first, is likely to increase the movement of water toward the depression from localities up the dip to the northwest of Houston, faster than from localities down the dip, to the southeast, due to the fact that the water-bearing sands are more permeable up the dip and the hydraulic gradient is greater. The first result, therefore, of a heavy increase in pumping may be to decrease the chloride content of the water, and increase its hardness. This has already occurred in one of the most heavily pumped areas of this region. If salt water does enter the localities of over pumping, its spread to other parts of the area also is likely to be slow, and the movement can be watched. The people of Houston need have no immediate apprehension, as ample time will be available in which to develop an additional water supply outside the Houston-Pasadena area. Plans toward that end should, however, be made at once.

New methods of subsurface investigation, particularly in the oil industry, have provided additional sources of information regarding the problem of salt-water contamination. Electric logs of both water wells and oil tests; drill-stem tests; and logs of the deeper water wells have provided additional data regarding the depth to which fresh-water sands are present and below which salt-water sands are found.

HISTORY OF INVESTIGATION

Since December 1930 the United States Geological Survey has cooperated with the Texas Board of Water Engineers in conducting a systematic survey of the ground-water supply available in the Houston district. Since 1938 the city of Houston has cooperated in carrying on the studies. Information sought and obtained in part includes the following: (1) data regarding the areal extent, thickness, and depth of fresh-water-bearing beds throughout the district; (2) the rate at which water is being replenished at the outcrops of the water-bearing beds; (3) the rate at which water moves through the sands from the outcrop to the areas of withdrawals; (4) the average daily withdrawals of ground water for municipal, industrial, and irrigation purposes throughout the district; (5) the relation between the rate of withdrawals and the rate of decline of artesian pressure; (6) the chemical character of the water; (7) the possibility of salt-water invasion into the fresh-water sands as a result of the decreased artesian pressures; and (8) data on any potential ground-water supplies that may be present in adjoining areas.

The data obtained have been summarized in 2 Geological Survey water-supply papers, 10 mimeographed reports, 13 special reports and technical papers, and reports on 5 adjacent counties that are related to or are hydrologically similar to the Houston district.

The field work and preparation of this report were done under the administrative direction of A. N. Sayre, chief of the Ground Water Branch, and under the direct supervision of W. L. Broadhurst, former district geologist, and R. W. Sundstrom, district engineer in charge of the cooperative ground-water investigations in Texas.

ACKNOWLEDGMENTS

Acknowledgments are due many persons who have contributed information used in this report. Officials of the Department of Utilities of the city of Houston, water-well drillers, and representatives of industries in the area and oil companies have been very cooperative in furnishing valuable information.

LOCATION OF AREA

Harris County is in the West Gulf Coastal Plain in southeastern Texas. It is bounded on the north by Montgomery County, on the east by Liberty and Chambers Counties, on the south by Galveston, Brazoria, and Fort Bend Counties, and on the west by Waller County (fig. 55). Houston, near the center of Harris County, is the county seat and the largest city in Texas. Before May 1954, it was the largest city in the United States using ground water exclusively for its public supply, although since that date an impounded reservoir on the San Jacinto River has provided a supplementary surface-water supply.

The large quantities of water needed to meet the requirements of the rapidly growing population and its expanding industries and for irrigation in the rice-growing areas nearby are obtained mostly from wells. Most of the ground-water pumping in Harris County

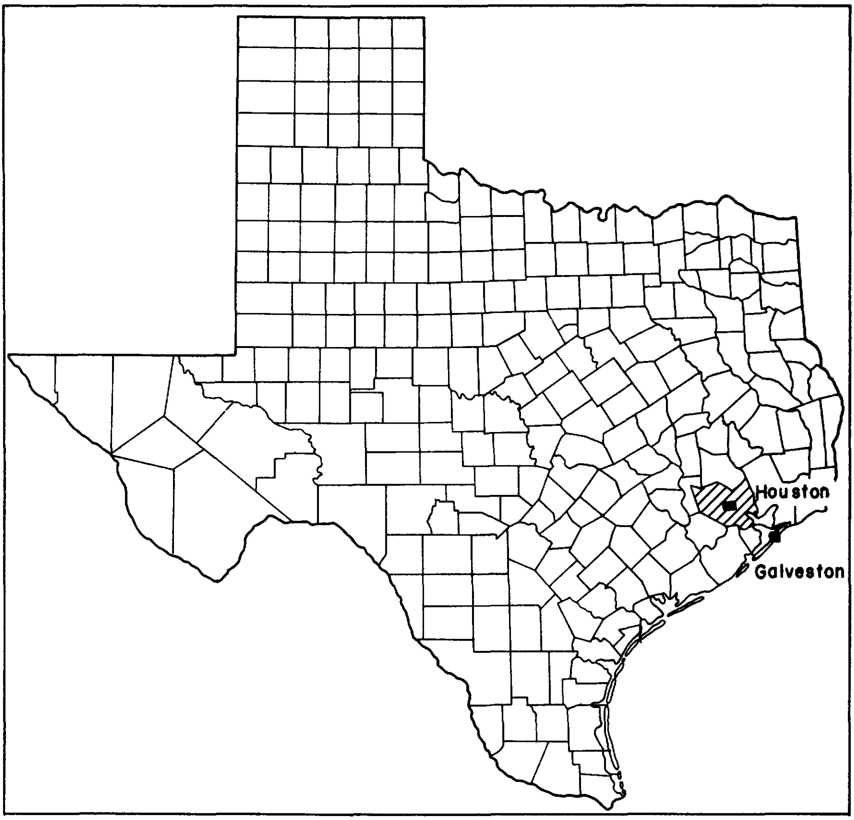


Figure 55. —Map of Texas showing location of Harris County.

is concentrated in four major areas (fig. 56) as follows: (1) the Houston area, which consists of the city of Houston and its environs, except on the east; (2) the heavily industrialized Pasadena area, which extends eastward from Houston along the Houston Ship Channel to the vicinity of Deer Park; (3) the Baytown-La Porte area, which includes the group of industries at the eastern end of the Houston Ship Channel and the municipalities in that area; and (4) the Katy rice irrigation area, which occupies much of western Harris County.

GEOLOGY AS RELATED TO THE OCCURRENCE OF GROUND WATER

PHYSIOGRAPHY

The Houston district is divided into two parts physiographically by the Hockley escarpment, which faces southeast and crosses

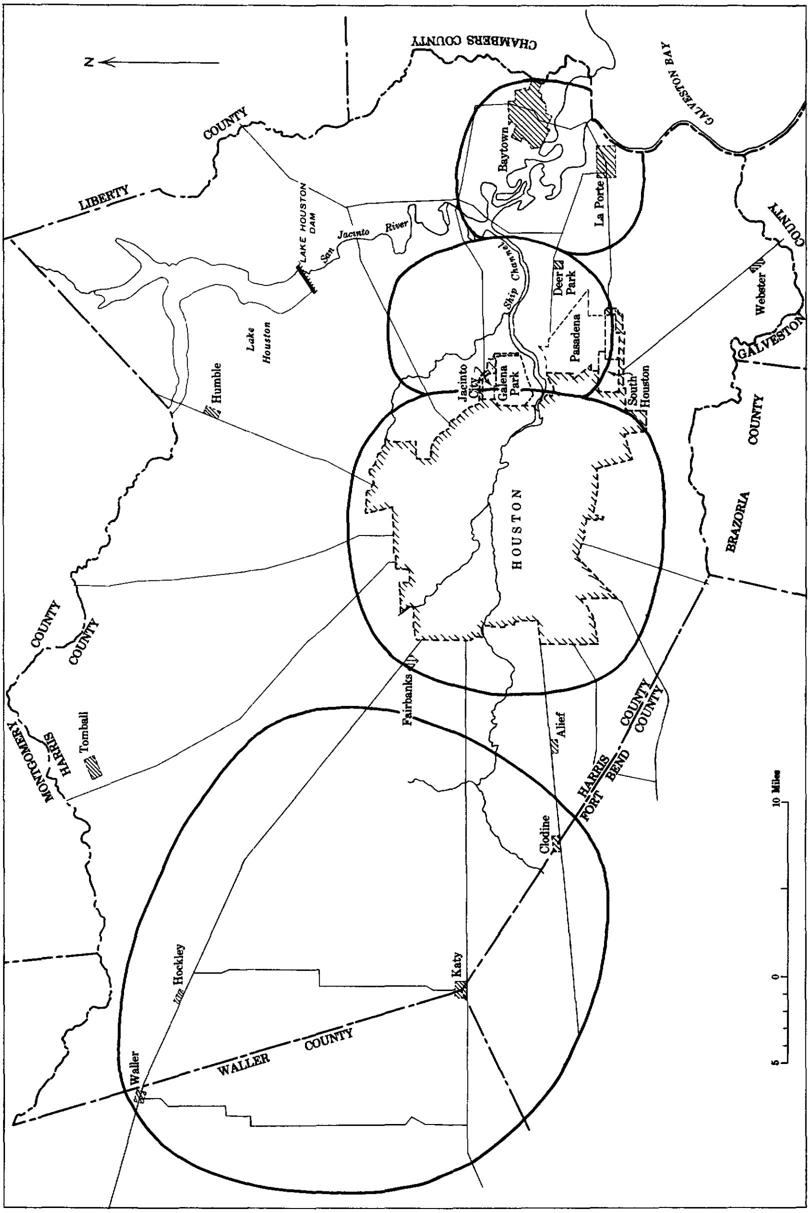


Figure 56. —Map of Houston district, Texas, showing heavily pumped areas.

southern Montgomery, northwestern Harris, and central Waller Counties. A smooth, nearly featureless plain rises from sea level at the Gulf Coast to an altitude of about 160 feet at the base of the escarpment 80 miles inland. West and northwestward from the scarp the surface forms a gently rolling plain dissected by stream channels and having a southeastward slope of about 8 feet to the mile. The highest point in Harris County is in the extreme northwestern part where the plain reaches an altitude of 318 feet.

STRATIGRAPHY AND STRUCTURE

Lang and Winslow (1950, p. 32–36) have summarized the work of previous investigators regarding the stratigraphy and structure of the formations yielding potable water to wells in the Houston district as follows:

> The geologic formations from which the district obtains its water supply are as follows, from oldest to youngest: sands in the Lagarto clay of Miocene (?) age, the Goliad sand of Pliocene age, the Willis sand of Pliocene (?) age, the Lissie formation, and sands in the Beaumont clay of Pleistocene age***. The formations crop out in belts parallel to the coast***. The dip of the beds is toward the southeast at an angle steeper than the slope of the land surface, and the formations are beveled at their outcrop by the land surface. Likewise, each formation is encountered at progressively greater depths toward the southeast***. The estimated dip of the older beds is 50–60 feet to the mile and of the younger beds about 20 feet to the mile. The formations thicken considerably down dip. The rate of dip is variable, owing to several salt-dome structures within, or adjoining, the district. Some of the salt domes, such as Pierce Junction and Blue Ridge, a few miles south of Houston, and Barber's Hill, about 20 miles east of Houston, are remarkable structural features consisting of upthrusts of large masses of salt piercing the younger formations from a deep-seated source, the geologic position of which is unknown.***
>
> Toward the interior successively older strata crop out, and the formation lowest in the geologic column has the highest topographic exposures. Such a structure, together with the arrangement of the rocks, whereby permeable sands are interbedded with relatively impermeable clays and shales, makes an ideal condition for artesian water. Rain falling on the outcrops is conducted by slow percolation into the porous beds and is then transmitted down the dip to great depths beneath the surface.
>
> Sediments making up these strata were derived largely from the limestones and marls of the Cretaceous formations, and from sands, gravels, silts, and clays of the older Tertiary formations. Redeposited Cretaceous fossils have been reported from the upper Miocene. The sediments were laid down during several cycles of continental deposition and are largely fluviatile, deltaic, and lagoonal. Several series of coalescing river-built fans developed as depositional plains to form the Goliad, Willis, Lissie, and Beaumont formations. Doering presented evidence to indicate that the Goliad strata have been overlapped by the Willis in Montgomery County. Most of the sediments comprising the upper Miocene, Pliocene, and Pleistocene strata were transported and redeposited several times as the coastal plain was built up. Marine and lagoonal deposition, together with wave and wind action, were in progress along the coast.
>
> Owing to the mode of deposition, the formations are similar in lithology and origin and do not have persistent individual characteristics that can be traced down dip; and efforts to classify the sediments by mechanical analyses and by lithology according to groups that correspond to recognized formations in the outcrops, have generally failed. White, Rose, and Guyton, however, were able to recognize zones in the Houston district that are predominantly sand and zones that are predominantly clay.** The sand zones consist of extremely irregular and lenticular beds of gravel, sand, silt, and clay. The clay zones are

made up of mottled calcareous massive clays that contain numerous thin beds and lenses of fine to medium-grained sands. Interfingering layers and lenses of massive clays grade laterally and vertically into the sand zones, and sands and gravels likewise grade into the clay zones. The thinner beds change character or pinch out within a few hundred feet.

Two cross sections have been drawn across Harris County for this report. One (pl. 24) is drawn from north to south following roughly the direction of dip, and the other (pl. 25) from west to east. Although no formations or zones have been correlated throughout the county, the sections are included to illustrate the lensing and interfingering of the sediments in short lateral distances and to show the approximate position of the lower limit of fresh water. The line showing the lower limit of fresh water is based on data shown on plate 26.

OCCURRENCE OF GROUND WATER

RELATION BETWEEN FRESH AND SALT WATER IN AQUIFERS

The basic principles governing the relation between fresh and salt ground water have been well established through the work of Badon Ghyben (1889, p. 21) and Herzberg (1901) and many others, including D'Andrimont (1902), Lindgren (1903), Pennink (1904), Dubois (1905), Brown (1925), Hubbert (1940), Wentworth (1942), Krul and Liefrinck (1946), and Bennett and Meyer (1952). Fresh water tends to float on salt water because its specific gravity is less than that of salt water. The position of the contact between fresh and salt water in an aquifer is determined by the difference between the heads and by the relative specific gravities.

Figure 57*A* shows a small tube, open at both ends, containing fresh water with the lower end of the tube immersed in a larger

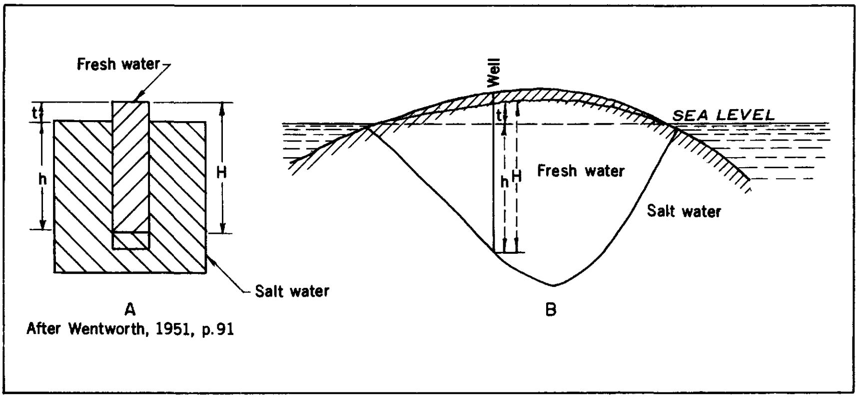


Figure 57. —Diagram showing relation between salt water and fresh water according to Ghyben-Herzberg principle (modified).

open vessel containing salt water. Because the fresh water is lighter than the salt water, the level of the fresh water will necessarily stand higher than the level of the salt water in order to balance the weight of salt water, and the salt water will invade the tube containing the fresh water. The position of the contact between the two waters, as well as the difference in the levels of their surfaces, is determined by the difference in specific gravities of the two liquids and the following formula will hold (Brown, 1925, p. 17);

$$H = h + t \tag{1}$$

in which H equals the total height of the column of fresh water, h equals the part of the column below the level of the column of salt water, and t equals the part of the column above the level of the salt water. Inasmuch as the column H of the fresh water must be balanced by a column h of the salt water and assuming the specific gravity of the salt water to be g, and that of fresh water to be 1, then:

$$H = h + t = hg \tag{2}$$

therefore:

$$h = \frac{t}{g - 1} \tag{3}$$

in which g-1 is the difference between the specific gravities of fresh and salt water.

The approximate depth to which fresh water is present below an island composed entirely of permeable material and completely surrounded by sea water can be computed by formula (3). In figure 57*B*, which is not drawn to scale, H equals the total thickness of the fresh water, h equals the depth of fresh water below sea level, and t equals the height of fresh water above sea level. Therefore, the depth to the base of the fresh water below sea level becomes the height of the fresh water above sea level divided by the difference in specific gravity between fresh water and salt water. If the average figure of 1.025 is used for the specific gravity of salt water, then, by formula (3) $h = 40\,t$, or, for every foot of fresh water above sea level, fresh water will extend 40 feet below sea level. This ratio will, of course, differ with any change in the specific gravity of the salt water; that is, the higher the specific gravity, the shallower the fresh water, and the lower the specific gravity, the deeper the fresh water. Wentworth (1951, p. 91) states:

> The chief essential for this condition in the case of water in the rocks of an island is that the flow of water must be sufficiently retarded so that the fresh water mass acts somewhat as a fixed mass and does not immediately mingle with salt water as it would in the open ocean.

The Ghyben-Herzberg principle applies also to beds which contain water under artesian pressure and which are hydraulically connected with the sea. If the bed crops out on the sea floor, and if it is confined by layers of impermeable materials, the only place for entrance of salt water will be at the submarine outcrop of the bed. Such a condition has been suggested for the Atlantic City area, N. J. (Barksdale, Sundstrom, and Brunstein, 1936, p. 117). Here the head of the fresh water will be determined by the altitude of the bed at the intake area less friction loss due to the movement of the water through the bed. The head of the salt water will, of course, be determined by sea level. The position of the contact of salt and fresh water can then be determined by formula (3) in which t equals the height of the piezometric surface above sea level, this surface being the imaginary surface defined by the level to which water will rise in wells drilled into an artesian aquifer. If the head in a bed is of sufficient magnitude at the submarine outcrop to overcome the weight of the salt water, a submarine spring will result. Such springs have been reported off the coast of southern California (Poland, Piper, and others, in press) and Florida (Ferguson, Lingham, Love, and Vernon, 1947, p. 9–10).

Formula (3) has been applied by many workers in describing the relation between fresh and salt water in aquifers which are hydraulically connected with open bodies of salt water. It has been shown by Hubbert (1940, p. 924), however, that formula (3) is valid only under conditions of hydrostatic equilibrium between fresh and salt water; whereas fresh ground water is continually in motion and in aquifers a state of dynamic equilibrium exists between fresh and salt water. Brown and Parker (1945, p. 240) and Krul and Liefrinck (1946, p. 16) have also stated that the principle is not strictly valid if dynamic equilibrium exists.

NATURAL FLUSHING OF CONNATE WATER FROM THE AQUIFER

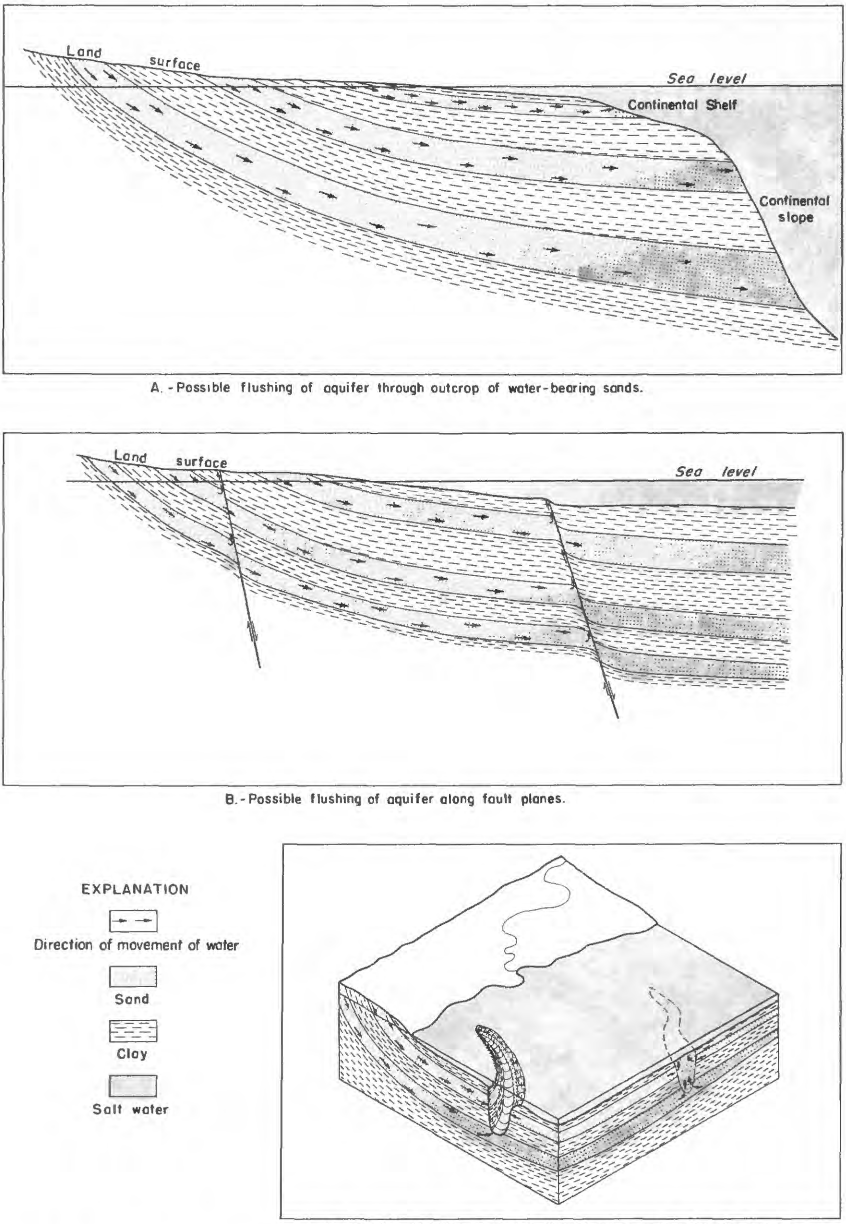
The fresh-water-producing beds in Harris County were laid down under deltaic, flood-plain, or lagoonal conditions and much of the connate water (water trapped at the time of deposition) was saline or slightly saline. As the sea retreated, the beds which were exposed above sea level were flushed gradually by percolating meteoric water; and artesian circulation was established in sands overlain by relatively impermeable clay layers. The few measurements of artesian head (Deussen, 1914) that were made before large ground-water withdrawals in the Houston area indicate that there was a low hydraulic gradient toward the coast. Consequently, water must have been moving through the sands in the direction of the coast and there must have been areas where the water was being discharged. The locations and types of the discharge areas have long been a subject of speculation (Turner and Foster, 1934; White, Turner, and Livingston, 1937, p. 7; C. V. Theis, written communication, 1939; Lang and Winslow, 1950, p. 41). Six possible types are discussed as follows: submarine outcrop of beds, fault planes, submarine canyons, areas around salt domes, migrating bar deposits, overlying clays (figs. 58 and 59).

It has been suggested by Turner and Foster (1934) that the formations extend out under the Gulf of Mexico and crop out on the continental slope about 100 miles offshore, and that salt water was flushed from the formations through these submarine outcrops as shown in figure 58*A*. White, Rose, and Guyton have pointed out (1944, p. 145) that the fresh-water-bearing sands underlying Harris County thin toward the gulf. Information is lacking concerning the sediments underlying most of the Continental Shelf, but studies of the type of rocks and the facies changes in the formations underlying the Coastal Plain indicate that the sands probably pinch out or grade into shale before reaching a submarine outcrop (Lowman, 1949; Carsey, 1950).

In many areas, ground-water discharge occurs along faults as shown in figure 58*B*. This is especially well illustrated along the Balcones fault zone in central Texas, where water is discharged from large springs in limestone at Austin, San Marcos, New Braunfels, and San Antonio (Sayre, 1936, p. 79; Livingston, 1947, p. 16; George, 1952, p. 39). However, because of the unconsolidated nature of the sediments in the area under consideration, the possibility that the aquifer was flushed in this manner appears very unlikely (Turner and Foster, 1934, p. 433).

A third possibility of an area of discharge is the presence of a submarine canyon cutting through the confining clays as shown in figure 58*C*. Mann (1953, p. 187) describes the outcrops of aquifers in submarine canyons off the California coast and states that ground-water discharge is taking place through them. A similar canyon is also present off the Louisiana coast (U. S. Coast and Geodetic Survey, 1943), and may be the discharge area for some of the aquifers in Louisiana. According to Osterhoudt (1946) the inland part of the canyon is filled with loosely consolidated sediments and has been traced almost to Houma, La. Although no canyons are shown on hydrographic charts of the Continental Shelf off the Texas coast, ancient canyons filled with permeable materials may exist as potential areas of discharge.

A fourth possible means of discharge is circulation upward around salt domes as shown in figure 59*A*. Many of the salt domes

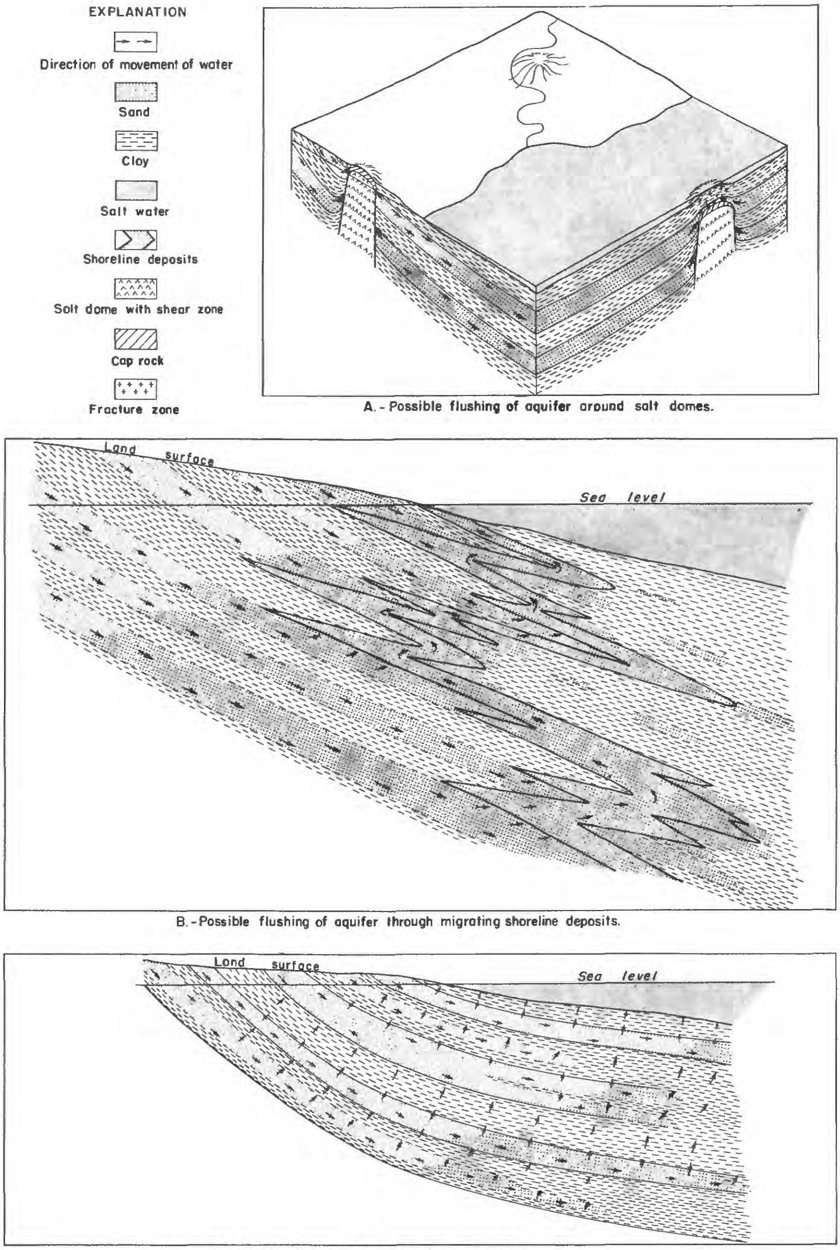


A. - Possible flushing of aquifer through outcrop of water-bearing sands.

B. - Possible flushing of aquifer along fault planes.

C. - Possible flushing of aquifer through outcrops in submarine canyons.

Figure 58. —Schematic diagrams showing possible processes of flushing of aquifer through outcrop of water-bearing beds, along fault planes, and through outcrops in submarine canyons before equilibrium is established.



A. - Possible flushing of aquifer around salt domes.

B. - Possible flushing of aquifer through migrating shoreline deposits.

C. - Possible flushing of aquifer through overlying clays.

Figure 59. —Schematic diagrams showing possible processes of flushing of aquifer around salt domes, through migrating shoreline deposits, and through overlying clays before equilibrium is established.

in the Gulf Coast area have penetrated the fresh-water-bearing beds and rise nearly to the land surface (Sawtelle, 1936). The faulting and distorting of beds around the domes may have provided escape channels for deeper waters under high pressure. However, even if there are openings of sufficient magnitude for appreciable vertical movement of water, the actual amount of flushing of the aquifer would be relatively small because of the local nature of the domes as compared to the areal extent of the aquifer.

A fifth possible means of discharge is upward movement through deposits of migrating shorelines (fig. 59*B*). During the deposition of the fresh-water-producing sediments, the shoreline advanced and retreated several times across the subsiding Coastal Plain (Malkin and Echols, 1948). The resultant shoreline facies would cross formational boundaries and might produce an almost continuous but somewhat devious path for vertical movement of ground water. Although erosion between oscillations of the shoreline might remove some of the deposits, it seems possible that at least in some places a continuous sandy zone could connect the surface with the deeper sands.

A sixth possibility, upward movement through the clays as shown in figure 59*C*, was probably the most important method of discharge. In a discussion of the requisites for artesian flow, Chamberlin (1885, p. 137) stated that no rocks are entirely impervious. Meinzer and Wenzel (1942, p. 450) also have pointed out that water may move slowly through rocks which are often considered impermeable. Theis (written communication, 1939) in discussing natural discharge in the Houston area stated:

> The conditions of natural discharge seem as difficult to ascertain here as they are in most localities on the Coastal Plain. Here as elsewhere in this ground-water province the original static head seems to have been essentially in equilibrium with the ocean water and if the original gradients and the dip of the beds are both projected seaward it seems impossible to reach a point where hypothetically the beds could outcrop and the fresh water be discharged against the overlying head of salt water. It is my opinion that the discharge took place through the confining beds, perhaps over an area extending inland from the coast a considerable distance as well as seaward from the coast. If so, the upper aquifers were recharged from the lower. I believe we should emphasize the concept that shales and clayey beds are materials of low permeability, rather than impermeable beds, and should look for large aggregate movements of water through such materials wherever hydraulic gradients in such materials exist. Thus if the transmissibility of the Houston aquifers aggregates 100,000 and the hydraulic gradient was originally 2.5 feet to the mile, all the water carried by these aquifers could pass through 500 feet of overlying clayey beds in a distance along the dip of 5 miles, if the difference in head between top and bottom of the clay was 5 feet and the clay has an average permeability of .04. That discharge takes place through the overlying beds was the conclusion reached by Jacob on Long Island.

Proceeding further along the line of reasoning presented by Theis, it can be shown that if the discharge through the clays took place in a belt 60 miles wide, or about the distance from Houston to a point about 10 miles offshore, an average permeability of .005 for the clays could account for the discharge of the total amount of water moving through the aquifer under natural conditions. That the shallow sands were partly flushed at least 8 miles offshore is evidenced by the occurrence of water containing 1,000 to 3,000 ppm of chloride in shallow water-supply wells drilled for oil exploration off the Galveston-Brazoria County coast. Other indications of offshore flushing of the coastal aquifers are shown by the presence of fresh water in wells off the coast of southwestern Louisiana (Jones, Turcan, and Skibitzke, 1954, p. 139). It should be emphasized that the figures used in these computations are only approximate and are given merely to show that appreciable percolation upward through the confining clays is possible. The possibility of discharge through confining beds has also been suggested by others including White, Turner, and Livingston (1937, p. 7) in the Houston area; Brookhart (1949, p. 34–35) in Anne Arundel County, Md.; Bennett and Meyer (1952, p. 76–77) in the Baltimore area; and Jones, Turcan, and Skibitzke (1954, p. 170–172) in southwestern Louisiana.

PROBABLE OCCURRENCE OF FRESH AND SALT WATER IN HARRIS COUNTY BEFORE GROUND-WATER WITHDRAWALS

Although it is possible that the aquifer may have been flushed by any combination of the methods discussed, it is believed that upward movement of water through the clays was the principal method of discharge. The original relation between the occurrence of fresh and salt water can then be explained by the following discussion.

On the Texas coast, the aquifer consists of a series of interbedded sands and clays, the sands probably pinching out seaward before reaching a submarine outcrop. Water moves from the intake areas down the dip of the beds, and when it passes beneath a confining layer artesian conditions are established. As soon as these conditions occur, water will move upward through the clays as well as laterally through the sands although, because of the low permeability of the clays, the vertical movement will be at a much slower rate than the lateral movement. The water will move through the beds pushing the salt water before it until the loss of head resulting from friction is balanced by the column of salt water extending to sea level. A state of dynamic equilibrium will then be established, for there will be sufficient pressure gradient in the fresh-water zone to move the fresh water upward through the clays and discharge it at the surface. In terms of geologic time the interbedded sands and clays will act as one homogeneous aquifer and one side of a Ghyben-Herzberg lens will be established. Because of the dynamic equilibrium the contact between fresh and salt water will not be at the shoreline but will be some distance offshore, in accordance with the principle as stated by Hubbert (1940, p. 925). Water levels in wells penetrating the salt-water section will stand approximately at sea level if the aquifer has been completely flushed. At Houston the original heads were high enough to account for the present thickness of the fresh-water zone; and the presence of only slightly saline water in shallow wells a few miles offshore indicates that the aquifer has been flushed at least that distance.

PRESENT OCCURRENCE OF SALT WATER

Plate 26 is a map of Harris County showing by means of 200-foot contours the approximate depth below sea level to the base of the lowermost fresh-water sands. Most of the control points used in the preparation of the map were based on the interpretation of electric logs of oil tests. However, in and immediately around Houston analyses of water obtained from drill-stem tests made in water wells were used to determine the depth to the base of the fresh water, and to verify the interpretations of the electric logs. Figure 60 shows a part of the electric log of city of Houston, Heights well 14, and the results of analyses of water obtained from drill-stem tests. The figure illustrates the relation between the quality of the water in the formation and the curves recorded on the electric log.

The interpretations of the electric logs were based on the comparative values of three curves recorded on the logs: the spontaneous-potential curve and two resistivity curves. The spontaneous-potential curve measures the differences in electrical potential across formation boundaries and is of little value in the fresh-water section. However, as the "formation water" (as opposed to water introduced during drilling) becomes more highly mineralized, the curve becomes more indicative of the quality of the water and is a valuable aid in determining the transition zone between fresh and salt water.

The first resistivity curve is called the short normal and is a shallow penetration curve based on an electrode spacing of 10 to 20 inches. It records the resistivity of the formation and the contained fluid for only a short distance from the wall of the hole and is, therefore, influenced by the drilling fluid which invades the formation during the drilling of the hole. The second resistivity curve, or long normal, is based on an electrode spacing of 20 inches to 7 feet and is a deep penetration curve recording the

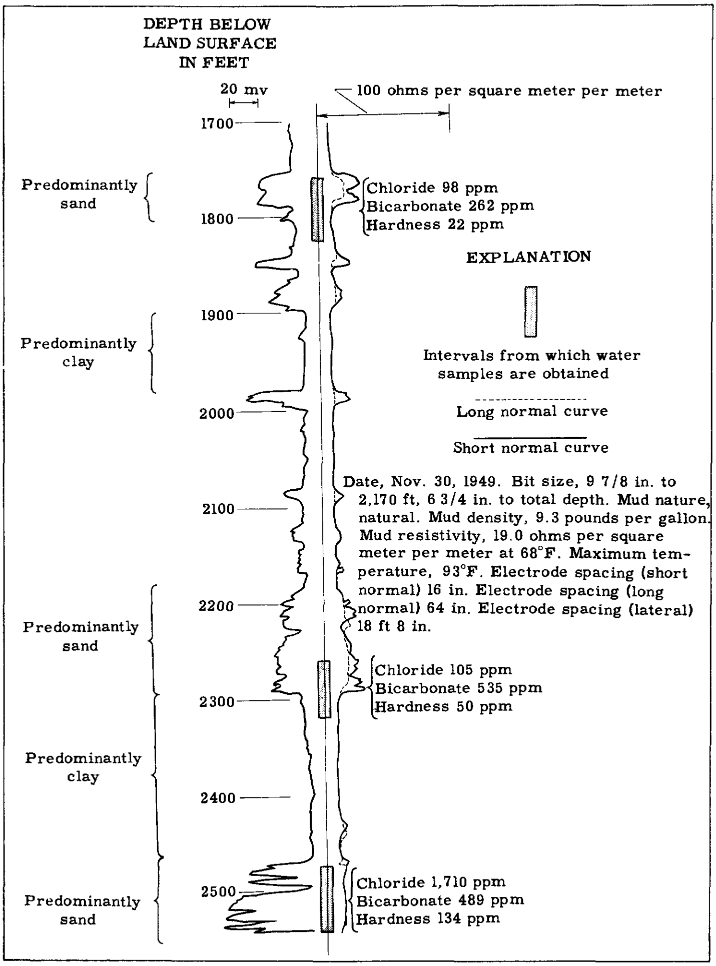


Figure 60.—Part of electric log of the city of Houston Heights well 14.

apparent resistivity of the formation and its fluid. From the apparent resistivity the true resistivity of the fluid may be computed through the use of a proportionality function often called the formation factor (Archie, 1942). A comparison of the short and long normal curves, taking into consideration the resistivity of the drilling fluid and the formation factor, will, therefore, give an indication of the quality of the water in a formation. As the water in the formation becomes more highly mineralized, the resistance values decrease and a consideration of the decrease, particularly as recorded by the long normal, together with the increase in the selfpotential, makes it possible to approximate the depth below which the water is highly mineralized. A more detailed explanation of the interpretation of electric logs has been made by many writers, including Archie (1942), Uren (1946, p. 631–643), Stratton and Ford (1950, p. 354–392), Schlumberger Well Surveying Corp. (1949), Jones and Buford (1951), and Guyod (1952).

In any discussion of fresh and salt water, the question of the definition of salt water will arise. According to the U. S. Public Health Service, a water to be acceptable for domestic use on a common carrier engaged in interstate commerce should not contain more than 250 ppm of chloride. However, in many parts of the country water having a much higher chloride content is used for public supplies. For example, in some of the Galveston municipal wells the chloride content of the water is as high as 800 ppm, although when mixed with better water from some of the other wells the resultant chloride content is not far above the Public Health Service standards. Water containing more than 2,000 ppm of chloride is used in other areas for industrial (Follett, 1947, p. 6) purposes, as well as for watering livestock (Knowles and Lang, 1947, p. 7). The definition of salt water in any given area will depend on the use of the water and on the quality of the fresh water that is available. In this report no numerical limits are given for fresh and salt waters. Any changes in salinity, indicated either by successive changes in analyses of water from the same well or substantial changes with depth as indicated by electric logs or drill-stem tests are considered significant.

In general, the base of the fresh-water sands in Harris County, as shown on the map (pl. 26), is in the shape of a trough trending northeast and southwest, paralleling the regional strike of the geologic formations. The base dips at approximately the same rate as the formations in the northwestern part of the county. Its steep rise in the southeastern part probably represents the limit to which salt water has been flushed from the individual sand members, and which is called the interface. Although the term "interface" is used, it is believed that there is not a sharp contact, but rather a zone in which there is a gradual change from fresh to salt water. It has been shown experimentally that there is a sharp contact between fresh and salt water in a sand when the two liquids are in static equilibrium (Pennink, 1904; D'Andrimont, 1905), though, of course, in time the sharp line would disappear as a result of diffusion. However, ground water is constantly in motion and a state of dynamic equilibrium exists at the contact between fresh and salt water in which the fresh water is in motion and the salt water is static. In most places the contact appears to be a transition zone between fresh and salt water (Turner and Foster, 1934, p. 433; White, Turner, and Livingston, 1937, p. 25; Krul and Liefrinck, 1946, p. 16; Stearns and Macdonald, 1947,

p. 55; Wentworth, 1948, p. 97–98). The vertical gradation between fresh and salt water in southern Harris County is illustrated in the geologic section *A–A'* (pl. 24). In this section the gradual change from fresh to salt water is shown by the decrease in resistivity with depth of the long normal resistivity curve, and the increase of the spontaneous potential in the electric logs of the Humble Oil and Refining Co's. Houston Development Co. No. 1 well, and the Hughes' H. J. Goar Estate No. 1 well.

Two features occupy most of the central part of the area mapped (pl. 26). A ridge in the base of the fresh-water sands extends from the Fort Bend County line across most of Houston. At the northeastern end of the ridge, the base slopes rapidly towards a depression. The deepest part of the depression, which is 18 to 20 miles east-northeast of the center of Houston, is more than 3, 000 feet deep, and represents the location of the deepest fresh-water sands underlying Harris County. These features may be the result of structural anomalies underlying the area or of changes of facies.

Some of the many irregularities of the base of the fresh-water sands are probably due to the method used in determining the base. The bottom of the lowermost fresh-water sand at any one location was assumed to be the base of the fresh-water section. However, if that sand grades laterally into a clay, an overlying sand would have been chosen as the base of the fresh-water section in an adjacent well and may be several hundred feet higher. Other irregularities of the base in and around oil fields may have resulted from oil-field contamination.

In some areas salt domes near the surface evidently affect the depth to which fresh water is present, probably as a result of the arching and disruption of the sediments as the salt pushes upward (Jones, Turcan, and Skibitzke, 1954, p. 99). The locations of three salt domes, Humble, Hockley, and Pierce Junction, are shown on the map. Only the zones overlying the domes appear to be affected. For example, salt water is found at depths of less than 800 feet overlying the Humble dome, but it occurs at depths of more than 2, 400 feet less than 2 miles away.

Although much information on the quality of the water in the Baytown area is available, the contours on the base of the fresh-water sands are generalized (pl. 26) because of structural complexities and rapid lateral changes in chemical character of the water. Owing to the relative proximity of salt water to the fresh water in formations which supply large quantities of water to industries in the Baytown area, a more detailed study of the geology and hydrology is needed in that area.

EFFECT OF GROUND-WATER WITHDRAWALS

Before large-scale withdrawals of ground water in Harris County, the artesian pressure in wells was sufficient to raise the water about 50 to 70 feet above sea level (Deussen, 1914). Although data necessary to map the piezometric surface accurately are lacking, enough early artesian-pressure head measurements are available to indicate that the surface sloped gently toward the gulf. When large-scale withdrawals of ground water began at Houston, a regional cone of depression was established in the piezometric surface and water began to flow toward the cone from all directions. Subsequent increases in pumpage have caused the cone to deepen and spread.

In 1952 the average pumpage in the Houston-Pasadena area was about 180,000,000 gallons a day (Doyel, Winslow, and Naftel, 1954, p. 7). The deepest part of the regional cone of depression was centered in the relatively small Pasadena area, where the average daily pumpage was about 74,500,000 gallons. The extent of the regional cone of depression is shown on the piezometric map (pl. 27), which is based on water-level measurements that were made in the spring of 1953. By comparing this map with plate 26, which shows the approximate position of the interface of fresh and salt water, it is apparent that the cone of depression extends into that part of the aquifer which contains salt water, and this is itself evidence that salt water is moving toward the areas of heavy withdrawals.

The piezometric map as shown in plate 27 represents a composite of the artesian pressures in the heavily pumped sands. Formerly, the entire fresh-water section could be treated as a single aquifer, and only slight differences in head were measured in wells of different depths. However, because some sands have been pumped more heavily than others, and because the individual ones do not have the same permeabilities and are only remotely interconnected hydraulically, the pressures today vary greatly with the depth of the sands from which the water is withdrawn. Figure 61 shows hydrographs of two wells, one deep and one shallow, at an industrial plant in the Houston Ship Channel area. The hydrographs show that although the artesian pressures were nearly the same until about 1942, there has since been a progressive difference of the heads in the two sands. This difference in head between different sands has become increasingly apparent throughout the entire Houston-Pasadena area. Since these differences in head do not show on the piezometric map, it is possible that much steeper gradients than the average shown may exist in certain sands, and that the movement of water through them, therefore, is more rapid than that indicated by the gradients shown on the map.

Figure 61. —Comparison of declines of artesian pressure in a shallow well and a deep well penetrating different sands in the eastern part of the Houston Ship Channel-Pasadena area, Texas.

POSSIBLE SOURCES OF SALT-WATER CONTAMINATION

Ground-water withdrawal is greater and more highly concentrated in the Houston-Pasadena area than almost anywhere else in the United States. All the population and most of the industry in the area are now using ground water for a water supply. In such an area the quality of the water is always of prime importance and the possibility of any change over a period of time should be given careful consideration.

In the Pasadena area the deepest sands that are heavily pumped contain salt water within 6 miles of the area of heavy withdrawals nearest the interface. Salt water is present also in the materials underlying the fresh-water aquifers throughout Harris County. In the Houston Ship Channel area and along Galveston Bay, the fresh-water aquifers are overlain by salty surface water. Consequently, there are three directions from which salt water could invade the aquifers: laterally, from below, and from above. More specifically, there are at least five possible sources of salt-water contamination in the Harris County area: lateral migration through the formations, vertical upward movement through the underlying materials, vertical upward movement along faults or around salt domes, downward seepage from surface sources, and contamination resulting from oil-field operations.

LATERAL MIGRATION THROUGH THE FORMATIONS

Lateral migration through the formations is the most likely source of contamination and should receive first consideration. This type of contamination has been observed in many areas; for example, it has been described by Poland, Garrett, and Sinnott (in preparation) in the Torrance-Santa Monica area in California.

Before there were any withdrawals of ground water in Harris County, the piezometric surface sloped gently toward the gulf; that is, the hydraulic gradient was toward the coast and the water was moving through the aquifer in that direction. As pumping began, cones of depression were established and water began to move from all directions toward the centers of pumping. As early as about 1931, water levels indicate that the regional cone of depression had reached the part of the aquifer containing salt water (White, Livingston, and Turner, 1932, p. 15), and salt water began to move toward the areas of withdrawal. As pumping continued, the hydraulic gradient became steeper and the rate of movement of the salt water increased.

The velocity of water through a sand depends on the permeability and porosity of the sand and on the hydraulic gradient. Their relation may be expressed by the formula:

$$v = \frac{P I}{p} \tag{5}$$

in which v is the average velocity of the ground water, P is the permeability, p is the porosity of the material, and I is the hydraulic gradient. Using this formula and assuming a permeability of 500 gpd per foot (one of the highest measured in the Houston region) and a porosity of 25 percent, computations were made of the velocities that would result from different hydraulic gradients. Figure 62 was prepared to show the relation between gradient and the time required for the water to travel 1 mile. On this graph are shown the gradients between centers of pumping and the interface of the fresh and salt water in 1935, 1940, 1945, 1950, and 1952. In 1952 a hydraulic gradient of slightly more than 18 feet per mile existed between a center of pumping at Deer Park and the interface at a point near La Porte. At a gradient of 18 feet per mile, it would take about 16 years for the water to travel 1 mile, or about 80 years for the water to travel from La Porte to Deer Park. However, as the rate of pumping increases, steeper hy-

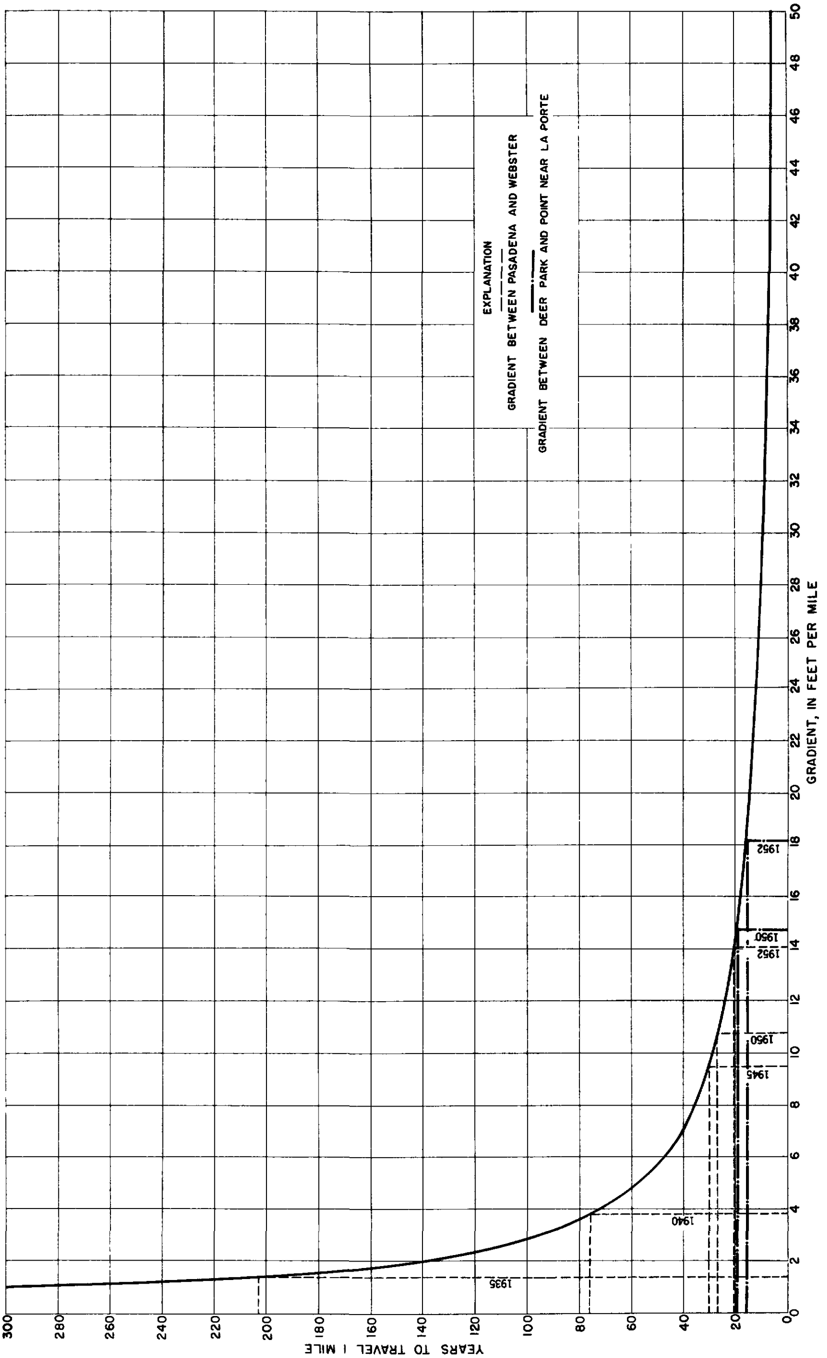


Figure 62. —Computed relation between hydraulic gradient and rate of advance of salt water in Harris County, Tex.

draulic gradients will be established and the rate of movement of salt water toward the areas of withdrawals will increase.

The gradients as shown by the piezometric map (pl. 27) represent a composite for all the heavily pumped sands. However, because of differences in permeability and in the rate of withdrawal of ground water from individual sands, hydraulic gradients both greater and lesser than those shown on the map doubtless exist in the different sands. As a result of these different gradients and differences in permeability, the advance of salt water probably will be in the form of an irregular front, with tongues advancing more rapidly in sands in which the greater hydraulic gradients exist or in which the permeabilities are higher (Wentworth, 1951, p. 92).

Although computations of the velocity of ground-water movement in an area as large and as complicated geologically as the Houston area are necessarily based on many assumptions, the figures are probably of the correct order of magnitude and may be used to obtain an approximation of the average rate of salt-water advance into the pumped areas. Because the exact location of the interface of the fresh and salt water is not known, strategically placed observation wells are needed to determine the location of the interface and to chart the movement of the water. At present, the southernmost observation wells tapping the deeper sands are about $3\frac{1}{2}$ miles south of Pasadena. Analysis of the most recent sample from one of these wells shows that the chloride content of the water increased about 122 ppm between March 1951 and October 1954. This increase in chloride content emphasizes the need for additional data in the area between the center of pumping and the interface. Figure 63 is a graph showing the chloride content of water from four wells in southeastern Harris County, which have been sampled periodically as part of a quality-of-water observation program.

VERTICAL UPWARD MOVEMENT THROUGH THE UNDERLYING MATERIALS

The possibility of serious salt-water contamination by upward vertical movement through the materials underlying the aquifers appears to be remote in most of Harris County, although it was suggested by Theis (written communication, 1939) in discussing salt-water contamination at Alta Loma in Galveston County, Tex. Throughout most of Harris County the part of the aquifer that contains fresh water is underlain by a thick clay. This is particularly well shown in the cross section *B–B'* (pl. 25), and is also evident in plate 24 in that part of the section underlying the city of Houston. The clays are not impermeable and water will move

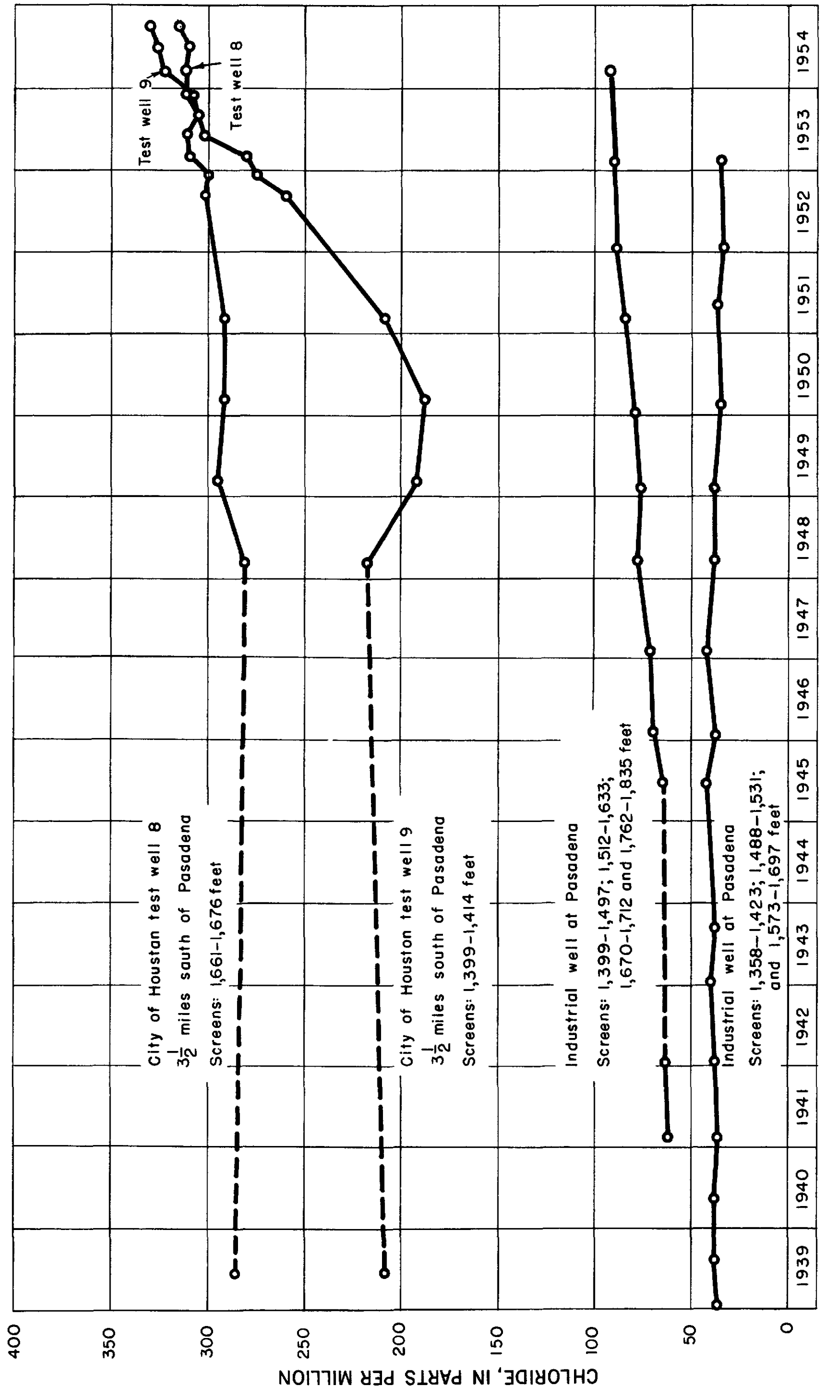


Figure 63. —Graph showing chloride content of water from four wells in eastern Harris County, Tex.

through them, although very slowly. However, as water is removed from a sand by pumping and the hydraulic gradient toward the area of discharge is increased, water will move laterally in the direction of the hydraulic gradient at relatively high velocities and will dilute the comparatively small amount of water discharged from the underlying clays into the sands. Furthermore, in the heavily pumped Houston and Pasadena areas, where the gradients between the fresh-water sands and the underlying clays are steepest, the clay zone separating the fresh- and salt-water sands is several hundred feet thick; and if the clay itself contains fresh water, although this seems improbable, salt water would have to travel through the entire clay section before contamination from below could occur.

However, in certain parts of Harris County the vertical distance separating the fresh- and salt-water sands is small. This is particularly noticeable in the southern part of the county, as shown in plate 24. In these areas where salt-water sands closely underlie the fresh-water sands, there is danger of vertical migration when large differences in head are caused by ground-water withdrawals.

VERTICAL UPWARD MOVEMENT AROUND SALT DOMES OR ALONG FAULTS

Another possible source of contamination is the migration of salt water upward through the disturbed areas surrounding salt domes or along fault planes. However, unconsolidated sediments will probably respond to faulting in a manner approximating plastic flow and there would be little likelihood of any openings large enough to permit the passage of appreciable quantities of water. Although there is no direct evidence of salt-water contamination in the areas around salt domes, ground water in sands overlying some of the domes contains more highly mineralized water than equivalent sands on the flanks of the domes. This has been observed at Humble and Pierce Junction domes in Harris County. The movement of ground water around salt domes and along faults is not well understood and some of the apparent contamination may be the result of lack of circulation rather than actual contamination from the salt or underlying salt-water sands.

DOWNWARD SEEPAGE FROM SURFACE SOURCES

Salt-water contamination from surface sources has been observed in many areas (Poland, Garrett, and Sinnott, in preparation; Bennett and Meyer, 1952, p. 130–131; Jones, Turcan, and Skibitzke, 1954, p. 228). As some of the streams in Harris

County are tidal in their lower reaches and contain slightly saline water, and as Galveston Bay overlies part of the fresh-water aquifer, downward seepage of salt water from the surface should be considered as a possible source of contamination. Tidal salt water may be disregarded as a serious source, however, because of the thick, predominantly clay section overlying the aquifer in the southern half of the county. Under Galveston Bay near La Porte about 400 feet of material that is predominantly clay overlies the principal fresh-water-bearing sands. In the Houston Ship Channel area, the clay cover is thinner, but even here it probably exceeds 250 feet in thickness. Although surface salt water is probably seeping downward, the rate of movement through the clays is so small in comparison to lateral movement through the sands that a comparatively small amount of salt water will be discharged into the sands and will have no noticeable effect on the quality of the water. Some of the extremely shallow sands in the southern part of the county may have been contaminated by surface salt water, but direct evidence is lacking. In Galveston and Chambers Counties some of the shallow sands yield highly mineralized water to wells near open bodies of salt water.

The surface disposal of oil-field brines is another possible source of contamination (Poland, Garrett, and Sinnott, in preparation). If the brine is placed in surface pits, at least part of it will sink into the ground and may contaminate the shallow aquifers, particularly if the pits are in the outcrop of the sands. If, however, the brine is injected into deep salt-water sands through properly constructed wells, there is very little danger of contamination.

CONTAMINATION THROUGH LEAKING WELLS

Fresh-water beds may be contaminated through defective wells. In some areas it is necessary to drill through beds containing salt water in order to penetrate fresh-water aquifers. If the wells are not properly constructed or if the casings develop holes because of corrosion, salt water under higher head may enter the fresh-water aquifers. This type of contamination is common and has been described in many areas (Thompson, 1928, p. 98–107; Sayre, 1937, p. 77; Bennett and Meyer, 1952, p. 158–173). However, it has not been observed in Harris County.

Fresh-water beds may also be contaminated through improperly cased oil wells. Figure 64 shows how salt water may move in an open hole from salt-water sands to fresh-water sands. In most wells the mud cake resulting from the solidifying of the drilling fluid may effectively seal the walls of the hole. If, however, the

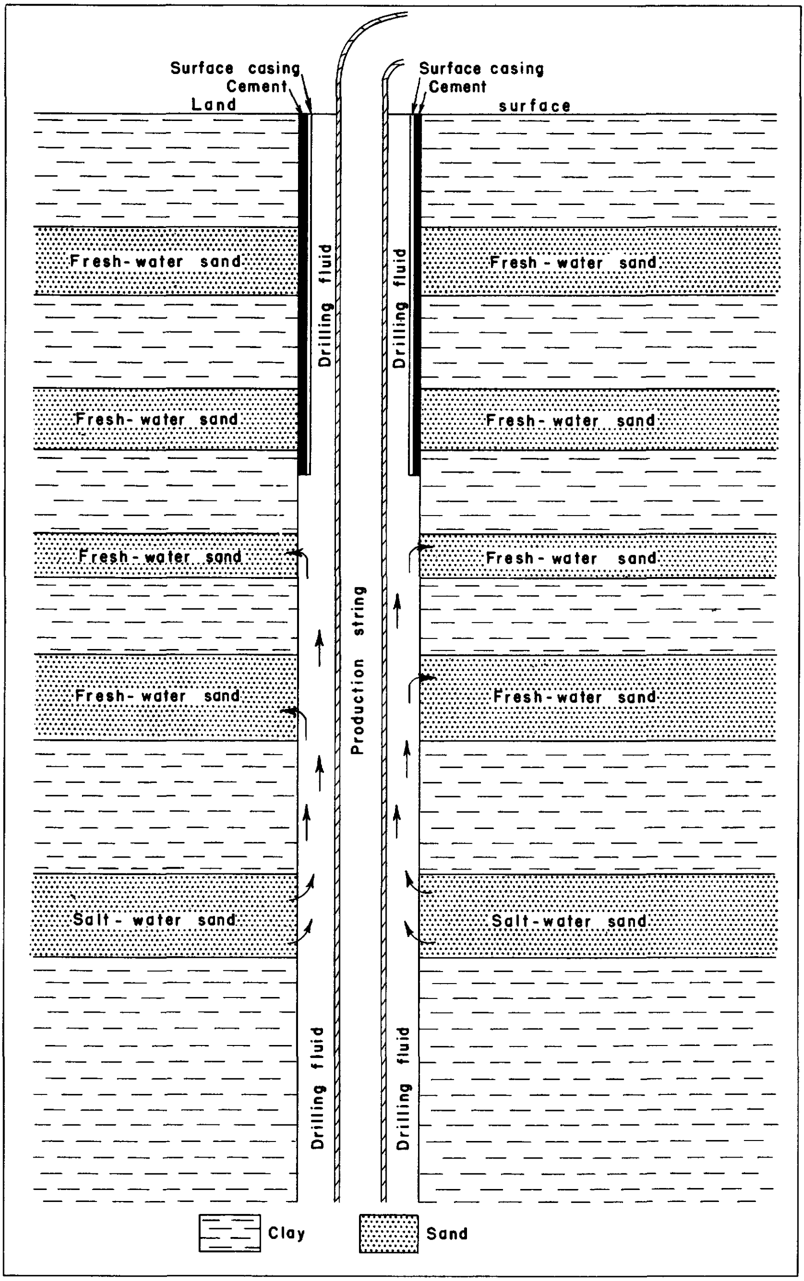


Figure 64. —Diagram of oil well showing possibility of circulation between sands in uncased part of hole.

differences in head become great enough, the resulting unequal pressures may cause the cake to break down and salt-water contamination can occur.

The Oil and Gas Division of the Railroad Commission of Texas is responsible for the proper construction of oil wells and in the last few years, by mutual agreement, the Texas Board of Water Engineers has furnished ground-water data to operators and to the Commission in order that all fresh-water sands may be adequately protected. The Railroad Commission requires fresh-water beds to be protected by casing and cement.

Figure 65 illustrates the approximate depth to which fresh-water sands are present in the oil fields in Harris County, as well as the amount of cemented casing required, according to published field rules. No cases have been recorded in which salt-water contamination has resulted from inadequately cased oil tests in Harris County, although in the Pierce Junction field, sands that contain salt water are found overlying fresh-water sands. These salt-water sands contain fresh water a few miles away.

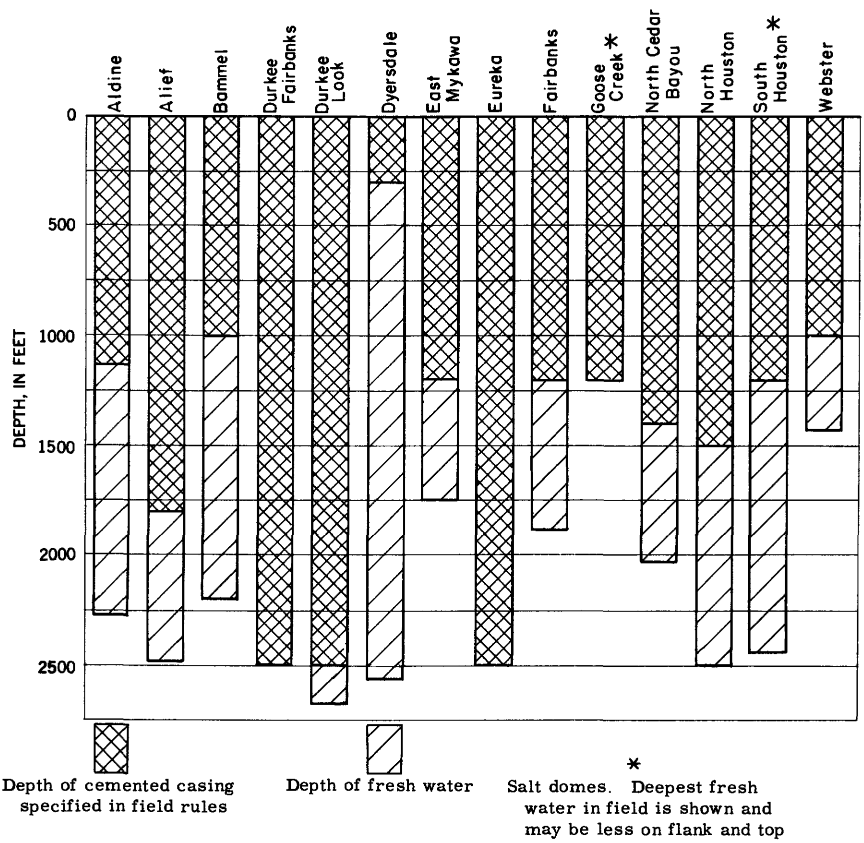


Figure 65. —Comparison between depth to base of fresh-water sands and amount of cemented casing required in oil fields in Harris County, Tex.

CONCLUSIONS

The most serious potential source of contamination of the fresh-water sands in Harris County is by lateral migration of salt water up the dip. The deepest sands, which are heavily pumped in the Houston-Pasadena area, contain salt water a few miles down the dip. A hydraulic gradient has been established from the salt water toward the area of withdrawal and, as water must flow down the gradient, salt water must be moving toward the areas of pumping. The data necessary for precise mapping of the interface of fresh and salt water are lacking, and although the rate of movement of the salt water is known to be slow, the interface in some sands may lie closer to pumped areas than is believed.

In the course of the intensive ground-water investigation in the Houston district approximately 70 observation wells have been sampled periodically in order to detect any salt-water contamination in the area. Chemical analyses of samples taken from these wells have shown no appreciable change in the quality of the water, except in City of Houston test well 8 screened between 1,661 and 1,676 feet and about $3\frac{1}{2}$ miles south of Pasadena, which has shown an increase in the chloride content of 47 ppm between June 1939 and October 1954 and in City of Houston test well 9, screened between 1,399 and 1,414 feet, and at the same location, which has shown an increase of 142 ppm chloride between March 1950 and October 1954. Although the sampling program is extensive, there are certain areas in the county, particularly in the eastern and southeastern parts, in which there are no wells of proper depth to detect changes in the quality of the water. In these areas test wells should be drilled at strategic locations to delineate more precisely the interface and to observe the movement of the salt water down the gradient. Additional data are needed particularly in the area between La Porte and Deer Park, where the interface is probably closest to areas of heavy pumping.

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