STATE OF LOUISIANA
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
OFFICE OF PUBLIC WORKS

Water Resources
TECHNICAL REPORT
No. 19

# SALTWATER ENCROACHMENT IN THE "600-FOOT" AND "1,500-FOOT" SANDS OF THE BATON ROUGE AREA, LOUISIANA, 1966-78, INCLUDING A DISCUSSION OF SALTWATER IN OTHER SANDS

Prepared by
UNITED STATES DEPARTMENT OF THE INTERIOR
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In cooperation with
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
OFFICE OF PUBLIC WORKS
1979

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Louisiana District

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) OF METRIC UNITS

| Multiply inch-pound units | By | To obtain SI units |
|---|---|---|
| foot (ft) | 0.3048 | meter (m) |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |
| foot per year (ft/yr) | 0.3048 | meter per year |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day ($m^2/d$) |
| gallon (gal) | 3.785 | liter (L) |
| gallon per day (gal/d) | 0.003785 | cubic meter per day ($m^3/d$) |
| gallon per day per foot [(gal/d)/ft] | 0.01242 | meter squared per day ($m^2/d$) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| inch (in.) | 2.540 | centimeter (cm) |
| mile (mi) | 1.609 | kilometer (km) |
| million gallons per day (Mgal/d) | 3,785 | cubic meter per day ($m^3/d$) |

(To convert temperature in degree Celsius (°C) to degree Fahrenheit (°F), multiply by 9/5 and add 32.)

# SALTWATER ENCROACHMENT IN THE "600-FOOT" AND "1,500-FOOT" SANDS OF THE BATON ROUGE AREA, LOUISIANA, 1966-78, INCLUDING A DISCUSSION OF SALTWATER IN OTHER SANDS

By C. D. Whiteman, Jr.


## ABSTRACT

Saltwater encroachment has been observed in the "600-foot" and "1,500-foot" sands and is indicated in the "800-foot," "1,000-foot," "2,000-foot," and "2,800-foot" sands of the Baton Rouge area. The encroachment is the result of leakage of salty water across the Baton Rouge fault in response to pumpage north of the fault.

Salty water in the "1,500-foot" sand may reach the Government Street well field in about 30 years, and a control strategy should be adopted and placed in operation as soon as possible to minimize contamination of the aquifer and damage to existing well fields. Encroachment in the "600-foot" sand may not produce serious problems for about 40 years, but the ultimate effects of encroachment in the "600-foot" sand may be more damaging than encroachment in the "1,500-foot" sand. If control measures are to be instituted for the "600-foot" sand, for maximum effectiveness, they should begin as soon as practical to do so and within about 20 years at the latest. Control measures in the other sands in which encroachment is indicated can probably be delayed longer if adequate monitoring is maintained.

Of several possible control strategies, the most practical will probably consist of discharge wells pumping salty water from the aquifers near the fault. Injection wells to dispose of the salty water will probably also be needed.

## INTRODUCTION

The "600-foot" sand has been an important source of water for industrial use since the first large industrial wells were drilled in the Baton Rouge area in 1909. Saltwater[1/] encroachment was first observed in the "600-foot" sand in 1948, when a municipally owned well (EB-123) in South Baton Rouge at City Park was abandoned following a sharp increase in salinity (Meyer and Turcan, 1955, p. 71). By 1956 the leading edge of the salty water had reached well EB-500 on North Boulevard, more than a mile north of the City Park well. With northward movement of salty water in the "600-foot" sand confirmed, concern grew, not only for the future of the "600-foot" sand but also that undetected encroachment might be an imminent threat to deeper aquifers supplying major pumping centers south of the industrial district.

Following a preliminary study based on analysis of existing data, Morgan and Winner (1964) recommended that a program of test drilling and increased data collection be started as soon as possible. The program was started in 1965, and Rollo (1969) reported the results of the test-drilling program and the first 2 years of data-collection activity. In his discussion of saltwater encroachment in the "600-foot" sand, Rollo pointed out the need for additional test drilling to better define the geohydrologic conditions controlling the advance of the saltwater front.

This report is based on an investigation undertaken as an extension of Rollo's work on the "600-foot" sand. The first phase of the investigation was devoted to determining the source of the encroaching salty water in the "600-foot" sand. The second phase of the investigation was devoted primarily to mapping the configuration of the "600-foot" sand to determine the path that the salty water will follow as it moves northward toward the major well fields of the industrial district. Salty water, being denser than freshwater, tends to flow along the lowest part of an aquifer system. On a regional basis, the "600-foot" sand dips southward at an average rate of about 15 to 30 ft/mi. Within the project area, however, local variations in thickness and depth to the base of the aquifer are more important than the regional dip in controlling the flow of salty water.

During the study, saltwater encroachment in the "1,500-foot" sand was confirmed when salty water reached a monitor well that had previously yielded freshwater. A third phase was added to the study to determine the probable direction and rate of encroachment in the "1,500-foot" sand.

Monitoring of the other aquifers of the area continued throughout the investigation. Water with chloride concentration higher than the normal background level has been detected in a production well in the "1,200-foot" sand in West Baton Rouge Parish and may indicate encroachment in this aquifer. Single monitor wells completed in the "1,000-foot"

1/In ground-water studies in Louisiana, freshwater is generally defined as that containing 250 milligrams per liter or less of chloride, and salty water as that containing more than 250 milligrams per liter of chloride. These definitions are used in this report.

and "2,000-foot sands in East Baton Rouge Parish yielded slightly salty water initially and have shown increases in chloride, but the high-chloride water has not reached any other wells in these aquifers.

## Area of Investigation

This study was confined primarily to townships 6 and 7 south in East Baton Rouge and West Baton Rouge Parishes. (See pl. 1.) Test drilling in the "600-foot" sand was concentrated along Dalrymple Drive at City Park Lake and along Choctaw Drive south of the industrial district; but two wells were installed in the intervening area to monitor the advance of salty water, and one test hole was drilled in West Baton Rouge Parish. During later stages of the project, monitor wells were installed in other aquifers in both East Baton Rouge and West Baton Rouge Parishes. (See table 3.)

## Acknowledgments

So many people and companies have contributed to this investigation that individual recognition is not practical, but the author wishes to thank all who helped by providing needed information and access to their wells. Special mention and thanks are due the late Mr. L. W. Eaton; Mr. P. C. Witter; Glazers' Wholesale Drug Company, Inc.; Pan American Import Company of Baton Rouge, Inc.; the Baton Rouge Recreation and Parks Commission; the Baton Rouge Port Commission; and the East Baton Rouge City-Parish Department of Public Works, who provided sites for the test wells that formed the basis for this investigation.

This investigation was made by the U.S. Geological Survey as part of the program of water-resources investigations conducted mainly in cooperation with the Louisiana Office of Public Works, Department of Transportation and Development. Work on this project was begun at the request of the East Baton Rouge Water Conservation Committee, and most of the matching funds were provided by East Baton Rouge City-Parish and the Louisiana Department (now Office) of Public Works. Since 1974, the Capital Area Groundwater Conservation Commission has provided local support.

# THE BATON ROUGE FAULT--A LEAKY BARRIER

## Recognition of the Fault As a Barrier

Test drilling by the U.S. Geological Survey in 1965 and 1966 and by the Louisiana Water Resources Research Institute in 1967 led to recognition of the Baton Rouge fault as a hydrologic barrier to northward movement of salty water in the major aquifers of the Baton Rouge area. Prior to the test drilling, little water-level information was available for sands deeper than the "400-foot" sand in the area south of the fault. The sparse data for the "2,000-foot" sand were interpreted as indicating a steepening of the water-level gradient south and southwest of the

Baton Rouge Water Works' Lafayette Street well field, but no discontinuity in water levels was recognized (Morgan and Winner, 1964, fig. 13). Observation wells installed by the U.S. Geological Survey in 1965, however, indicated that the fault produced a major discontinuity in water levels; water levels south of the fault in the "1,200-foot," "1,500-foot," and "2,000-foot" sands were above land surface instead of 50 to 100 ft below land surface as expected (Meyer and Rollo, 1965).

Following recognition of the hydrologic significance of the Baton Rouge fault, the emphasis during the remainder of the 1965-66 test-drilling program was shifted slightly to concentrate on obtaining as much information as possible on the location and geologic and hydrologic effects of the fault. Test holes and observation wells drilled by the Louisiana Water Resources Research Institute in 1967 provided additional data on the effects of the fault on the "600-foot" and shallower sands. As a result of these test-drilling programs, it was realized that displacement across the fault was greater at relatively shallow depths than had been recognized previously. The "400-foot" sand south of the fault was downthrown opposite the "600-foot" sand north of the fault, a displacement of more than 200 ft at a depth of about 350 ft (Rollo, 1969; Smith, 1969). Above the "400-foot" sand, displacement decreases to a few feet or a few tens of feet in the shallow Pleistocene sands and along the surface trace of the fault.

On the basis of available geologic data, water-level differences across the fault, and the location and extent of salty water in the aquifers on each side of the fault, Rollo (1969) concluded that salty water in the "600-foot" sand north of the fault had leaked across the fault from the downthrown "400-foot" sand. The fault was believed to form a more effective barrier against leakage of salty water into the major aquifers below the "600-foot" sand, but isolated bodies of salty water were detected north of the fault in the "800-foot," "1,000-foot," "1,500-foot," and "2,000-foot" sands. At about the same time, and using much of the same data, Smith (1969) concluded that the fault provided an impermeable barrier, preventing leakage of salty water from the "400-foot" sand to the "600-foot" sand, and that the observed saltwater encroachment in the "600-foot" sand in Baton Rouge was fed by the movement of an isolated body of salty water trapped north of the fault in the "600-foot" sand in West Baton Rouge Parish.

## Importance of Determining the Effect of the Fault

Resolution of the question of whether the fault provides an effective barrier or only restricts movement of salty water from the downthrown "400-foot" sand to the "600-foot" sand north of the fault is vital for proper evaluation of possible control strategies. If the only source of salty water is a limited body trapped north of the fault in the "600-foot" sand, theoretically it would be possible to pump all of the salty water out of the aquifer. In that case, when all of the salty water had been removed, the threat of encroachment would be eliminated and control measures could be discontinued. On the other hand, if salty water is entering the "600-foot" sand from the large reservoir of salty water in the "400-foot" sand south of the fault, elimination of the threat of encroachment would be impractical. Any control strategy adopted would have to be based on the premise that operation of the control system would be maintained as long as significant amounts of water are to be pumped from the "400-foot," "600-foot," or "800-foot" sands north of the fault. Determination of the effectiveness of the fault as a barrier to movement of salty water into the "600-foot" sand could also indicate the fault's effectiveness as a barrier to encroachment in the deeper sands.

## SALTWATER ENCROACHMENT IN THE "600-FOOT" SAND

### Test Drilling Across the Fault--1971

Initial test drilling conducted during this investigation was designed to determine the most probable source of saltwater encroachment in the "600-foot" sand. Particular emphasis was placed on resolving the question of whether or not salty water was leaking across the fault to the "600-foot" sand from the downthrown "400-foot" sand.

#### Design of the Experiment

The general design of the experiment was to construct observation wells on each side of the fault, as close to the fault as possible, with one or more wells in the "600-foot" sand north of the fault and one or more wells in the "400-foot" sand south of the fault. After the observation wells were completed and the geologic and hydrologic conditions at the fault determined, a larger well would then be constructed north of the fault if conditions were favorable. Cyclic pumping of the large well would produce corresponding cycles of drawdown and recovery in the observation wells south of the fault if leakage were occurring across the fault. Comparison of observed drawdown in wells south of the fault with the theoretical drawdown that would be expected at the same sites if the fault produced no flow restriction would provide an indication of the permeability of the fault zone.

The area selected for the first test wells, along the west side of City Park Lake between Dalrymple Drive and the lake, seemed to provide very good conditions for detecting leakage if it were occurring. This area is directly south of the area where encroachment was first observed, and water-level differences across the fault would be near their maximum. (See pl. 3.) Available well logs indicated a probable overlap of at least 20 ft between the base of the "600-foot" sand north of the fault and the top of the "400-foot" sand south of the fault. The north-south orientation of the strip of land chosen for the test drilling, almost perpendicular to the strike of the fault, permitted near optimum location of the test holes and observation wells. (See fig. 1.)

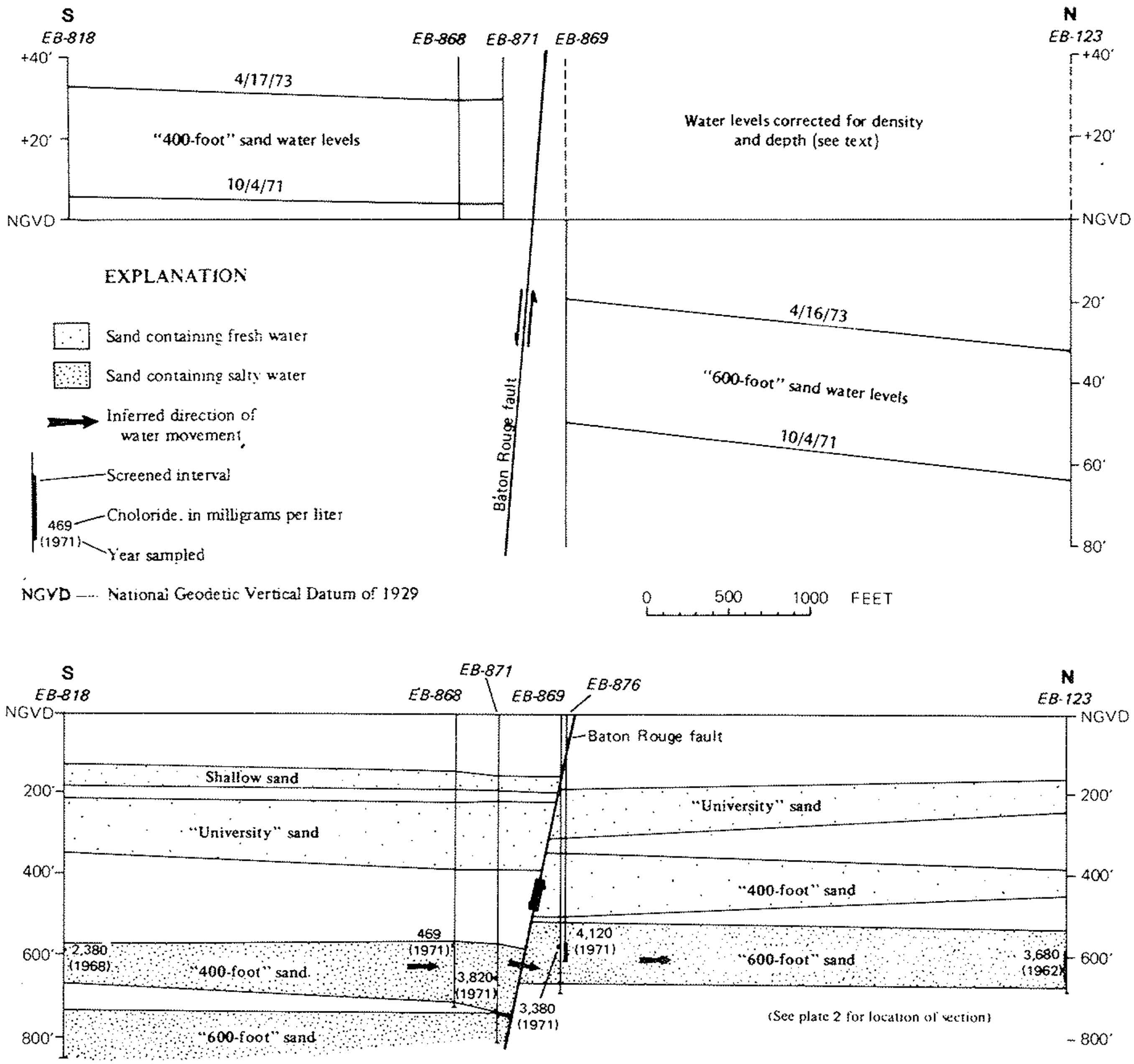


Figure 1.--Water-level profiles and geohydrologic section showing the shallow aquifers near the Baton Rouge fault.

## Test-Drilling Results

The first test hole (EB-868) was located about 800 ft south of the approximate surface trace of the fault. The electrical log of this hole indicated that the hole had not reached the fault; and water levels in the observation well completed in the test hole, EB-868, confirmed that the well was in the "400-foot" sand south of the fault. Because of uncertainty as to the amount of overlap between the "400-foot" and "600-foot" sands, well EB-868 was completed near the top of the "400-foot" sand in a zone where the electrical log indicated that the water was relatively fresh.

The second test hole (EB-869) was drilled about 100 ft south of the surface trace of the fault but was expected to cut through the fault above the "600-foot" sand. The electrical log of this hole indicated that the hole had cut the fault above a shallow Pleistocene sand known locally as the "University" sand (Smith, 1969). Water levels in the observation well completed in this test hole, EB-869, confirmed that the well was in the "600-foot" sand north of the fault. Well EB-869 was completed at the same depth as well EB-868.

Confirmation of the subsurface position of the fault provided by well EB-869 aided in the selection of a site between the first two wells for a second well (EB-871) to be completed closer to the fault in the downthrown "400-foot" sand. This well, EB-871, was located about 270 ft north of well EB-868 and was completed lower in the "400-foot" sand to obtain a more representative water sample than that from well EB-868.

The electrical logs of the three test holes, combined with logs of other wells in the area, indicate that the Baton Rouge fault is a typical growth fault. Displacement is downward to the south and decreases from about 350 ft at the level of the "2,000-foot" sand (Durham and Peeples, 1956; Rollo, 1969) to about 225 ft at the top of the "400-foot" sand and to only 30 to 35 ft at the top of the shallow Pleistocene "University" sand. Displacement at land surface, as indicated by the height of the visible scarp, is about 20 ft. About 8 ft of rollover, or sag toward the fault, of the downthrown "400-foot" sand is indicated between wells EB-868 and EB-871, and additional rollover probably occurs between well EB-871 and the fault. No rollover or other distortion is evident in the downthrown "University" sand or in any of the sands north of the fault. (See fig. 1B.)

The electrical log of well EB-869 confirms that the deep base of the "600-foot" sand observed at well EB-123 continues southward to the fault. The test site along City Park Lake is apparently near the west edge of an ancient stream channel. The base of the "600-foot" sand is 70 ft lower and the sand is about 60 ft thicker at well EB-869 than at well EB-777, 1,000 ft to the northwest. The "600-foot" sand may be slightly thicker and deeper a short distance east of well EB-869. (See pl. 5.)

South of the fault, the "400-foot" sand is relatively thick at the test site (well EB-871), thins to the east and south, and thickens and merges with overlying sands to the west. The base of the "400-foot" sand is deeper at the test site and to the west than to the south and east.

## Water Quality Near the Fault

If leakage across the Baton Rouge fault is the source of the encroaching salty water, the downthrown "400-foot" sand must contain water at the fault that is at least as salty as the saltiest water in the "600-foot" sand. No mechanism is known by which the salinity of water would increase during movement across the fault. At the time this investigation was started, no well completed in the downthrown "400-foot" sand yielded water as salty as that collected from well EB-123, completed in the "600-foot" sand north of the fault. Of the wells completed in the downthrown "400-foot" sand, well EB-818 yielded the saltiest water, a chloride concentration of 2,380 mg/L (milligrams per liter) in 1968. In contrast, a water sample collected from well EB-123 in 1962 had a chloride concentration of 3,680 mg/L.

The electrical logs and well records of three key wells south of the fault, EB-818, EB-822, and EB-823, indicate that all three wells were completed near the top of the downthrown "400-foot" sand and that water in the sand increases in salinity with depth. The estimated chloride concentration in water at the base of the sand ranges from 2,700 mg/L at well EB-823 to 3,600 mg/L at well EB-822. Water at the base of the sand at well EB-822 could easily be as salty as water from well EB-123, and the possibility of saltier water occurring between well EB-822 and the fault could not be ruled out.

The test wells installed at the City Park Lake site confirmed the concept developed in the preliminary investigation. (See fig. 1B.) Well EB-868, completed at the top of the downthrown "400-foot" sand, yielded water with a chloride concentration of 469 mg/L; but the electrical log indicated much saltier water lower in the sand. Well EB-869, completed in the "600-foot" sand north of the fault and higher in the sand than well EB-123, yielded water with a chloride concentration of 3,380 mg/L. The third observation well at this site, EB-871, was completed near the middle of the downthrown "400-foot" sand and yielded water with a chloride concentration of 3,820 mg/L, the highest observed from either side of the fault at that time. The electrical log of the test hole for well EB-871 indicates increasing salinity below the interval screened for the observation well; the chloride concentration near the base of the "400-foot" sand south of the fault probably is more than 5,000 mg/L. Production well EB-876, installed in the "600-foot" sand near well EB-869, subsequently yielded water with a chloride concentration of 4,120 mg/L, well below the estimated maximum chloride concentration in water in the downthrown "400-foot" sand.

Comparison of chemical analyses of water from the two wells nearest the fault, EB-869 in the "600-foot" sand and EB-871 in the downthrown "400-foot" sand, provided additional indication of leakage across the fault at this site. Although similarity of composition of water from the two wells does not prove leakage, it does indicate that leakage is a possible source of the salty water. Large differences in composition, on the other hand, would have provided strong evidence that leakage was not occurring at this site. Comparison of the analyses is facilitated by expressing the concentrations of the dissolved ions as milliequivalents per liter and calculating the percentage composition. As shown in table 1, water from the two wells is almost identical in composition; water from well EB-869 is equivalent to slightly diluted water from well EB-871. None of the major ionized constituents differ in their contributions to the total ionized dissolved-solids content by as much as 0.5 percent. Thus, the water chemistry indicates that the downthrown "400-foot" sand could be the source of the salty water entering the "600-foot" sand.

Table 1.--Composition of salty water in the "400-foot" and "600-foot" sands near the Baton Rouge fault

| Dissolved constituents and properties | Well EB-869 "600-foot" sand north of fault | | | Well EB-871 "400-foot" sand south of fault | | |
|---|---|---|---|---|---|---|
| | Milligrams per liter | Milli-equivalents per liter | Percentage of ionized constituents | Milligrams per liter | Milli-equivalents per liter | Percentage of ionized constituents |
| Calcium | 180 | 8.982 | 4.43 | 190 | 9.481 | 4.15 |
| Magnesium | 51 | 4.185 | 2.07 | 48 | 3.986 | 1.75 |
| Sodium | 2,040 | 88.699 | 43.79 | 2,320 | 100.873 | 44.19 |
| Potassium | 10 | .256 | .13 | 16 | .409 | .18 |
| Bicarbonate | 237 | 3.884 | 1.92 | 248 | 4.065 | 1.78 |
| Carbonate | 0 | .000 | .00 | 8 | .267 | .12 |
| Sulfate | 58 | 1.208 | .60 | 68 | 1.416 | .62 |
| Chloride | 3,380 | 95.350 | 47.07 | 3,820 | 107.762 | 47.21 |
| Hardness as $CaCO_3$ | 659 | ------ | ----- | 674 | ------- | ----- |
| Specific conductance (micromhos at 25° C) | 10,400 | ------ | ----- | 11,600 | ------- | ----- |
| pH (units) | 8.1 | ------ | ----- | 8.4 | ------- | ----- |

Some mention should be made of the thin layer of low-salinity water at the top of the "400-foot" sand near the fault, shown by the electrical logs of wells EB-868 and EB-871 and the water sample from well EB-868 (chloride concentration, 469 mg/L). This layer of low-salinity water floats on top of the denser, saltier water below and is apparently trapped in its present position by rollover of the "400-foot" sand toward the fault (fig. 1B). Under static conditions, the base of this layer of fresher water should be level; but the electrical logs of wells EB-868 and EB-871 indicate that it is tilted downward toward the fault. Movement of water toward the fault in the downthrown "400-foot" sand could account for the observed tilt of the base of the relatively fresh layer (Hubbert, 1940 and 1953).

## Water Levels Near the Fault

The large differences in water levels in wells of approximately the same depth on opposite sides of the fault provide indisputable evidence that the fault restricts movement of water from the downthrown "400-foot" sand to the "600-foot" sand. These differences cannot resolve the question of whether or not leakage occurs, but they provide a potential driving force for leakage. Establishment of the existence of a water-level gradient toward the fault in the downthrown "400-foot" sand, on the other hand, would provide good evidence of leakage across the fault. A corresponding component of head produced by leakage should occur in the "600-foot" sand north of the fault, but gradients produced by pumping are so large and variable that detection of the small component of head produced by leakage would be very difficult.

South of the fault, pumpage from the "400-foot" sand is small and widely dispersed. The nearest pumpage of any significance is several miles southeast of the City Park Lake site, so any gradient introduced by pumpage would be small and directed away from the fault. Water levels in wells completed in the "400-foot" sand south of the fault fluctuate more than 20 ft in response to changes in stage of the Mississippi River because the "400-foot" sand is hydraulically connected with the river through the alluvium and the shallow Pleistocene sands (pl. 4C). Gradients accompanying these fluctuations are generally low and are oriented in an east-west direction, roughly parallel to the fault. Any long-term gradient toward the fault indicates movement of water in that direction. As there is no pumping near the fault and no long-term change in the amount of water in storage in the aquifer, water moving toward the fault in the "400-foot" sand must leave the aquifer by migration to other sands. Movement of water upward or downward along the fault plane into overlying or underlying sands is very unlikely, but leakage of water across the fault into the juxtaposed "600-foot" sand could easily account for the loss of water from the "400-foot" sand.

Completion of observation well EB-868 provided, for the first time, an opportunity to determine the gradient near the fault in the downthrown "400-foot" sand. Water levels from this well, when compared with water levels from wells EB-818, EB-822, EB-823, and EB-789A, indicate a persistent northward component superimposed on the alternating eastward and westward gradients that occur as water levels in the aquifer respond to changes in stage of the Mississippi River. Water levels from wells EB-818 and EB-868, alined almost north-south and completed at equivalent depths, probably provide the best indication of the northward component of gradient south of the fault. (See fig. 2.)

Evaluation of head gradients in the "400-foot" sand is complicated by differences in the salinity, and thus in the density, of water in the observation wells. The density differences are small and can be ignored

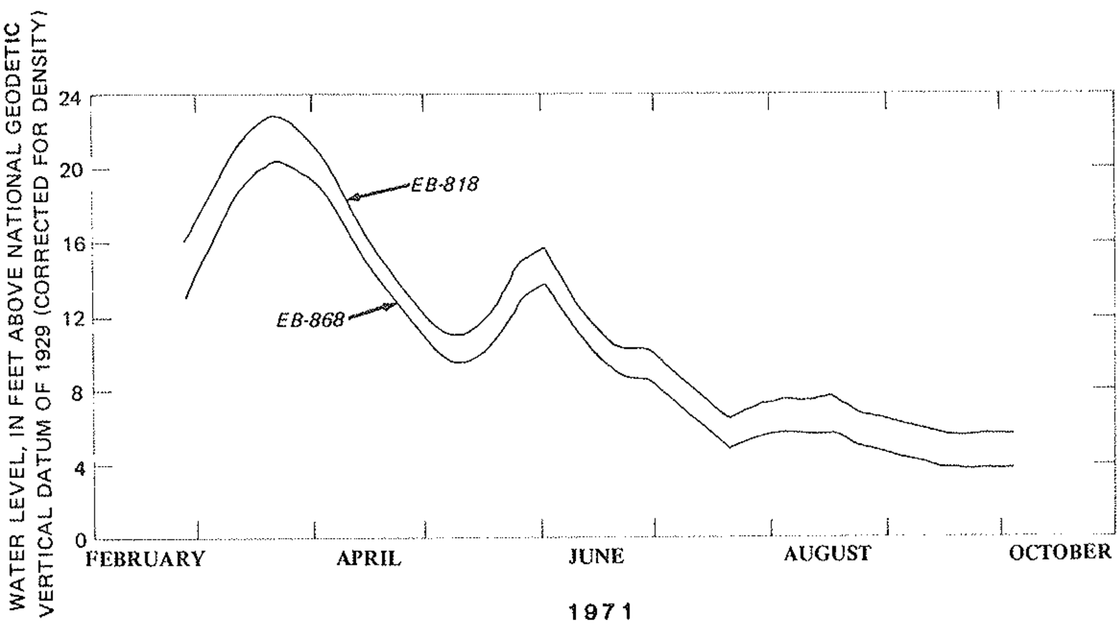


Figure 2.--Water levels of the downthrown "400-foot" sand near City Park Lake indicating a persistent northward gradient toward the Baton Rouge fault.

for some purposes; but, accumulated over hundreds of feet of water column in an observation well, the density differences produce significant effects on water levels. Corrections can be made for the effect of density differences by calculating the water levels that would occur if each well contained water of a uniform reference density. Where the density of the water in the well exceeds the reference density, measured head is increased by an amount that is proportional to the length of water column in the wells and the density difference. Because the temperature of the water is very nearly the same in each of the wells, no correction is needed for density differences caused by differences of water temperature. The reference density used for correcting water levels in this report is 0.99788 gram per cubic centimeter, equivalent to water with 300 mg/L dissolved solids at 22.5°C.

When the density corrections are applied to water levels in wells EB-818 and EB-868, the equivalent freshwater gradient is increased. Measured water levels indicate a northward gradient varying from 0.04 to 5.5 ft/mi; the corrected water levels indicate a gradient of 2.9 to 8.4 ft/mi. When density corrections are applied to well EB-871, however, the freshwater head in well EB-871 is 0.3 to 0.4 ft higher than the water levels in well EB-868. The difference can be accounted for by the salinity increase with depth at well EB-871. Data are not available to calculate the increase of freshwater head with depth for well EB-871, but it should be on the order of 0.3 ft. This vertical gradient should be considered when comparing heads in well EB-871 with heads in wells EB-868 and EB-818.

Another correction should be applied to the water levels of well EB-871 for the vertical component of head near the fault; but data are not available to allow calculation, or even estimation, of this correction. The correction probably is small enough to be ignored for most purposes.

During the fall of 1971 the Mississippi River remained at a relatively constant stage, varying by less than 2 ft, from late August to mid-October. This allowed the potentiometric surface in the "400-foot" sand south of the fault to flatten, with very little east-west gradient. Under these conditions the northward gradient toward the fault in the vicinity of City Park Lake is most apparent. On October 4, 1971, when the water-level difference across the fault was near its maximum for the year, corrected measurements of wells completed in the "400-foot" sand south of the fault indicated closure of water-level contours against the fault. (See pl. 2.) This permits an estimate to be made of the quantity of water moving toward the fault across the closed contour lines, in this case about $6x10^5$ gal/d (based on the formula Q=TIL, where Q is quantity of water; T, transmissivity, is $8x10^3$ $ft^2/d$ or $6x10^4$ (gal/d)/ft; I, average gradient, is 3 ft/mi; and L, length of 5-foot contour, is 3.25 mi).

## Pumping-Test Results

The results of test drilling near City Park Lake indicated that the site was suitable for the proposed pumping test and that useful information could be obtained from the test. If leakage across the fault could be demonstrated at this site, the question of whether or not leakage was occurring would be positively resolved. If no leakage could be detected under the favorable conditions existing at this site, it could be reasonably inferred that leakage would be unlikely at less favorable sites and that leakage across the fault would be too slight to account for the observed saltwater encroachment in the "600-foot" sand.

A 6-inch production well, EB-876, was drilled 25 ft from well EB-869 and was completed with 40 ft of screen set from 595 to 635 ft below land surface in the coarsest part of the "600-foot" sand. The well was pumped by airlift, and discharge was measured with a V-notch weir. Maximum yield obtained was 350 gal/min. Observations during development and testing of well EB-876 indicated that water levels in wells EB-868 and EB-871 did fluctuate in response to changes in the pumping rate of well EB-876, but that fluctuations in the water levels of more distant wells in the downthrown "400-foot" sand (such as well EB-818) were too small to be reliably measured.

The large volume of salty water produced by pumping well EB-876 at its maximum rate presented disposal problems that limited both the length of the individual pumping cycles and the number of times that the cycles could be repeated. For the formal test, well EB-876 was pumped at 350 gal/min for 2 hours, allowed to recover for slightly over 2 hours, and then pumped at 350 gal/min for 70 minutes. Drawdown in the "600-foot" sand near the fault was measured by electric tape in well EB-869. Well EB-123 was used as a distant observation well in the "600-foot" sand and was monitored by a continuous water-level recorder. Continuous water-level recorders on wells EB-868 and EB-871 were used to monitor water levels in the downthrown "400-foot" sand.

The results of the test are illustrated in figure 3. Drawdown in observation well EB-869 reached a maximum of 6.46 ft at the end of the first pumping cycle. Calculated drawdown at the fault, using the Theis nonequilibrium formula and assuming the fault acts as a barrier, was almost 4 ft. Maximum drawdown in well EB-868 was 0.04 ft and in well EB-871 was 0.05 ft, in contrast to drawdowns of about 0.6 and 0.9 ft, respectively, that would have occurred if the fault caused no flow restriction. The interval between the start of pumping of well EB-876 and the start of water-level declines in wells EB-868 and EB-871 was not determined precisely but was no more than 1 or 2 minutes.

The response of water levels in the downthrown "400-foot" sand to changes in hydraulic stress across the fault shows conclusively that leakage across the fault does occur. The rapidity of the response noted during this test indicates that leakage occurs at or very near the test site.

## Possible Alternate Sources of Salty Water

Although leakage of salty water across the fault can account for the observed saltwater encroachment in the "600-foot" sand, the possibility of other sources of salty water should be examined for two reasons. First, elimination of possible alternate sources would further confirm that leakage across the fault is the source of the salty water. Second, even if leakage across the fault is the primary source of salty water, any secondary sources should be considered in the design and evaluation of control measures.

### Salty Water Trapped North of the Fault in the "600-Foot" Sand

One possible source of salty water would be a body of salty water trapped north of the fault in the "600-foot" sand. Such a body of trapped water could have remained relatively immobile in a low part of the aquifer until a gradient induced by pumping caused it to start moving toward the pumping center. The saltwater encroachment is occurring along the deepest part of the aquifer south of the major pumping center in the industrial district. If salty water had been present in the aquifer either east or west of the present area of encroachment, it would have been at a higher level than at present and should have moved to the lowest part of the aquifer by gravity flow long before pumping began.

Recent test drilling has provided additional evidence that salty water does not occur in the "600-foot" sand north of the fault either east or west of the mapped area of encroachment (pl. 3). To the east

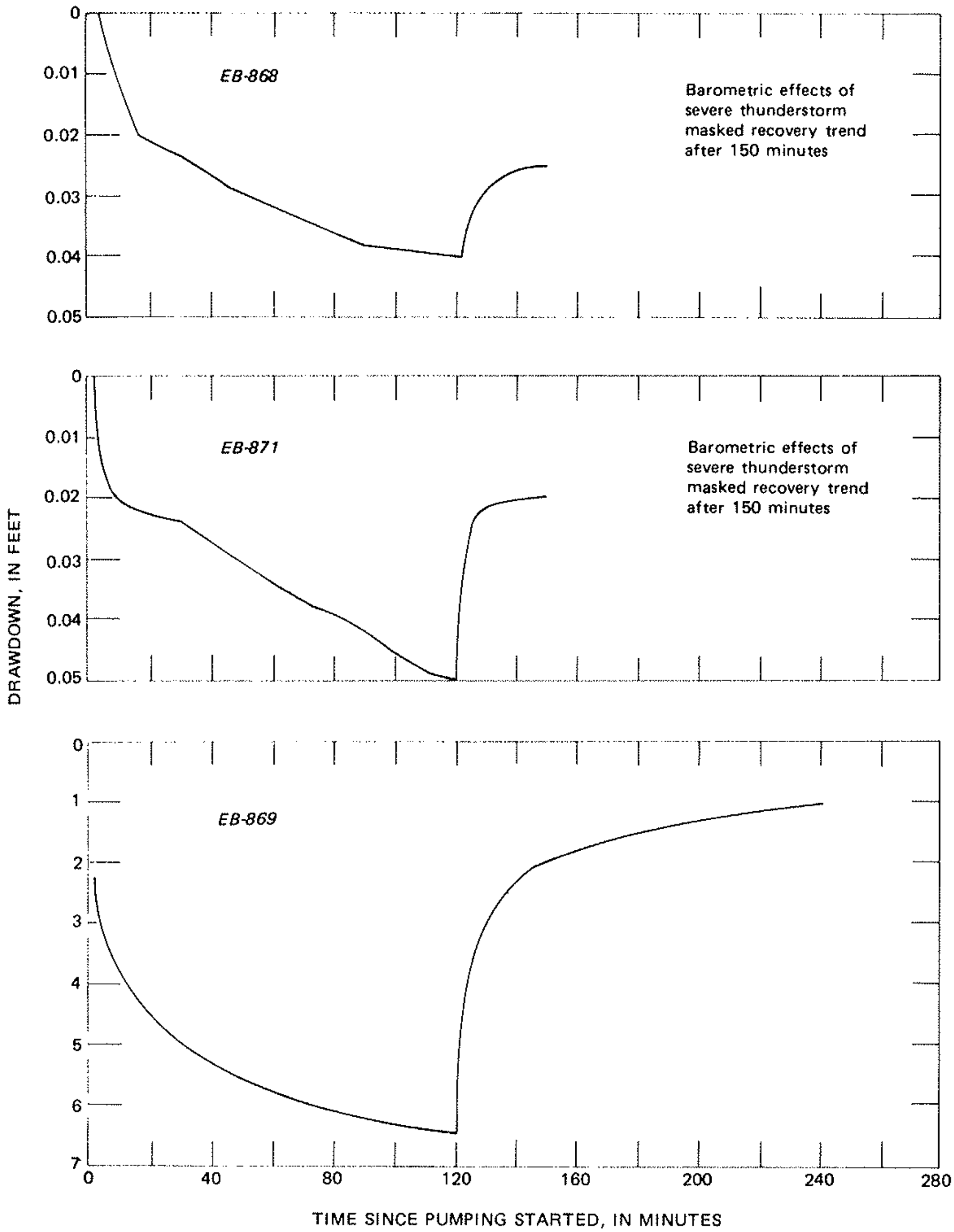


Figure 3.--Hydrographs showing response to the pumping test.

near the fault, the base of the "600-foot" sand rises sharply, and the sand thins and breaks up into stringers. At test well EB-824, 0.65 mi southeast of well EB-123, only 20 to 25 ft of sand occurs in a sandy interval about 104 ft thick, and the base of the "600-foot" sand is at least 75 ft higher than at well EB-123. Water from well EB-824, completed near the middle of the sandy interval, shows no evidence of saltwater encroachment (chloride content, 3.2 to 4.6 mg/L). Electrical logs of wells east of well EB-824 show only freshwater in the "600-foot" sand north of the fault. Instead of a source of salty water to the east, the higher base and lower hydraulic conductivity of the aquifer have retarded encroachment to the east.

A possible source of salty water in the "600-foot" sand north of the fault in West Baton Rouge Parish, suggested by Smith (1969), was investigated in some detail. The base of the "600-foot" sand rises to less than 600 ft below NGVD (National Geodetic Vertical Datum of 1929, formerly called mean sea level)just west of the area where encroachment was first observed, then drops to more than 750 ft below NGVD in central West Baton Rouge Parish. (See pl. 5.) Salty water present in any sand in hydraulic connection with the lower part of the "600-foot" sand should have moved down these slopes under the influence of gravity before pumping began, but no water samples were available to confirm interpretations of water quality made from electrical logs of wells west of the river. Several factors make interpretation of the electrical logs of the key wells in this area ambiguous: marked changes in lithology within sand beds may cause significant changes in formation factor, differences in chemical character of water in adjacent sands produce shifts in log response related to the composition rather than to the concentration of dissolved solids, and large shifts occur in the shale baseline of the spontaneous potential curve between the top and bottom of sand units.

To obtain positive verification of the water quality in this area, test hole WBR-121 was drilled on the batture at the I-10 bridge. The electrical log of this test hole correlated well with the logs of wells WBR-36 and WBR-37 to the southwest and well WBR-100 to the northwest, indicating little or no fault displacement between any of these wells. The water levels in well WBR-36 indicate that it is completed in the "1,200-foot" sand north of the fault, so a well completed in the "600-foot" sand at the site of well WBR-121 about 900 ft to the north would also be north of the fault.

At the site of well WBR-121 the "600-foot" sand is represented by 46 ft of fine to medium sand separated from the "400-foot" sand by about 45 ft of clay. This sand bed is apparently the one that was thought to contain salty water--electrical logs of wells in this area indicate a decrease in resistivity in this sand from top to bottom. A temporary well was completed near the base of this sand, and a water sample was obtained. The sample showed the water to be fresh (chloride concentration, 17 mg/L) and to have somewhat higher hardness and iron concentrations than typical of water from the "600-foot" sand. Water from well WBR-121 is probably a mixture of water typical of the "600-foot" sand and water from the overlying sands. Electrical logs show that none of the clays between the base of the alluvial aquifer and the top of the "600-foot" sand is continuous across the area west of the river and that water could move downward through the shallow Pleistocene and "400-foot" sands to the "600-foot" sand. The high water level in well WBR-121, about 9 ft below land surface and only about 5 ft below the level of the Mississippi River at the time, provides good evidence that recharge to this unit of the "600-foot" sand from the overlying sands is occurring near the site of well WBR-121. The high water level also indicates that this sand is not in good hydraulic connection with the "600-foot" sand east of the Mississippi River.

The lower part of the "600-foot" sand interval at the site of well WBR-121 consists predominantly of clay and silt with a few feet of fine sand and silty sand near the base. Comparison with logs of wells west of well WBR-121 indicates that sands equivalent to the lower part of the "600-foot" sand contain freshwater and are well developed to the west but thin and pinch out near the river. With freshwater to the west and the sands pinching out to the east (pl. 4B), the sands in the lower part of the "600-foot" sand interval west of the Mississippi River are not a source of salty water.

## Vertical Leakage From Other Sands

Leakage of salty water downward into the "600-foot" sand from shallower sands can be eliminated as a source of the encroaching salty water because the major shallower sands contain only freshwater north of the fault throughout the area of interest. A few very thin lenticular sands in the upper 100 to 200 ft of the Pleistocene terrace deposits may contain connate salty water, but the hydraulic isolation that prevented flushing of the sands also prevents the salty water from migrating to other aquifers. Any salty water leaking downward from these sands would first enter and contaminate the major shallow Pleistocene sands and the "400-foot" sand, and no such contamination has been observed. These lenticular sands could constitute a source of contamination to individual wells with leaky casings, but they are not a major source of salty water.

Upward movement of salty water from deeper aquifers presents a more serious possibility because large volumes of salty water do occur north of the fault in sands below the "600-foot" sand. The "800-foot," "1,000-foot," "1,500-foot," and "2,000-foot" sands are known to contain salty water in places along the north side of the fault; and thick, potentially productive sands contain salty water below the base of freshwater beneath all of the Baton Rouge area. Salty water could move upward from the deeper sands by leakage through intervening sediments or by flow up abandoned wells or test holes. From a practical standpoint, leakage through intervening sediments is a potential threat only from the "800-foot" and "1,000-foot" sands because water moving upward from deeper sands would have to pass through the "800-foot" and "1,000-foot" sands to reach the "600-foot" sand. Water levels in the "600-foot" sand are higher than water levels in any of the deeper aquifers above the "2,800-foot" sand, so upward leakage is not possible under present conditions. Leakage upward along the fault zone is very unlikely. Although faults may form zones of high permeability in consolidated rocks, faults in the unconsolidated shallow sediments of the gulf coast are zones of reduced permeability.

Flow up improperly plugged abandoned wells or test holes from deeper saltwater-bearing sands would constitute a potential source of salty water, but only one well, EB-122, is known to have been drilled below the "600-foot" sand in the area where encroachment was first observed. Tests were made in the "1,200-foot" sand at this site before well EB-122 was completed near the base of the "600-foot" sand. Any upward leakage of salty water from the "800-foot" or "1,000-foot" sands through the test hole below the screen would have rapidly contaminated the water from well EB-122. Well EB-122 was used for 10 years before mechanical problems caused it to be replaced by well EB-123 completed at a similar depth. Although flow up an abandoned well cannot be totally eliminated as a source of salty water, the probability of such a well being the primary source of salty water is very small. Practical control strategies designed to control saltwater encroachment fed by leakage across the fault should also be effective for controlling leakage from a well near the fault.

## Movement of Salty Water North of the Fault

### Rate and Direction From Well Records

Saltwater encroachment in the "600-foot" sand was first documented in the Baton Rouge area at well EB-123 in City Park. The recorded increase in the chloride concentration in water from well EB-123 was very rapid--from 7 mg/L in November 1947 to 362 mg/L in January 1948. This increase is much more rapid than would be expected on the basis of the records of other wells that have subsequently experienced encroachment, such as well EB-500. Moderate increases in the chloride concentration in water from well EB-123 would not have greatly affected use of the water for filling a swimming pool at the park and may have gone unnoticed, or at least unrecorded. The leading edge of the salty water in the base of the "600-foot" sand probably reached the site of well EB-123 several years before the recorded sharp increase in chloride concentration that led to abandonment of the well in 1948. The sharp increase probably was caused by upward coning of the salty water and likely does not indicate rapid lateral movement.

The leading edge of water with a chloride concentration above background level had passed a point 0.5 mi west-northwest of well EB-123 before June 1950, when a sample of water from well EB-129 had a chloride concentration of 128 mg/L. Well EB-493, 0.7 mi northwest of well EB-123, yielded water with a chloride concentration of 235 mg/L in August 1952. Thus, by 1952, salty water was advancing northward across a front at least 0.5 mi wide and, in part, north of Myrtle Avenue.

The next well in the path of the advancing salty water was EB-500 on Convention Street, 0.7 mi north of Myrtle Avenue and 1.0 mi north of well EB-123. The leading edge of the high-chloride water reached well EB-500 between February 1952, when the chloride concentration in water from the well was 5 mg/L, and January 1956, when the chloride concentration had reached 85 mg/L. The chloride concentration in water from this well increased slowly from 1956 until 1963, when it reached 232 mg/L. The chloride increase has been more rapid since 1966 and reached 3,700 mg/L in 1977 (fig. 4).

An estimate of the rate of northward movement of the salty water can be made by determining the time required for water with a given chloride concentration to move from well EB-123 to well EB-500. The water from well EB-123 had a chloride concentration of 716 mg/L in July 1950. At well EB-500, chloride increased from 600 to 920 mg/L between April and November 1966, so water with a chloride concentration of 716 mg/L reached the well during the summer of 1966. The salty water moved northward a distance of 1.0 mi in 16 years at an average rate of about 330 ft/yr.

Rollo (1969) provided an independent estimate of the rate of northward movement of the salty water, based on the hydraulic characteristics of the "600-foot" sand and hydraulic gradients derived from water-level maps. Rollo's estimate of an average rate of movement of 320 ft/yr compares well with the observed rate.

Applying this estimated rate to movement of the salty water beyond well EB-500, we find that it should have moved more than 7,000 ft farther north since 1956. Two monitor wells completed near the base of the "600-foot" sand are in a position to detect such movement: well EB-793, 3,000 ft north-northwest, and well EB-870, 3,600 ft north-northeast (pl. 4D). Neither of these wells had shown any evidence of approaching salty water as late as April 1978, indicating that the average rate of movement of the salty water since 1956 has been substantially less than the previously estimated rate. The average rate of movement toward wells EB-793 and EB-870 has been less than 140 and 165 ft/yr, respectively. An increase in the chloride concentration in water from well EB-806A, 2,600 ft west-northwest of well EB-500, was apparently caused by contamination from water entering a casing leak opposite a shallow lens of sand containing highly mineralized water. The increase in chloride was accompanied by anomalously high water levels, an increase in hardness of the water, and rapid plugging of the well screen. This well has been abandoned as a monitor well after attempts to rework it failed.

## Controls Affecting Movement of Salty Water

Salty water in the "600-foot" sand is moving northward in response to hydraulic gradients induced by pumping in the industrial district. The rate and the direction of movement are controlled by the combined effects of the hydraulic gradients, the hydraulic characteristics of the aquifer, the effect of gravity on the relatively dense salty water, and

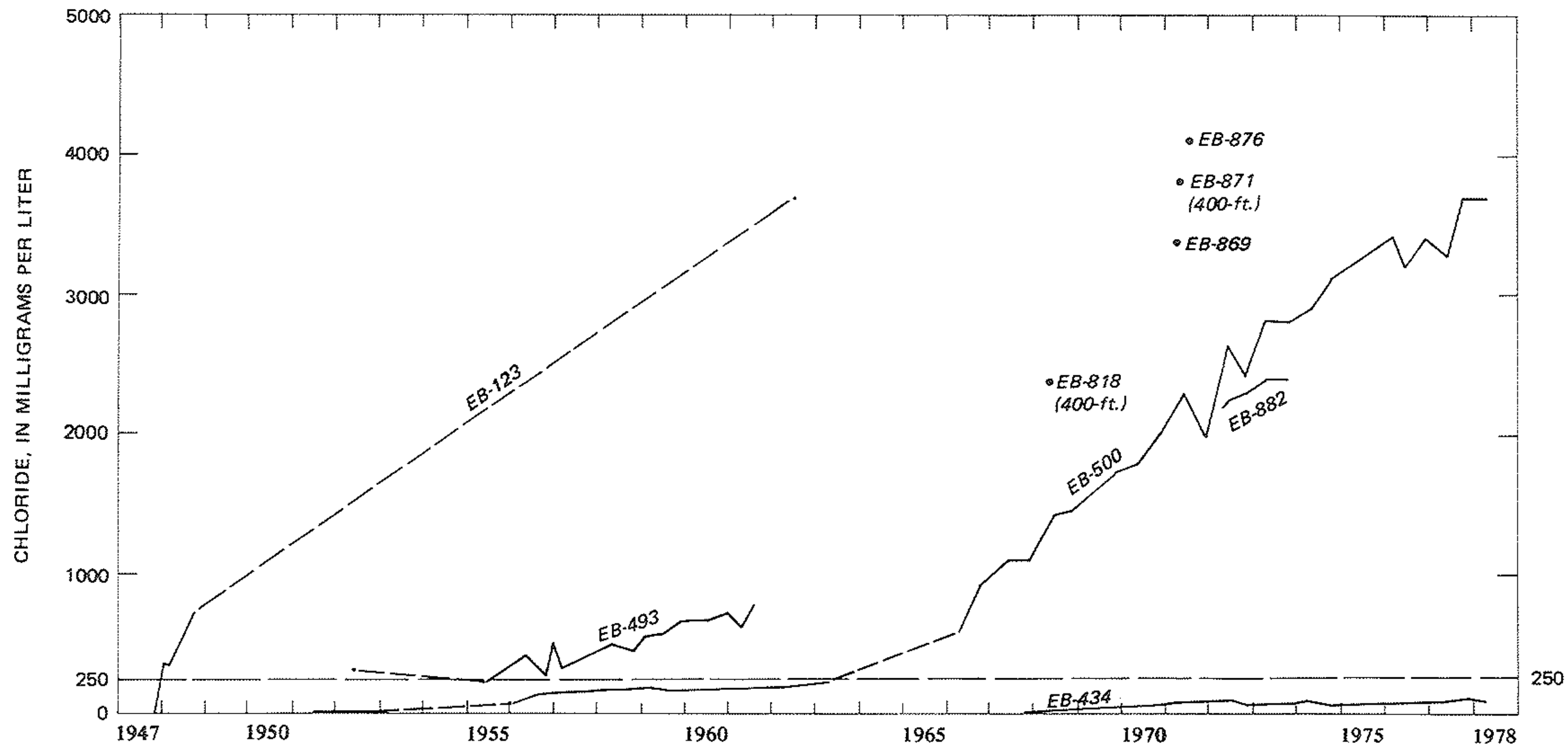


Figure 4.--Chloride concentration in water from selected wells in the "400-foot" and "600-foot" sands.

the configuration of the base of the aquifer. The general direction of movement can be predicted from hydraulic gradients determined from potentiometric maps, such as plate 3. However, the actual rate and direction of saltwater movement depends heavily on the configuration of the base of the aquifer.

Saltwater is denser than freshwater, so advancing salty water tends to flow along the base of an aquifer. Under static conditions the upper surface of the salty water should be horizontal, but under dynamic conditions the freshwater-saltwater interface may be tilted. Under the gradient induced by pumping, saltwater is apparently moving northward in the "600-foot" sand as a relatively steep-fronted wedge. (See pl. 4A.) In March 1971 the electrical log of well EB-869 showed salty water at this site from the top of the "600-foot" sand at about 518 ft below NGVD to the base of the sand at about 670 ft below NGVD. In February 1976 the electrical log of test hole EB-972 (near well EB-674) showed salty water at a depth of about 587 ft below NGVD. Water samples collected in April 1978 from monitor wells EB-793, 4,500 ft northwest of well EB-972, and EB-870, 3,700 ft north-northwest of well EB-972, however, showed no increase in chloride near the base of the aquifer at depths of 652 and 642 ft below NGVD, respectively. The toe of the advancing wedge of saltwater has followed the deepest part of the aquifer, possibly aided by greater permeability of the sand. The upper surface of the saltwater slopes upward to the south much more steeply than it would under static or near-static conditions. The presence of salty water throughout the "600-foot" sand near the fault indicates that salty water is entering the aquifer in sufficient volume to replace all of the salty water moving northward.

## The Effects of Past Pumpage

Relatively little information is available concerning pumpage from the "400-foot" and "600-foot" sands before 1940 and water levels in the "600-foot" sand near the Baton Rouge fault before 1956. For the period 1940-75, pumpage from the "400-foot" and "600-foot" sands (almost entirely for industrial use) averaged slightly over 25 Mgal/d. Based on the history of plant construction and expansion in the area, the dates of construction of high-capacity wells, and some reported water levels, pumpage increased from about 1910 through the 1920's, dropped in the early 1930's, and then increased rapidly in the late 1930's. Except for a brief decline in 1946 and 1947, pumpage was about equal to or above the average of 25 Mgal/d each year from 1940 through 1959. Peak yearly pumpage occurred in 1944, averaging more than 36 Mgal/d. Peak monthly pumpage, averaging 50 Mgal/d, occurred in August 1949. Pumpage declined in 1960 and has been below the average of 25 Mgal/d each year since then except for 1969. Pumpage in 1975 averaged less than 17 Mgal/d, probably the lowest since the late 1930's. Pumpage in 1977 averaged slightly under 19 Mgal/d.

Reconstruction of the pumpage history provides some insight into the water-level history of the area between the Baton Rouge fault and the industrial district. Recent records demonstrate the direct relationship between pumpage in the industrial district and water levels and gradients in the area south of the industrial district. As pumpage increases, the northward gradient in the "600-foot" sand increases; and the difference in water levels between the "600-foot" sand north of the fault and the "400-foot" sand south of the fault increases. Thus, an increase in pumpage in the industrial district will tend to cause an increase in the rate of leakage of salty water across the fault into the "600-foot" sand and an increase in the rate of northward movement of the salty water toward the pumping center. Correspondingly, reduction in pumpage will tend to reduce both the rate of leakage and the rate of movement of the salty water.

Leakage of salty water across the fault and northward movement of the salty water probably began at a low rate between 1910 and 1915 as the natural southward gradient was reversed by the start of pumping in the industrial district. The rates of leakage and movement probably increased to peaks in the 1940's and 1950's and then began to decline as pumpage decreased. With pumpage since 1975 at the lowest rates since before 1940, leakage of salty water into the "600-foot" sand and northward movement of the salty water should now be at the lowest rates of the last 35 to 40 years.

## Test Drilling--1972

### Objectives

Earlier mapping (Smith, 1969) indicated that the base of the "600-foot" sand is relatively deep along the Baton Rouge fault in the area where saltwater encroachment has occurred and in the industrial district in the area of greatest pumpage. In the intervening area the base of the aquifer rises to form an east-west-trending divide located roughly along Choctaw Drive at the south edge of the industrial district. South of the divide, along the east and west sides of the area where saltwater encroachment has occurred, the base of the "600-foot" sand rises; and in places the sand pinches out, forming a troughlike depression in the base of the aquifer. (See pl. 5.)

Although control in the form of drillers' logs and electrical logs of existing wells provided a general picture of the configuration of the base of the "600-foot" sand, the continuity of the divide was not assured. Spacing of the control points was such that one or more deep channels could be present across the divide connecting the deeper saltwater-bearing part of the aquifer south of the divide with the deeper part of the aquifer in the industrial district. If such a channel were present, the toe of the saltwater wedge could move along the channel and be well past the existing monitor wells before detection.

The second phase of test drilling was designed primarily to determine the continuity of the divide by establishing an east-west line of closely spaced control points to enable detailed mapping. Four test wells were drilled along the south side of Choctaw Drive. Together with drillers' logs and electrical logs of existing wells, these holes provided a line of control points along Choctaw Drive from the Mississippi River to the intersection of Choctaw Drive and Greenwell Springs Road, about 2.5 mi east of the industrial district. Average spacing of the control points is less than 0.5 mi, which should be adequate to detect any major breach in the divide.

## Results

The deepest part of the divide along this line south of the industrial district is at the site of well EB-883, near the corner of Madison Avenue and North 15th Street, where the base of the "600-foot" sand is 597 ft below NGVD. North of this site, logs of wells indicate that the base of the aquifer rises to about 575 ft below NGVD along the south edge of the industrial district. After salty water reaches one of the monitor wells to the south (EB-793 or EB-870), it will be desirable to install a permanent monitor well near the site of test hole EB-883.

An additional well, EB-882, was drilled to investigate the northeastward extent of salty water. (See pl. 1 for location.) The base of the "600-foot" sand was expected to be relatively shallow, and freshwater was expected to occur throughout the sand. Instead, the electrical log showed the base of the sand to be 672 ft below NGVD, comparable to the deepest levels near the fault. Monitor well EB-882 installed near the base of the aquifer showed that salty water was present in the lower part of the aquifer. The initial water sample showed a chloride concentration of 2,200 mg/L in March 1972. The final sample obtained from well EB-882 in October 1973 showed that the chloride concentration had risen to 2,400 mg/L. The well was vandalized late in 1973 and was finally plugged following several unsuccessful attempts to clear an obstruction in the casing.

Following the discovery of salty water at the site of well EB-882, a test hole was drilled in 1974 at the end of North 40th Street near Zion Street, 0.6 mi north-northeast of well EB-882. This test hole, EB-936, closed the most significant gap in control along the east side of the area affected by saltwater encroachment and indicated that there is little danger of encroachment extending eastward much beyond the present eastern limits of encroachment south of Choctaw Drive. The "600-foot" sand at the site of test hole EB-936 is represented by less than 20 ft of clean, very fine sand at the top of the interval occupied by the "600-foot" sand to the west. Clay and silty or very fine sandy clay form an effective barrier to the eastward movement of salty water in the lower part of the "600-foot" sand interval.

## Current Status of Saltwater in the "600-Foot" Sand

The thick, deep section of the "600-foot" sand at the site of well EB-882 (pl. 1) explains, at least in part, the discrepancy between the calculated and observed rates of northward movement of the salty water beyond well EB-500. (See section "Movement of Salty Water North of the Fault," subsection "Rate and Direction From Well Records.") Instead of being confined to a relatively narrow channel, as in the vicinity of well EB-123, the salty water is now in an area where the deep channel in the base of the "600-foot" sand is relatively wide in an east-west direction. (See pl. 5.) Comparison of water levels between individual pairs of wells indicates that in recent years salty water has been moving in a northeasterly direction from well EB-500 and into the east extension of the channel, possibly aided by higher permeability of the aquifer in this direction.

Relatively little flow is indicated in a northwesterly direction toward well EB-793, so well EB-870 should be the next monitor well to detect the advancing saltwater. Recently observed gradients from well EB-500 toward well EB-870 have been about 8 to 10 ft/mi, giving a calculated rate of water movement of about 200 ft/yr. If the estimated 1978 position of the leading edge of the saltwater is correct (pl. 5) and there is no major change in the northward gradient, saltwater should reach well EB-870 in the early 1980's with some increase in chloride possibly detectable by 1980.

There is now (1978) an estimated $11x10^9$ gal of salty water in the "600-foot" sand north of the Baton Rouge fault in the area subject to encroachment. This estimate is based on the map of the base of the aquifer (pl. 5), the thickness of the aquifer, the estimated present position of the freshwater-saltwater interface within the aquifer, and a porosity of 0.25. This salty water includes some freshwater contaminated by dispersion and diffusion with the advancing saltwater, but the volume of contaminated freshwater is probably small compared to the volume of salty water that has entered the aquifer from across the fault. Electrical logs of two wells that penetrate the interface show a sharp transition from freshwater to saltwater over a vertical range of about 20 ft.

The estimated volume of salty water in the "600-foot" sand north of the fault can be compared to the volume that would have accrued at a constant rate of leakage. The leakage rate of $6x10^5$ gal/d calculated for October 1971 would have been near the maximum for that year. (See section "Water Levels Near the Fault.") A rate of $5x10^5$ gal/d would be more reasonable to use as an average for 1971. The leakage rate during 1971 would have been less than during years of peak pumpage in the 1940's and 1950's, more than during much of the period before 1940, and probably near average for the period after 1960. Assuming a constant rate of $5x10^5$ gal/d from 1910 to 1978, slightly over $12x10^9$ gal of saltwater would have leaked across the fault. Similarly, a leakage rate of $4.4x10^5$ gal/d can be calculated from the estimated volume ($11x10^9$ gal) of accrued saltwater. The agreement of these figures indicates that $5x10^5$ gal/d is a reasonable figure to use for the leakage rate.

Of the $11x10^9$ gal of salty water estimated to be present in the "600-foot" sand north of the fault, about $4x10^9$ gal occur below the 600-foot contour and $7x10^9$ gal above 600 ft. The volume of freshwater remaining below the 600-foot contour in the area subject to encroachment is estimated to be about $4x10^9$ gal. Thus, there is already enough salty water in the "600-foot" sand north of the fault to fill the lower portion of the aquifer to a depth of 600 ft below NGVD and probably enough to fill it to 575 ft--the estimated lowest level of the divide south of the industrial district.

Even if all pumping from the "600-foot" sand were halted today, which is neither practical nor desirable, saltwater encroachment would not stop. Leakage of saltwater across the fault would halt, or even reverse, as the natural southward gradient was reestablished; but the effect of gravity on the relatively dense salty water would cause encroachment to continue, though at a relatively slow rate. Ultimately, salty water would spread throughout the lower part of the "600-foot" sand from near the Mississippi River on the west to at least Acadian Thruway on the east (pl. 4B) and at least as far north as Choctaw Drive.

## Outlook for the Future

Reduction in pumpage from the "400-foot" and "600-foot" sands in recent years has resulted partly from increased use of water from the Mississippi River and deeper aquifers, and partly from conservation efforts and increased reuse of water by the major industrial users. Future pumpage cannot be predicted accurately in the absence of direct controls, but recent trends are likely to continue. Pumpage from the "400-foot" and "600-foot" sands will probably remain in the 15 to 25 Mgal/d range unless increasingly strict waste-discharge regulations force further reductions in industrial water use.

The relatively high water levels and low capital costs of wells completed in the "400-foot" and "600-foot" sands make these an attractive source of water for many industrial purposes, but the major users of water from these sands are aware of the threat of saltwater encroachment. Although some new wells have been completed in the "400-foot" and "600-foot" sands in recent years, most were drilled to replace existing wells and did not increase the design capacity of the shallow-well systems.

At least one major industry is tentatively considering the possibility of limiting or eliminating pumpage from the "600-foot" sand. If pumpage from the "600-foot" sand can be reduced by additional conservation and reuse of water or by increased use of water from the Mississippi River, the results will be beneficial. Saltwater encroachment will be slowed and pumping costs for water use from the "600-foot" sand will be reduced because of the resulting higher water levels. If reduced pumpage is attained by pumping from deeper aquifers, on the other hand, it will be at the expense of lower water levels, higher pumping costs, and an increased potential for saltwater encroachment in the deeper sands.

If control measures are not begun and if pumpage remains in the range of 15 to 25 Mgal/d, northward encroachment of saltwater will continue at approximately its present rate for several years. Saltwater should reach monitor well EB-870 by the early 1980's, and the vicinity of Choctaw Drive 15 to 20 years later. From Choctaw Drive, saltwater will move northward more rapidly in response to steeper hydraulic gradients in the industrial district and will be aided (rather than slowed, as it now is) by the effect of gravity. Salty water should reach the southernmost "600-foot" sand wells of the industrial district within 20 years of the time it reaches Choctaw Drive. If individual wells are abandoned as they begin to yield salty water, encroachment across the industrial district will be rapid. If no new high-capacity wells are completed in the "600-foot" sand north of the industrial district, encroachment should essentially cease when the last well completed in the "600-foot" sand within the industrial district is abandoned. Pumpage from the "600-foot" sand outside of the industrial district is now so low and widely dispersed that little gradient would exist to cause encroachment to continue. If even a few wells in the "600-foot" sand in the industrial district were continued in service despite increasing salinity of the water, saltwater encroachment would not spread beyond the industrial district. Maximum chloride concentration in water from wells in the industrial district should be lower than the maximum concentrations near the fault (4,120 mg/L observed and about 5,000 mg/L calculated) because of mixing with freshwater moving to the pumping center from the north.

Allowing saltwater encroachment to proceed across the industrial district would be undesirable for several reasons. Most obviously, a major aquifer would be impaired for future use. Less obvious, but probably more important from a long-term view, the threat of saltwater contamination of other major aquifers would be significantly increased. The "400-foot" and "800-foot" sands would be directly threatened if saltwater reached natural "windows" where these sands are hydraulically connected to the "600-foot" sand, but all major aquifers would be subject to contamination by leakage of salty water through abandoned wells. Wells abandoned in recent years have generally been properly plugged, but many wells were abandoned in the past without plugging or with only a surface plug. Some of these old wells could be reentered and properly plugged, but many could not because their locations are unknown now or major structures have been built over them.

## Possible Control Strategies

Rollo (1969) discussed several possible methods of controlling saltwater encroachment in the aquifers of the Baton Rouge area. His conclusions that some type of barrier-well system would be effective and that increasing recharge in the outcrop areas would be ineffective still appear valid. Another method that should be considered is the installation of one or more discharging wells in the area near the fault and behind the advancing saltwater front, as suggested in part by Kazmann (1970). Several variations of barrier-well systems are possible, and the type of system selected will determine both the optimum time to begin control operations and the location of the wells to be used. Although active measures to control saltwater encroachment in the "600-foot" sand may not be required for some time, selection of the appropriate control strategy should be made before saltwater has advanced so far that some of the options are eliminated or made impractical. Selection of the general strategy to be used should be made within a few years after salty water reaches one of the monitor wells, EB-793 or EB-870. At that time, saltwater will still be more than 0.7 mi south of Choctaw Drive, and at least 10 years should be available for detailed planning and construction if barrier wells along Choctaw Drive are selected as the control method.

## Discharge Barrier-Well System

An east-west line of discharging barrier wells could provide direct control of saltwater encroachment in the "600-foot" sand, but at considerable cost for construction and operation. In the simplest form, as suggested by Rollo (1969), saltwater encroachment would be allowed to continue until water from the southernmost producing wells in the industrial district became too salty for further industrial use. At that time, these wells would be combined with wells drilled specifically as barrier wells to form the barrier. This system has the advantage that the longest possible time would elapse before active control would begin. The principal disadvantages of this system are that, because of the nearness of the barrier to the pumping center, large volumes of salty water would have to be pumped and disposed of and water levels throughout the industrial district would be lowered substantially.

Hydrologically, a more desirable location for the barrier-well system would be along the divide near Choctaw Drive. Encroachment could be halted here with less total pumpage of salty water, with less effect on water levels in the producing wells of the industrial district, and with a smaller area of the aquifer affected. The principal disadvantages of a discharging well system along Choctaw Drive are (1) control would have to start much sooner, possibly as much as 20 to 30 years earlier than if saltwater were allowed to advance into the industrial district, and (2) all of the barrier wells would have to be specially constructed for the purpose.

Operation of either of the discharging barrier-well systems discussed above would require disposal of relatively large volumes of salty water. Although salty water from barrier wells in the industrial district might be used for some purposes by mixing it with freshwater from other wells, increasing salinity would probably make such use impractical after a few years. At that time, or from the start of operation of a barrier-well system along Choctaw Drive, it would be necessary to dispose of the salty water in an environmentally acceptable manner. Use of deep injection wells (completed below depths of 4,000 ft) probably would be required for acceptable disposal. Capital construction and operating costs of a combined barrier-well and injection-well system at either potential site will be high--possibly too high to be practical.

## Recharge Barrier-Well Systems

A recharging barrier-well system offers advantages over a discharging well system in two respects. Control of saltwater encroachment can be achieved without having to dispose of large volumes of salty water, and water recharged to the aquifer will raise the water levels of the aquifer. The principal disadvantage of a recharging barrier-well system is that a large volume of relatively high-quality freshwater must be injected into the aquifer to create a pressure ridge and halt the advance of the salty water. Treatment of surface water to a level that would allow long-term injection to be maintained may be too costly to be practical. Use of water from aquifers deeper than the "600-foot" sand would be undesirable because the increased pumpage would lower water levels in existing wells and increase the danger of saltwater encroachment in the deeper aquifers.

Rollo (1969) suggested the possibility of constructing a recirculating system in which recharging barrier wells would be supplied with water from production wells located in the protected part of the aquifer. Such a system would operate with no net effect on the volume of water in the aquifer, and the suitability of the water for long-term injection would be assured. Hydraulically, the efficiency of this type of system would increase as separation between the production and recharge wells is increased. Location of the barrier wells along the divide near Choctaw Drive and the production wells in the southern part of the industrial district would probably be the most practical arrangement. Increased pumpage from the "600-foot" sand in the industrial district would lower water levels of the sand throughout the district and increase pumping costs from existing industrial wells. Wide separation of production and recharge wells would also increase construction and operating costs of the barrier system. These two factors may combine to make a recirculating system impractical.

A recharge system using water from the "400-foot" sand would probably be the most efficient and cost-effective method that would provide positive control of saltwater encroachment. Across most of the divide along Choctaw Drive, the "400-foot" sand is thick enough for a single production well to supply an injection well. Wells could be paired on small sites, with a well completed in the "400-foot" sand pumping water directly into an injection well completed in the "600-foot" sand. Water in these sands is chemically similar, and no compatability problems or degradation of water quality in the "600-foot" sand should occur. Although water levels in the "400-foot" sand in the industrial district would be lowered by the increased pumpage, this would be compensated by higher water levels in the "600-foot" sand.

Water from the shallow Pleistocene "University" sand could also be used to supply the injection wells, but this sand is not thick enough to support high-capacity production wells except at the west side of the area where the barrier would be needed. Extensive use of water from the "University" sand would require piping the water to the line of injection wells from a well field near the Mississippi River. Because water from the "University" sand has higher hardness and iron concentrations than water in the "600-foot" sand, some long-term degradation of water quality in the "600-foot" sand could result from injecting water from the "University" sand.

Injection or recharge of potable water into freshwater aquifers is now practiced in many areas of the country. At the present time, however, injection of any fluid into a freshwater aquifer in Louisiana is contrary to the policy of State regulatory agencies.

## Discharge Wells Near the Fault

A high-capacity discharge well pumping water from the "600-foot" sand in the area between the fault and the leading edge of the saltwater front should be considered as an alternative to or in addition to a barrier-well system. If some chloride increase in water from wells in the "600-foot" sand can be tolerated, the discharge well alone can probably provide adequate control. If positive control is desired, a discharge well near the fault would reduce the number of wells and the volume of pumpage needed to form an effective barrier-well system. Although pumping a well near the fault would lower water levels in the "600-foot" sand near the fault and increase leakage of salty water across the fault, the increase in leakage should be relatively small. If the estimate of the present rate of leakage of $5x10^5$ gal/d is approximately correct, continuous pumping at a rate of 500 to 1,000 gal/min should be enough to remove all of the saltwater currently leaking across the fault, plus some of the accrued saltwater. The lower water levels in the "600-foot" sand near the fault would also reduce, and locally reverse, the northward gradient and reduce the rate of saltwater encroachment. Operation of several wells in the area affected by encroachment could, over a period of years, remove most of the saltwater from the aquifer north of the fault. At that time, control could be maintained by continuing to pump one or two wells near the fault.

As with a discharging barrier-well system, the principal problem with discharge wells near the fault would be disposal of the salty water produced. Deep injection wells would probably be required for disposal, though some disposal might be made by dilution and discharge with sewage or storm-water outflows. Proposals have been made in the past to deepen and improve City Park and University Lakes and to supplement natural inflow to the lakes with ground water during dry periods. It may be possible to use salty water from the "600-foot" sand in combination with freshwater from the shallow Pleistocene "University" sand as a source of supplemental water if care is taken to limit the maximum salinity of the lakes to an acceptable level. Flushing during periods of heavy rainfall would prevent any long-term salinity buildup.

The effectiveness of wells near the fault in slowing or controlling saltwater encroachment will decrease as the saltwater nears the industrial district. Thus, if discharge wells near the fault are to be used as the control method or as part of a larger system, they should be installed and placed in operation as soon as possible.

During informal discussions of possible control strategies, the possibility has been suggested that leakage of salty water across the fault could be slowed or stopped by pumping water from wells along the south side of the fault. Although possible, this strategy would not be practical. Because of the relatively high water levels south of the fault, it would be necessary to pump and dispose of many millions of gallons per day of salty water to prevent leakage of less than 1 Mgal/d.

## SALTWATER ENCROACHMENT IN THE "1,500-FOOT" SAND

The "1,500-foot" sand is a major source of water for public supply (about 12 Mgal/d, 1977) and a relatively minor source of water for industrial use (about 3 Mgal/d) in the Baton Rouge area. More than half of the pumpage from the "1,500-foot" sand is concentrated in two well fields, the Government Street and Lula Avenue public-supply pumping stations. The remainder of the pumpage is widely distributed, most occurring in the central part of East Baton Rouge Parish. The "1,500-foot" sand is thin or absent beneath most of the Baton Rouge industrial district. In the northern part of East Baton Rouge Parish, water from the "1,500-foot" sand is less suitable for public-supply and many industrial uses than water from deeper sands.

### Observed Saltwater Encroachment

Salty water was discovered in the "1,500-foot" sand north of the Baton Rouge fault in a test well, EB-781, that cut through the fault just above the "1,500-foot" sand (Rollo, 1969; fig. 5, this report). Monitor well EB-782B was completed near the freshwater-saltwater interface at the site of well EB-781. Later in the test-drilling program, wells EB-792A and EB-807A were completed near the base of the "1,500-foot" sand to monitor possible northward movement of the salty water. (See pl. 6.) Neither well EB-792A nor well EB-807A showed any indication of salty water at their sites at the time of installation in 1965 and 1966, respectively. Well EB-792A failed soon after installation and has been abandoned as a monitor well. Samples collected during redevelopment attempts in 1970 gave no indication of approaching salty water. Water from well EB-807A first showed a chloride increase in 1972, and since then the chloride concentration has increased to 430 mg/L (November 1978). (See fig. 6B.) Following the initial increase in chloride at well EB-807A, wells EB-917 and EB-918 were installed to replace well EB-792A and to check for the presence of salty water near the Baton Rouge fault east of the area of known occurrence. Neither of these wells has shown any indication of salty water at their sites.

### Source of the Salty Water

Salty water in the "1,500-foot" sand is almost certainly the result of leakage across the Baton Rouge fault from the downthrown "1,200-foot" sand. The lower part of the "1,200-foot" sand contains salty water south

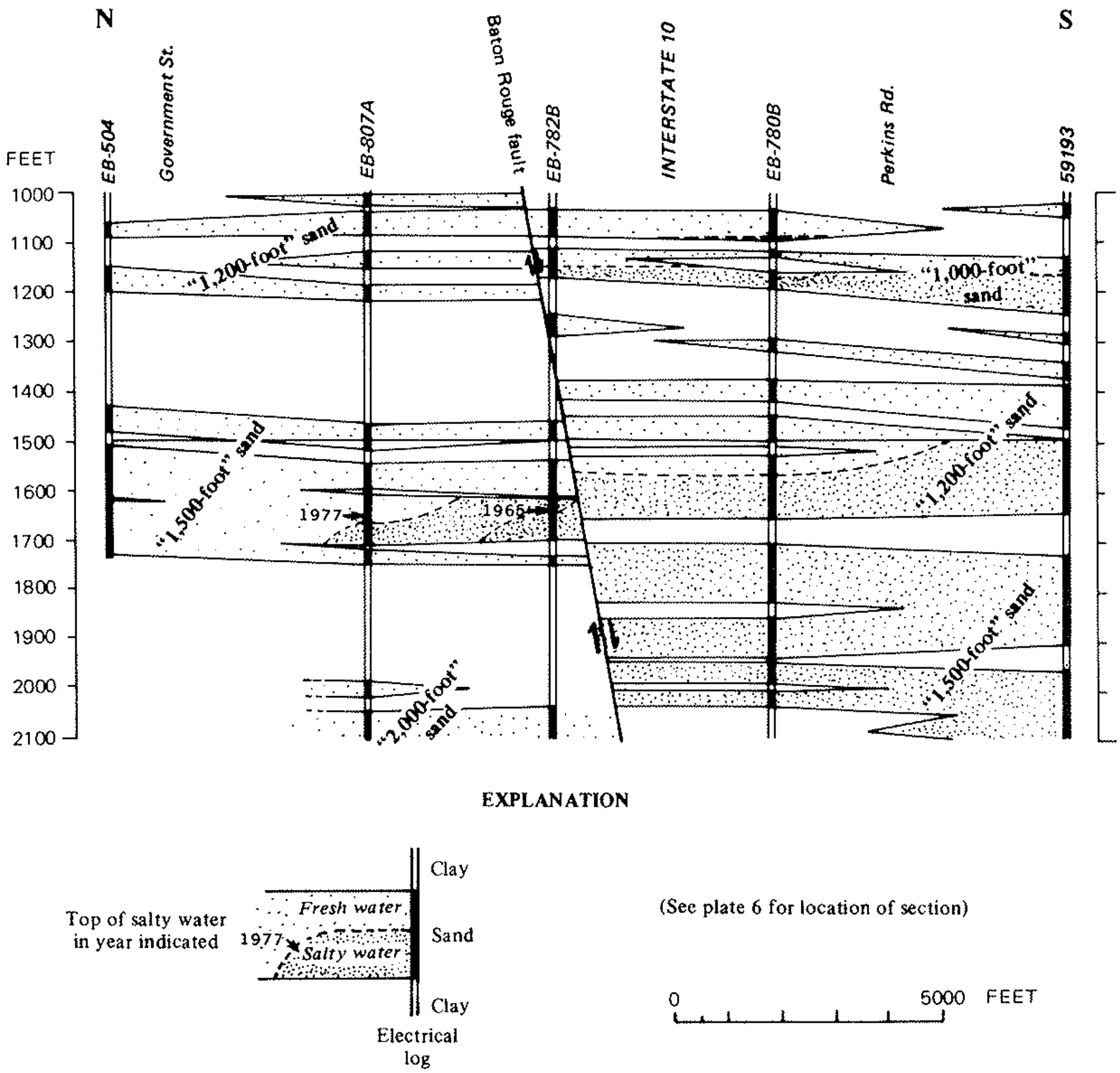


Figure 5.--North-south geohydrologic section across the Baton Rouge fault showing the "1,500-foot" and related sands and the vertical distribution of freshwater and salty water.

of the fault. At least 40 ft of overlap is indicated in the vicinity of well EB-781 between the saltwater-bearing portion of the "1,200-foot" sand and the section of the "1,500-foot" sand in which encroachment has been observed. If rollover occurs along the south side of the fault here, as is probable, the overlap could be even greater.

Composition of salty water in the "1,500-foot" sand north of the fault and in the "1,200-foot" sand south of the fault is given in table 2.

Table 2.--Composition of salty water in the "1,200-foot" and "1, 500-foot" sands near the Baton Rouge fault

| Dissolved constituents and properties | Well EB-782B "1, 500-foot" sand north of fault | | | | | | Well EB-780A "1, 200-foot" sand south of fault | | |
|---|---|---|---|---|---|---|---|---|---|
| | April 22, 1965 | | | May 26, 1977 | | | April 19, 1965 | | |
| | Milli-grams per liter | Milli-equiv-alents per liter | Percent-age of ionized constit-uents | Milli-grams per liter | Milli-equiv-alents per liter | Percent-age of ionized constit-uents | Milli-grams per liter | Milli-equiv-alents per liter | Percent-age of ionized constit-uents |
| Calcium----------- | 5.0 | 0.250 | 0.95 | 26 | 1.297 | 3.54 | 20 | 0.998 | 3.16 |
| Magnesium -------- | .9 | .070 | .27 | 4.1 | .341 | .93 | 3.4 | .291 | .92 |
| Sodium------------ | 294 | 12.800 | 48.80 | 390 | 16.957 | 46.29 | 334 | 14.500 | 45.86 |
| Potassium---------- | .8 | .020 | .08 | 1.6 | .041 | .11 | 1.2 | .031 | .10 |
| Bicarbonate-------- | 206 | 3.376 | 12.87 | 172 | 2.819 | 7.69 | 165 | 2.704 | 8.55 |
| Carbonate --------- | 0 | .000 | .00 | 0 | .000 | .00 | 0 | .000 | .00 |
| Sulfate------------ | .4 | .008 | .03 | 5.6 | .117 | .32 | 5.6 | .117 | .37 |
| Chloride----------- | 344 | 9.704 | 37.00 | 530 | 15.064 | 41.12 | 460 | 12.977 | 41.04 |
| Hardness as $CaCO_3$-- | 16 | ------ | ----- | 82 | ------ | ----- | 64 | ------ | ----- |
| Specific conductance (micromhos at 25° C) --------- | 1,430 | ------ | ----- | 2,030 | ------ | ----- | 1,770 | ------ | ----- |
| pH (units)--------- | 7.8 | ------ | ----- | 8.3 | ------ | ----- | 7.1 | ------ | ----- |

The initial samples collected from these sands in 1965 showed a similarity in composition of the water, but also minor differences in the relative concentrations of individual constituents. A sample collected from the "1,500-foot" sand in 1977 shows that as the salinity of the water in the "1,500-foot" sand north of the fault has increased, the differences in relative concentrations have almost disappeared. Thus, the "1,200-foot" sand can be considered the likely source of the salty water on the basis of water chemistry.

Water levels also provide good evidence that the "1,200-foot" sand is the source of the salty water. Figure 6A shows that water levels in the "1,200-foot" sand south of the fault respond in subdued fashion to water-level changes in the "1,500-foot" sand north of the fault, indicating some hydraulic connection between the sands. Note also that when the rate of water-level decline for the "1,500-foot" sand increased in 1969, the rate of decline for the downthrown "1,200-foot" sand also increased, although there is no pumping from the "1,200-foot" sand south of the fault. The difference in water levels averaged about 60 ft before 1969 but has since increased to an average of about 75 ft. Thus, despite some leakage, the fault acts as a rather effective barrier to the northward movement of salty water.

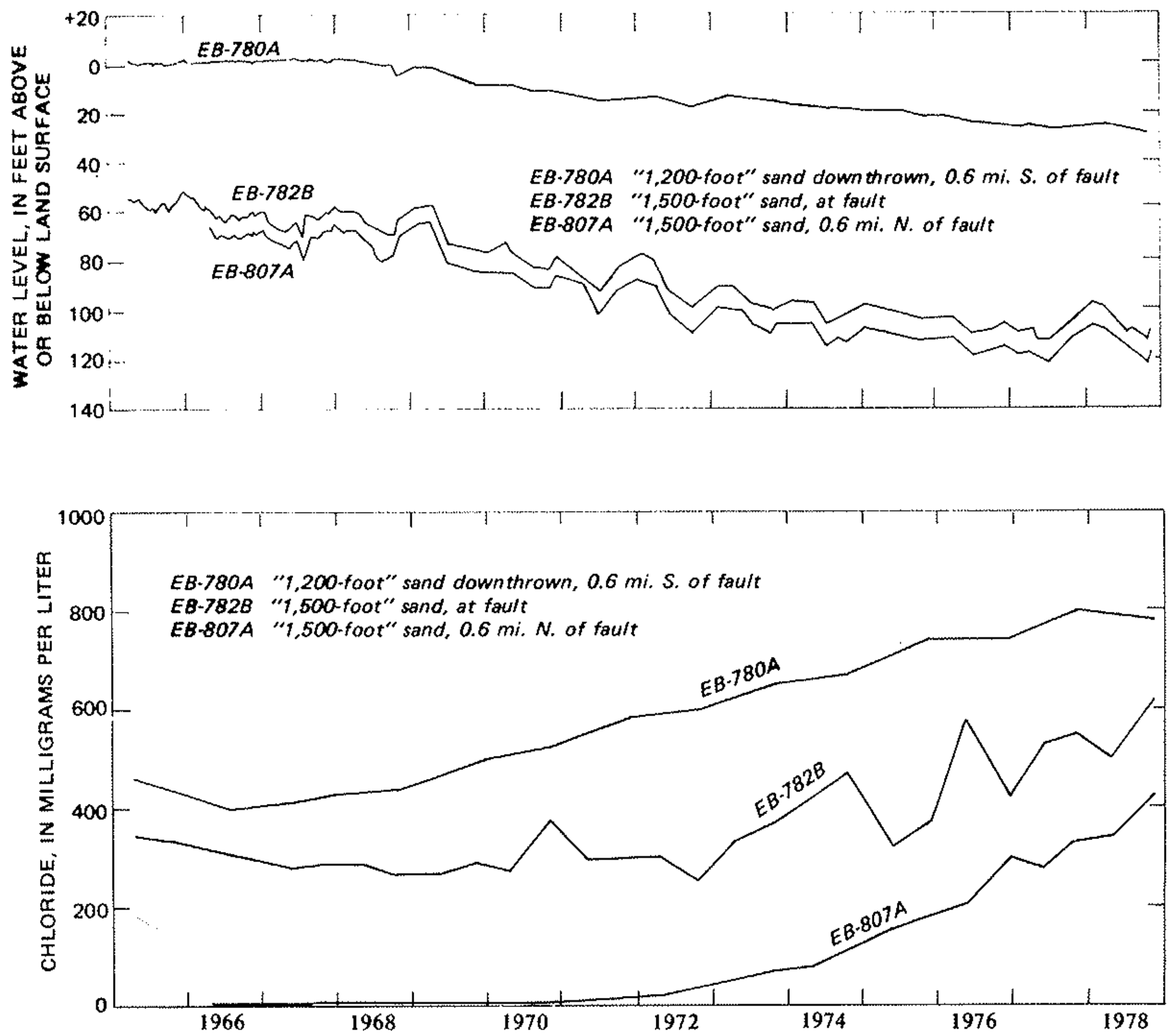


Figure 6.--Water levels and chloride concentration in water from wells in the "1,500-foot" sand and in the downthrown "1,200-foot" sand near the Baton Rouge fault.

Available data do not permit an accurate calculation of the volume of salty water in the "1,500-foot" sand north of the fault or the present rate of leakage across the fault. A crude calculation, based entirely on estimates, indicates that the volume of salty water north of the fault may have increased by about $2.2 \times 10^9$ gal from 1965 to 1977, giving an average rate of leakage of about $5 \times 10^5$ gal/d.

## Rate and Direction of Movement of the Saltwater

The base of the "1,500-foot" sand is relatively deep near the Baton Rouge fault in the area where salty water was first observed. The deepest part of the aquifer trends northeastward from the area of present encroachment (pl. 6). In the absence of any pumping stresses, salty water would tend to flow to the east and northeast along the lowest part of the aquifer. The present pumping pattern, however, has created a northward gradient from the area of known salty water and a westward to northwestward gradient across the deeper part of the aquifer to the east of the salty water. (See pl. 7.) Because of the small difference in density between the freshwater and slightly salty water in the "1,500-foot" sand, the hydraulic gradient should be strong enough to override the tendency of the salty water to follow the deep part of the aquifer to the east. Thus, the probable flow direction at this time is almost due north.

Although salty water has reached a well (EB-807A) that originally yielded freshwater, the rate of flow cannot be calculated directly because the position of the leading edge of the salty water is not known for any earlier time. Rollo (1969) calculated a rate of flow of 240 ft/yr based on hydraulic characteristics of the aquifer and a hydraulic gradient of 6 ft/mi. Subsequent leveling of wells in the area indicates that the hydraulic gradient in the vicinity of the saltwater front was only 1 to 2 ft/mi in 1966 and 1967. At this lower gradient the calculated rate of saltwater movement would be only 40 to 80 ft/yr. Water levels in the "1,500-foot" sand have declined significantly since 1967, and the northward hydraulic gradient has increased (fig. 6A, wells EB-782B and EB-807A). Since mid-1969 the northward gradient in the vicinity of the saltwater front has averaged about 2 to 3 ft/mi, indicating northward flow of the saltwater at 80 to 120 ft/yr.

Although the potentiometric contours on plate 7 seem to indicate that salty water could flow northward to the Lula Avenue station without being diverted to the Government Street station, this is unlikely to occur. When all wells in the "1,500-foot" sand at the Government Street station are pumping, the local cone of depression enlarges. This cone of depression (not indicated on pl. 7 because of the contour interval) will divert at least part of the salty water to the station. Assuming movement at the maximum estimated rate of 120 ft/yr, the leading edge of the salty water would reach the Government Street well field in about 30 years. The hydraulic gradient will increase as the salty water approaches the well field, which will increase the rate of movement of the salty water. A clay near the base of the aquifer pinches out between wells EB-807A and EB-504 (fig. 5). The increased effective thickness of the aquifer will tend to decrease the rate of encroachment. The increasing gradient and the increased thickness of the aquifer will tend to counteract each other, and the resulting rate of movement may be close to the calculated rate of about 100 ft/yr.

## Outlook for the Future

Pumpage from the "1,500-foot" sand in Baton Rouge has increased steadily from an average of 8.8 Mgal/d in 1966 (Rollo, 1969) to 15.1 Mgal/d in 1977. As about 80 percent of the total pumpage is for public supply, water-conservation efforts by industry and variations in industrial output have had little effect on pumpage. Instead, pumpage has increased with the rising population of the area--a trend that will probably continue. Much of the future increase in pumpage from the "1,500-foot" sand may be in the eastern part of the parish, however, well to the east or southeast of the Government Street and Lula Avenue pumping stations. Increased pumpage from the "1,500-foot" sand several miles east or southeast of the present major pumping centers will probably have little effect on the rate of saltwater encroachment toward those centers.

Once the leading edge of salty water reaches the first well at the Government Street station, several courses of action are possible. If each well is shut down as soon as salty water reaches it, encroachment across the field will be rapid, probably within a few months. Each of the wells completed in the "1,500-foot" sand at the Government Street station has two or more sections of screen separated by blank pipe across thin clay beds. Plugging of the lowest screen section of each well as the salty water reached it would provide a temporary remedy, the effectiveness of which would depend on the areal extent and continuity of the clay beds. With the relatively high hydraulic gradients within and near the well field, however, plugging the lower screens would provide only short-lived relief from encroachment. Salty water would soon move upward through windows in the clays or migrate around the edges of the clays to reach the upper screens.

The simplest, and probably most effective, method of dealing with the salty water would be to continue using the wells as long as possible after the salty water reaches them. As shown in figure 6B, the chloride concentration of the advancing salty water is only moderately high. Relatively large amounts of such water can be mixed with the low-chloride water from the "2,000-foot" and "2,400-foot" sands that supply the other wells at the Government Street station without exceeding a chloride concentration of 250 mg/L, the recommended limit for public supply (U.S. Environmental Protection Agency, 1977). The blended water would have somewhat higher hardness than users in the area are accustomed to now, but the change would be gradual and should cause no great problems. Continued use of wells completed in the "1,500-foot" sand at the Government Street station after the salty water reaches them would not represent a final solution to the problem of encroachment, but it would extend the useful life of these wells and slow, or possibly even halt temporarily, further northward movement of the salty water toward the Lula Avenue station. Northward encroachment would resume or speed up when the Government Street wells are finally abandoned either because of increasing chloride or failure of the wells.

If no positive control measures are taken, saltwater encroachment may ultimately force abandonment of all wells completed in the "1,500-foot" sand at the Government Street and Lula Avenue stations and a single well at the North 45th Street station. If this happens, water levels in the "1,500-foot" sand would rise sharply in the present cone of depression, hydraulic gradients in the vicinity of the saltwater would flatten, and the difference in water levels across the Baton Rouge fault between the "1,500-foot" sand and the downthrown "1,200-foot" sand would decrease. Northward encroachment should essentially cease at that time, but the salty water may begin moving slowly eastward toward newer pumping centers. Prediction of a future rate or direction of eastward encroachment is not feasible because neither the location nor rate of pumping from the new centers can be accurately predicted at this time. Assuming a rational pattern of development in view of the present knowledge of the location of salty water in the aquifer, however, the rate of eastward encroachment should be no more than a few tens of feet per year in contrast to the present northward rate of about 100 ft/yr.

## Possible Control Strategies

### Barrier-Well Systems

As with the "600-foot" sand, a line of barrier wells can provide positive control of saltwater encroachment in the "1,500-foot" sand. The barrier system could be of any of the types discussed for the "600-foot" sand--discharge wells, recharge wells, or a combination system. The same factors that may make a barrier-well system in the "600-foot" sand impractical are even more limiting for the "1,500-foot" sand. Capital costs of construction would be higher because of the greater depth of the wells needed. Water from the shallow Pleistocene or "400-foot" sands would probably require treatment before injection in recharge wells to insure chemical compatibility and to prevent degradation of water quality in the "1,500-foot" sand. Water from existing wells in the "1,500-foot" sand at the Government Street or Lula Avenue well fields could be diverted to supply injection wells, but this would reduce the output of water for public supply from these fields and would require the laying of several miles of pipeline through developed residential and commercial areas.

### Discharge Well Near the Fault

Because of the relatively small area now affected by saltwater encroachment and the relatively low salinity of the salty water now in the aquifer, a single high-capacity discharge well near the Baton Rouge fault could probably provide effective control of encroachment. If the estimated rate of leakage of salty water across the fault ($5x10^5$ gal/d) is approximately correct, a single well discharging 500 to 1,000 gal/min would remove all of the increasingly salty water leaking across the fault and would remove some of the salty water already present in the aquifer. The remaining salty water near the leading edge of the area of encroachment could be allowed to continue moving to existing production wells, where it could be used by mixing with low-chloride water from other aquifers. A deep injection well would probably be needed at the site of the discharge well to dispose of the salty water.

## SALTWATER IN OTHER AQUIFERS OF THE BATON ROUGE AREA

### "400-Foot" Sand

Direct encroachment of salty water in the "400-foot" sand is not a threat in the Baton Rouge area. No salty water is known to occur in the "400-foot" sand north of the Baton Rouge fault in East Baton Rouge Parish or eastern West Baton Rouge Parish. In addition, across most of the area, the downthrown sands opposite the "400-foot" sand at the fault contain freshwater. The only real threat of saltwater encroachment in the "400-foot" sand is from upward migration of salty water from the "600-foot" sand, and this will not become a serious threat unless saltwater encroachment in the "600-foot" sand is allowed to reach the industrial district. If salty water does reach the industrial district in the "600-foot" sand, present production wells and old wells that were abandoned without proper plugging would provide open channels for movement of salty water to the "400-foot" sand; and the encroachment across the industrial district could be very rapid. The impossibility of locating and properly plugging all of the old abandoned wells and test holes provides a strong incentive for stopping encroachment in the "600-foot" sand south of the industrial district.

Some salty water occurs north of the Baton Rouge fault in the "400-foot" sand in the west-central part of West Baton Rouge Parish. (See fig. 7.) The sand in this area is isolated from the effects of pumping near Baton Rouge by hydraulic connection with the overlying alluvial and shallow Pleistocene aquifers in the intervening area, and there is no threat of encroachment toward existing pumping centers. This salty water is part of a large body of residual salty water that was never flushed from aquifers of intermediate depth beneath the Atchafalaya basin and is not the result of encroachment. Heavy industrial development is unlikely in this area, and adequate water of good quality for public supply is available from deeper aquifers. Thus intensive development of water from the "400-foot" sand close enough to the saltwater front to cause encroachment is not probable. Scattered stock or domestic wells near the saltwater front would not develop hydraulic gradients steep enough to cause noticeable encroachment.

### "800-Foot" Sand

The "800-foot" sand is a minor aquifer in the Baton Rouge area; pumpage has declined from about 2.8 Mgal/d in 1966 to about 1.1 Mgal/d in 1977. Three wells in the industrial district, two commercial wells southeast of the industrial district, and scattered domestic wells across the northern part of the area are the only points of withdrawal. Seasonal water-level fluctuations in the "800-foot" sand indicate that it is hydraulically connected to the overlying "600-foot" sand and that water is probably moving from the "800-foot" sand to the "600-foot" sand. The areas of connection have not been determined, but as long as water levels in the "800-foot" sand are higher than water levels in the

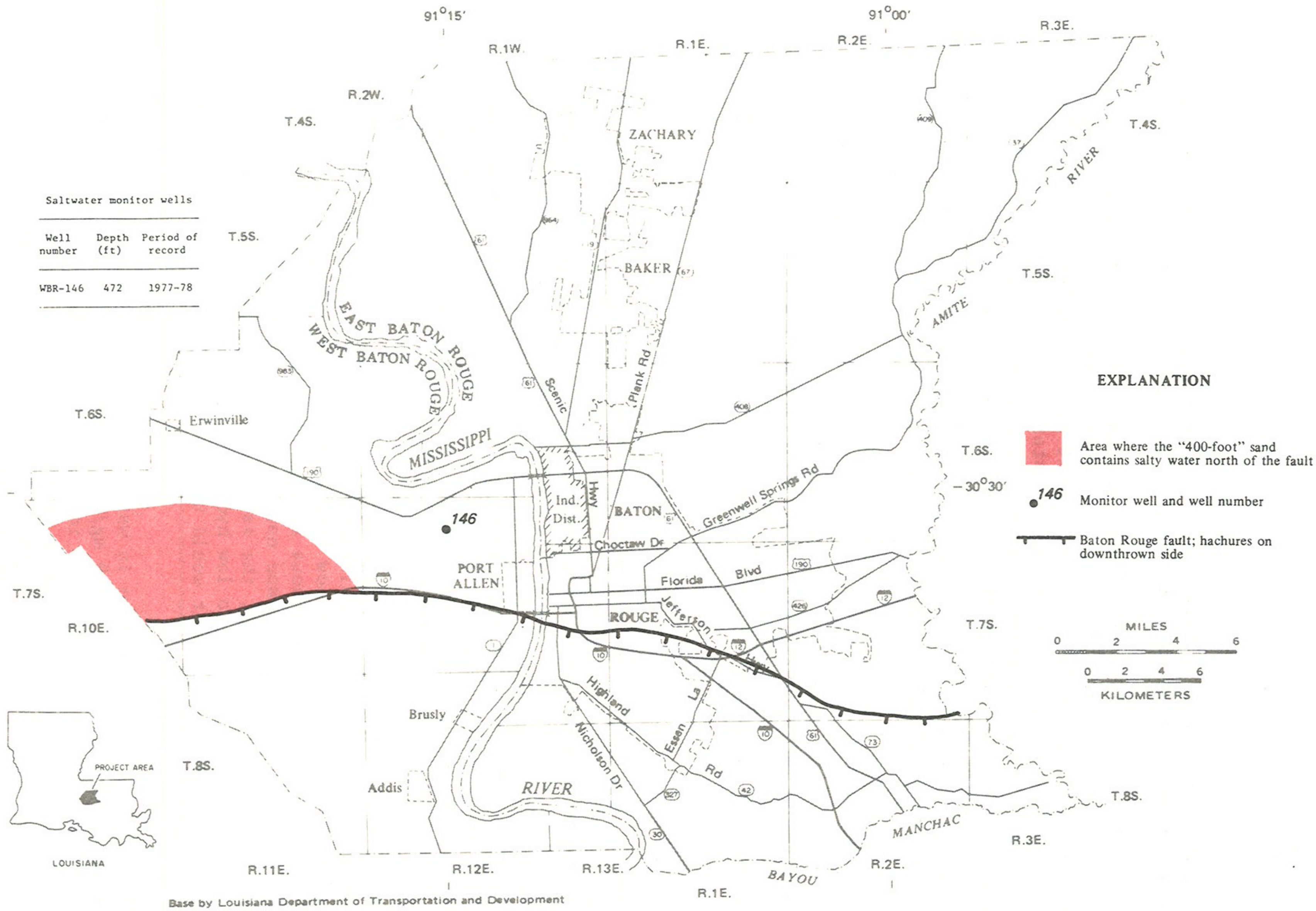


Figure 7.--Location of salty water in the "400-foot" sand north of the Baton Rouge fault.

"600-foot" sand, there is little chance of contamination of the aquifer by downward movement of salty water from the "600-foot" sand.

No wells completed in the "800-foot" sand north of the Baton Rouge fault yield salty water, but electrical logs of several wells near the fault indicate that salty water is present in the aquifer north of the fault. (See fig. 8.) The known salty water is confined to a narrow band no more than a few thousand feet wide next to the fault. Salty water is apparently entering the area by leakage across the fault at a low rate from the downthrown "600-foot" sand. Leakage to the "800-foot" sand probably began soon after leakage began to the "600-foot" sand, but much less salty water has entered the "800-foot" sand.

The indicated low rate of leakage and movement of salty water in the "800-foot" sand confirms Rollo's (1969) conclusion that saltwater encroachment will not represent a significant problem in the "800-foot" sand for many years. Collection and evaluation of data should be continued, but intensive investigation or control measures other than discouraging development of new wells near the fault do not seem justified.

## "1,000-Foot" Sand

The "1,000-foot" sand is a minor aquifer in the Baton Rouge area. Pumpage has been averaging about 3 Mgal/d recently, almost all for public supply in the Cortana-North Sharp Road area of Baton Rouge and in the area north of Port Allen. Electrical logs of several wells near the fault show that salty water occurs in the "1,000-foot" sand north of the fault in both East Baton Rouge Parish and West Baton Rouge Parish. (See fig. 9.) Two monitor wells, EB-805 on Airline Highway at the Nesser overpass and WBR-104 about 1 mi west of Port Allen, were completed in the "1,000-foot" sand to monitor the salty water.

The initial water sample from well WBR-104 confirmed the presence of salty water at this site (chloride, 358 mg/L), but the well failed soon after completion and has now been abandoned and plugged. The "1,000-foot" sand is discontinuous between well WBR-104 and the nearest production wells to the north and northeast. If saltwater encroachment is occurring in this vicinity, the salty water is moving slowly along a circuitous path in response to low hydraulic gradients; and it will be many years before encroachment would be a threat to any present or proposed production wells.

The chloride concentration in water from well EB-805 has shown a steady increase from a low of 650 mg/L in 1967 soon after the well was completed to a level of 4,600 mg/L in 1978. The steady rise in chloride is strong evidence that salty water is leaking across the fault from highly saline aquifers to the south. Although no other wells are nearby to detect encroachment, the electrical log of a well drilled recently (well EB-990, drilled August 1976) 0.8 mi north of well EB-805 shows no evidence of saltwater in the "1,000-foot" sand. Thus, saltwater encroachment has progressed less than 0.8 mi in this area. Assuming

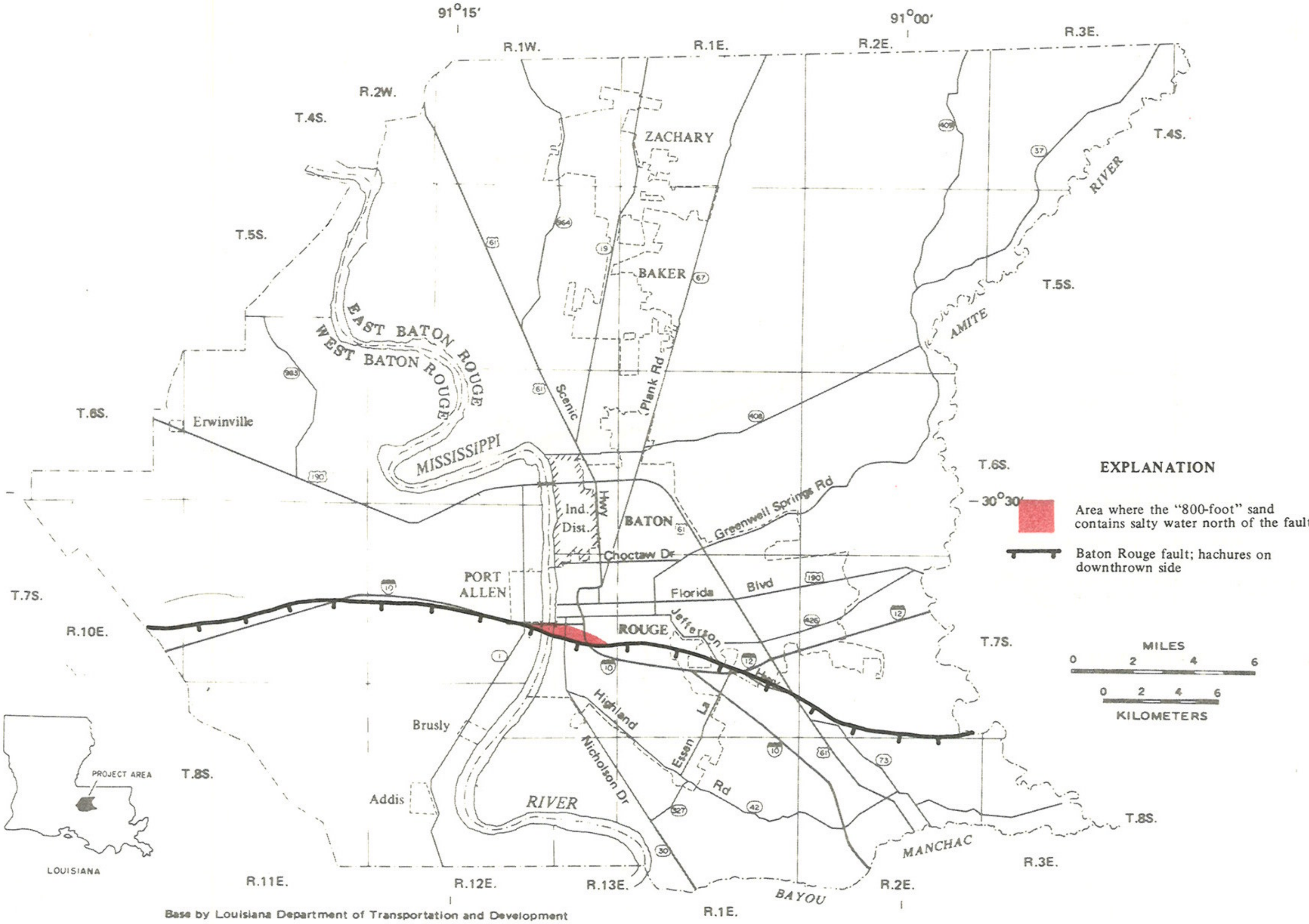


Figure 8.--Location of salty water in the "800-foot" sand north of the Baton Rouge fault.

Saltwater monitor wells

| Well number | Depth (ft) | Period of record | Remarks |
| --- | --- | --- | --- |
| EB-782A | 1,189 | 1965-78 | |
| EB-805 | 1,072 | 1966-78 | |
| WBR-147 | 1,292 | 1977-78 | S. of fault. |

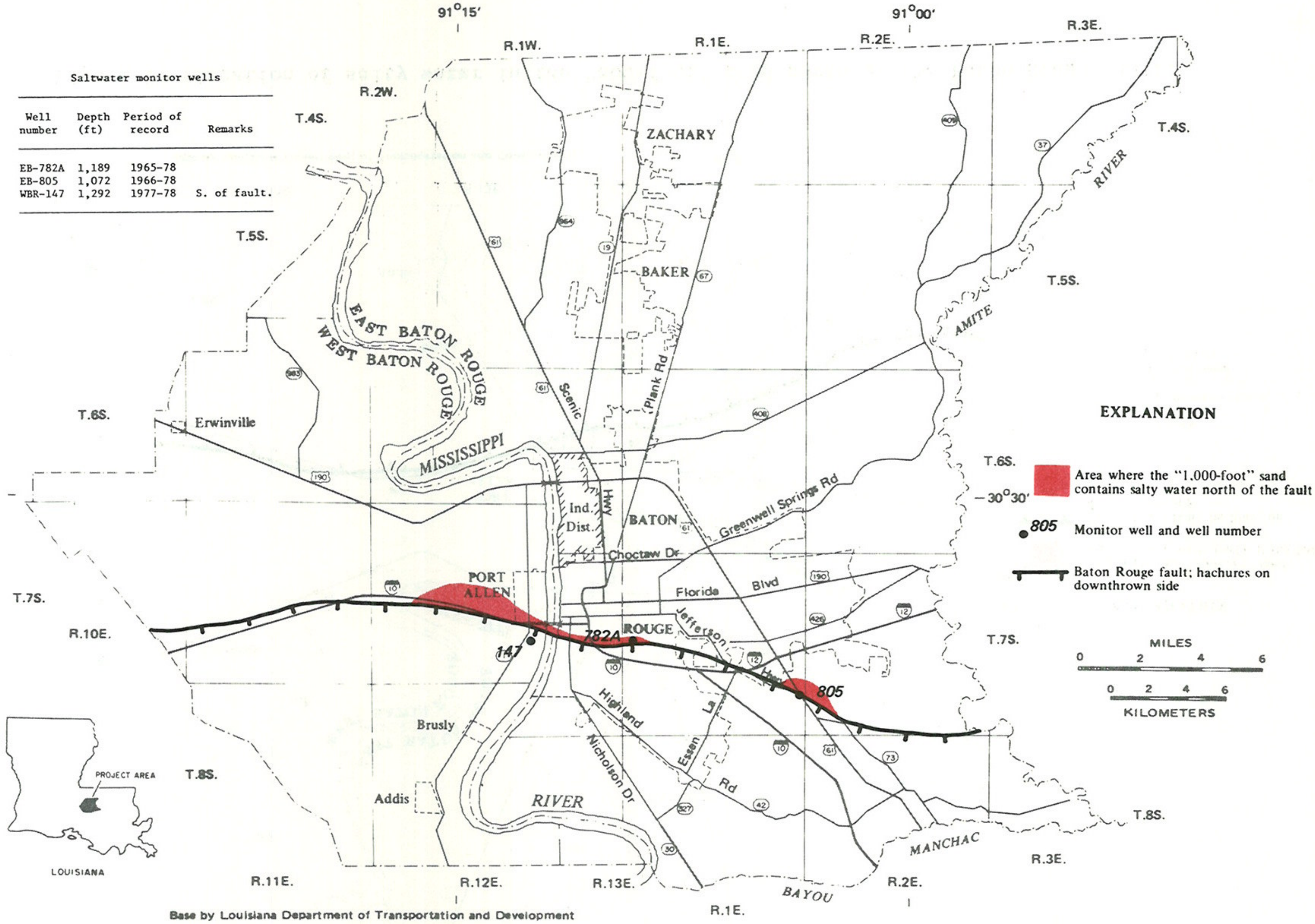


Figure 9.--Location of salty water in the "1,000-foot" sand north of the Baton Rouge fault.

encroachment began in 1957, when the first high-capacity well was completed in the "1,000-foot" sand east of the industrial district, the average rate of encroachment has been less than 200 ft/yr. If encroachment began earlier in response to pumpage in the industrial district, the rate of encroachment has been even less. At a rate of 200 ft/yr, it would take salty water more than 75 years to move from its present position near well EB-805 to the nearest production wells 3 mi to the northwest.

Present indications are that use of water from the "1,000-foot" sand for public supply may increase in the future in both East Baton Rouge Parish and West Baton Rouge Parish. If the increase in usage becomes substantial, monitor wells should be installed between the pumping centers and the areas of known salty water. In the meantime, collection and evaluation of data from existing and newly drilled wells should be continued.

## "1,200-Foot" Sand

Saltwater has not been positively detected in the "1,200-foot" sand north of the Baton Rouge fault. No electrical logs of wells north of the fault show evidence of saltwater in the "1,200-foot" sand; and except for wells WBR-36 and WBR-37 discussed below, none of the monitor wells have shown any increase in chloride above background levels. Locations of the monitor wells are shown on plate 1.

Wells WBR-36 and WBR-37 at the Greater Baton Rouge Port Commission's Port Allen facilities began yielding water with higher than normal chloride concentrations in 1972. These wells are close to the fault in an area where water-level differences across the fault, 65 to 70 ft in November 1977, are near their maximum. The increase in chloride was initially interpreted as possibly resulting from encroachment, but recent investigation disclosed a cross connection between the wells (well WBR-37 was feeding high-chloride water to well WBR-36). When the cross connection was eliminated and well WBR-36 was pumped heavily, the chloride concentration in water from the well decreased. Well WBR-36 is south of well WBR-37 and thus should be affected first by encroachment, so the decreasing chloride concentration indicates that encroachment has not occurred. The increase in chloride in water from well WBR-37 is likely the result of a casing leak opposite the "800-foot" sand, which contains salty water at this site. This possibility should be investigated when the pump is pulled for maintenance or if the chloride concentration reaches unacceptable levels. A recent test hole and monitor well, WBR-147, installed 1,500 ft south of well WBR-36 confirms Rollo's (1969) conclusion that the danger of encroachment in this area is slight. Little sand occurs south of the fault opposite the "1,200-foot" sand in this vicinity. The chloride concentration in water in the thin sands that are present is relatively low, only 780 mg/L in water from well WBR-147.

Collection and evaluation of data from the existing monitoring system should be continued, as well as evaluation of data from future wells that may be drilled. No other action seems needed until some positive evidence of encroachment is obtained.

## "1,700-Foot" Sand

No saltwater is known to occur in the "1,700-foot" sand north of the Baton Rouge fault, and pumpage is so low and widely dispersed in the vicinity of the fault that encroachment is very unlikely. Several million gallons per day of water are pumped near the northwest corner of East Baton Rouge Parish from sands that are equivalent to the "1,700-foot" sand, but the effect at the fault is minor. Other than continued collection and evaluation of data, no action seems needed at the present time.

## "2,000-Foot" Sand

The "2,000-foot" sand is the most heavily pumped aquifer of the Baton Rouge area. Average daily pumpage during 1977 was more than 33 Mgal/d, or about 24 percent of the total pumpage in East Baton Rouge Parish. The water is used for both public-supply and industrial purposes.

Salty water has been found in the "2,000-foot" sand north of the Baton Rouge fault at only one site in the Baton Rouge area, on Acadian Thruway north of Perkins Road. (See fig. 10.) It was discovered during the 1965-66 test-drilling program, and monitor well EB-781 was installed (Rollo, 1969). At that time, data were inadequate to clearly identify the source of the salty water, and Rollo discussed several possible sources and several possible courses that encroachment might follow. He concluded that salty water could be moving toward the Lafayette Street pumping station at a rate of 930 ft/yr and could reach the station within 10 to 15 years.

Smith (1976), using data collected by the U.S. Geological Survey since Rollo's work, recently completed a study in which he concluded that salty water is leaking across the Baton Rouge fault into the "2,000-foot" sand from the downfaulted "1,500-foot" sand at a relatively low rate--possibly on the order of 450,000 gal/d. Smith estimated that it may take as long as 100 years for salty water to reach either the Government Street or the Lafayette Street pumping stations and indicated that the present monitoring network will provide adequate warning of impending encroachment at either station. Although Smith's calculations are, as he points out, only estimates based on reasonable assumptions, it appears that salty water is not moving as rapidly as calculated by Rollo.

One significant gap exists in the present monitoring network. (See fig. 10.) If salty water is moving northward or northwestward from a

Saltwater monitor wells

| Well number | Depth (ft) | Period of record | Remarks |
|---|---|---|---|
| EB-151 | 2,664 | 1949-78 | |
| EB-444 | 2,172 | 1949-78 | |
| EB-575 | 2,500 | 1955-78 | S. of fault. |
| EB-674 | 2,250 | 1960-78 | |
| EB-778 | 2,586 | 1965-78 | S. of fault. |
| EB-781 | 2,286 | 1965-78 | |
| EB-783B | 2,675 | 1965-78 | S. of fault. |
| EB-792B | 2,286 | 1965-78 | |
| EB-803B | 2,565 | 1966-78 | S. of fault. |
| EB-807B | 2,264 | 1966-78 | |
| EB-817 | 2,284 | 1968-78 | |
| WBR-102B | 2,100 | 1966-78 | |
| WBR-106 | 2,017 | 1966-78 | |
| WBR-111 | 2,650 | 1968-78 | S. of fault. |

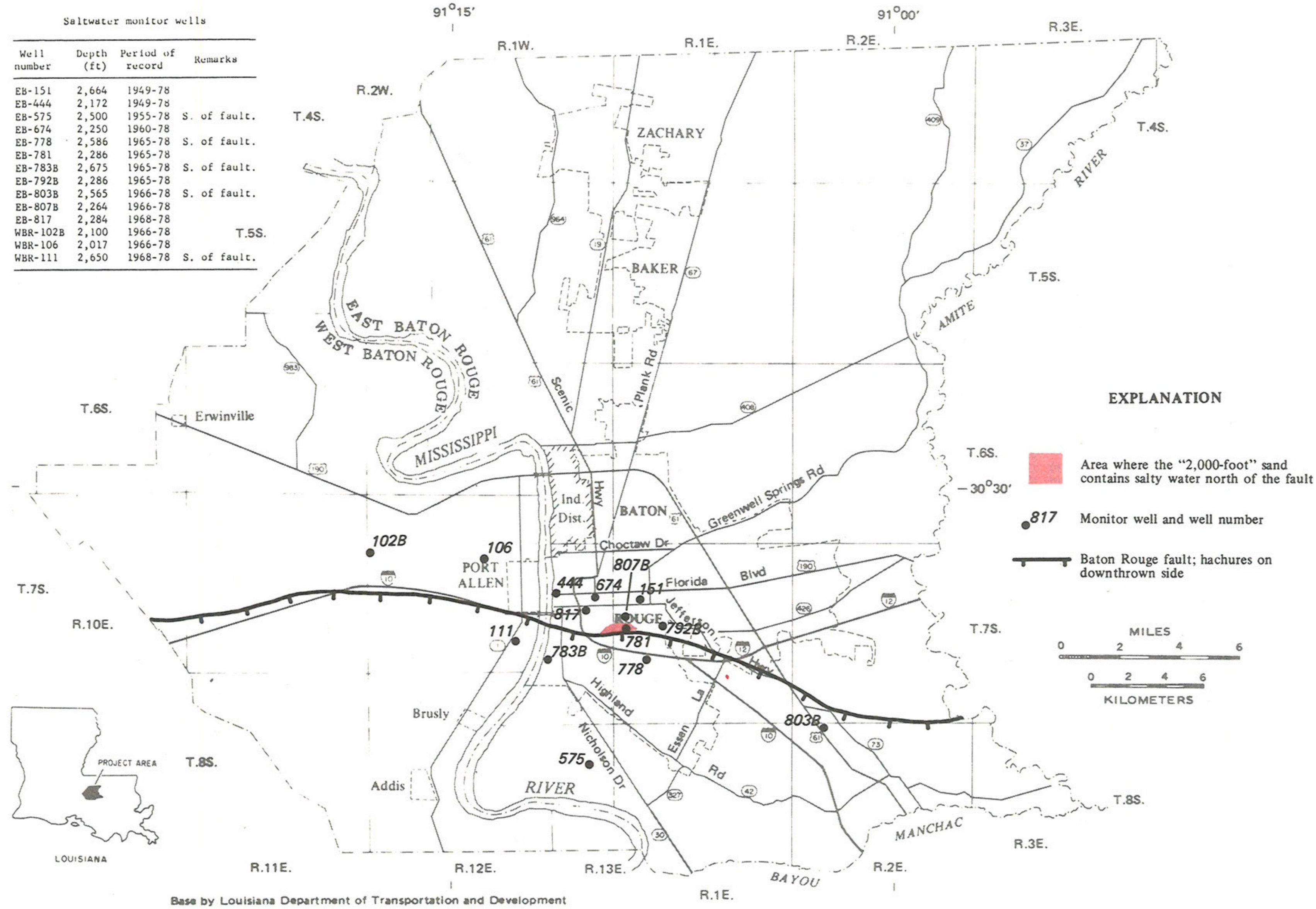


Figure 10.--Location of salty water in the "2,000-foot" sand north of the Baton Rouge fault.

source of leakage near well EB-781, monitor well EB-807B will detect it before a large area of the aquifer is contaminated. However, as Rollo suggested, the salty water may be swept westward along the fault before moving northward, well EB-807B could be bypassed, and salty water could reach the Lafayette Street station without prior warning. A monitor well is needed near the north edge of City Park to close this gap. If salty water has reached this site by the time the well is drilled, it will provide evidence that encroachment is progressing more rapidly than calculated by Smith and that control measures will be needed soon. If salty water has not reached this site, control could be delayed.

A discharge well near the fault coupled with a deep injection well seems to be the only practical control method. The water leaking across the fault is too saline (the chloride concentration is at least 2,200 mg/L, and dissolved solids are more than 3,500 mg/L) to be used by mixing with freshwater from other aquifers. A single high-capacity discharge well should provide adequate control.

## "2,400-Foot" Sand

No salty water has been found in the "2,400-foot" sand north of the Baton Rouge fault in either East Baton Rouge Parish or West Baton Rouge Parish. Across most of the area the downthrown "2,000-foot" sand, which abuts the "2,400-foot" sand north of the fault in places, contains fresh to only slightly saline water (Rollo, 1969; Smith, 1976). Saltwater encroachment in the "2,400-foot" sand will not occur until the freshwater adjacent to the fault has leaked across the fault and has been replaced by salty water. The high head differences across the fault zone provide a strong driving force to cause leakage across the fault, but they also indicate actual leakage must be slight. Continued monitoring of wells near the fault should provide adequate warning of impending encroachment, and no control measures seem needed now. Locations of the present monitor wells are shown on plate 1.

## "2,800-Foot" Sand

The "2,800-foot" sand is the principal aquifer for industrial and public supplies in northern East Baton Rouge Parish. Pumpage has increased rapidly in recent years as industries have moved into the area north of the industrial district. Public supplies have been expanded to serve a growing population and to serve rural areas formerly supplied by shallow domestic wells. Average pumpage in 1977 was about 27 Mgal/d in East Baton Rouge Parish, making the "2,800-foot" sand second only to the "2,000-foot" sand in the amount of water withdrawn.

Unlike other aquifers of the area, the "2,800-foot" sand contains salty water over a broad area north of the Baton Rouge fault. (See fig. 11.) This salty water is a natural occurrence and is a result of incomplete flushing of the aquifer rather than encroachment in response to

Saltwater monitor wells

| Well number | Depth (ft) | Period of record |
| --- | --- | --- |
| EB-750 | 2,643 | 1963<br>1975<br>1978 |
| EB-798 | 2,647 | 1965<br>1978 |
| EB-1000 | 2,926 | 1977-78 |

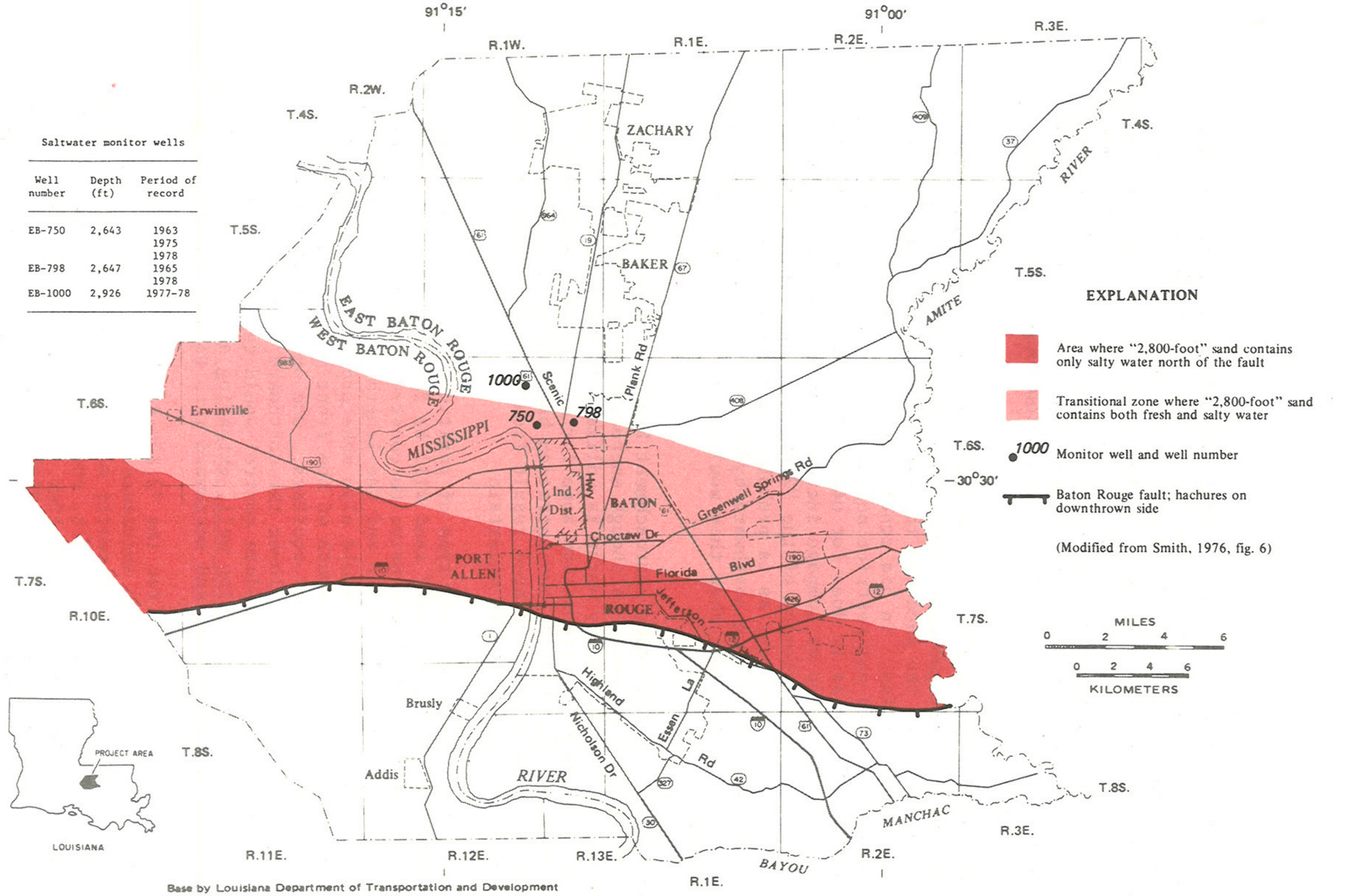


Figure 11.--Location of salty water in the "2,800-foot" sand north of the Baton Rouge fault.

pumping. The "2,800-foot" sand contains only salty water in a band several miles wide extending across the area along the north side of the Baton Rouge fault. North of the band of salty water, a broad transitional zone occurs with salty water in the lower part of the aquifer and freshwater in the upper part. A few relatively small supplies of fresh to slightly saline water have been developed from the "2,800-foot" sand in the transitional zone, but most of the pumpage is in the area north of the transitional zone in northern East Baton Rouge Parish, where the aquifer contains only freshwater.

Smith (1976) has made a detailed study of the "2,800-foot" sand, which includes several geologic cross sections and maps showing the altitude of the base of the sand and the distribution of freshwater and saltwater in the aquifer. In his conclusions, Smith points out that the Baton Rouge fault does not restrict northward encroachment of saltwater in the "2,800-foot" sand as it does for other sands of the area and that encroachment may develop as pumpage increases in the northern part of the area. If the displacement of the "2,800-foot" sand by the Baton Rouge fault forms a barrier, as is probable, the fault could indirectly slow encroachment by causing northward hydraulic gradients toward major pumping centers to be lower than they would be in the absence of a hydraulic barrier.

No evidence of saltwater encroachment has been detected north of the natural transition zone. Although encroachment may be occurring, it is probably very slow. Salty water is unlikely to reach any of the pumping centers north of the transition zone for many years. Within the transition zone, the chloride concentration has increased in water from a few wells; whether the increases result from lateral movement or vertical coning of salty water is uncertain.

It seems unlikely that any type of positive control of saltwater encroachment in the "2,800-foot" sand will be feasible. A system of barrier wells would be very expensive to construct and to operate because of the depth of the aquifer and the length of the front requiring protection. The same factors would also make protection by means of high-capacity discharge wells south of the front more expensive and less effective than for the shallower aquifers. One or two high-capacity wells south of the front could lower the northward hydraulic gradients and slow encroachment; but complete control would require a line of wells, each with an associated injection well, extending across East Baton Rouge and West Baton Rouge Parishes and northward into Pointe Coupee Parish.

The monitor-well network for the "2,800-foot" sand is being reviewed and adjusted in response to the increased pumpage in northern East Baton Rouge Parish. A test hole was recently drilled through the "2,800-foot" sand north of the industrial district, and monitor well EB-1000 (fig. 11) was completed at the base of the aquifer. The electrical log of well EB-1000 shows that salty water in the "2,800-foot" sand does not extend as far north as was thought previously. Data from well EB-1000 should provide a warning of future saltwater encroachment.

## CONCLUSIONS

Saltwater encroachment has been observed in the "600-foot" and "1,500-foot" sands and is indicated, though not proven, in the "800-foot," "1,000-foot," "2,000-foot," and "2,800-foot" sands of the Baton Rouge area. The encroachment is the result of leakage of salty water across the Baton Rouge fault in response to pumpage north of the fault.

Salty water in the "1,500-foot" sand may reach the Government Street well field in about 30 years, and a control strategy should be selected and placed in operation as soon as possible to minimize contamination of the aquifer and damage to existing well fields.

Saltwater encroachment in the "600-foot" sand may not produce serious problems for about 40 years, but the ultimate effects of encroachment in the "600-foot" sand may be more damaging than encroachment in the "1,500-foot" sand. For maximum effectiveness, control measures should be instituted in the "600-foot" sand as soon as practicable and within about 20 years at the latest.

Control measures in the other sands in which encroachment is indicated can probably be delayed if adequate monitoring is maintained. Operating experience gained from a control system in the "1,500-foot" sand would be valuable in the design of control systems for the other aquifers.

Of several possible control strategies, the most practical will probably consist of discharging wells pumping salty water from the aquifers north of the Baton Rouge fault. Deep injection wells to dispose of the salty water will probably also be needed.

The existing monitor network should be maintained, with periodic reviews and adjustment to meet changing conditions. An observation and monitor well in the "1,500-foot" sand is needed west of the Government Street station to define the cone of depression around the station and to detect northward movement of salty water west of the station. Monitoring of the "2,800-foot" sand should be increased, and a monitor well is needed in the "2,000-foot" sand northwest of the area of known saltwater occurrence north of the fault. When saltwater reaches one of the present key monitor wells in the "600-foot" sand, one or two new monitor wells should be drilled along Choctaw Drive.

Well WBR-37 should be checked at the first opportunity to determine the cause of rising chloride concentration. Although probably the result of a casing leak, it could possibly indicate the beginning of encroachment in the "1,200-foot" sand.

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Table 3.--Test holes and monitor wells drilled as a part of this investigation
[Location shown on pl. 1]

| Well number | Location | Date drilled | Test hole depth (ft) | Well depth (ft) | Aquifer screened | Remarks |
|---|---|---|---|---|---|---|
| | | EAST BATON ROUGE PARISH | | | | |
| EB-868 | Dalrymple Drive south of April Street | February 1971 | 750 | 602 | "400-foot" sand | South of fault. |
| 869 | Dalrymple Drive south of March Street | March 1971 | 715 | 599 | "600-foot" sand | |
| 870 | North 19th Street at I-110 | do | 844 | 692 | do | |
| 871 | Dalrymple Drive north of April Street | do | 842 | 685 | "400-foot" sand | Do. |
| 876 | Dalrymple Drive south of March Street | July 1971 | 642 | 635 | "600-foot" sand | 6-inch well. |
| 882 | Kernan Street at Laurel Street | March 1972 | 729 | 710 | do | Plugged April 1976. |
| 883 | Madison Avenue west of North 15th Street | April 1972 | 765 | ----- | ----- | Test hole only. |
| 888 | Monroe Avenue at West Belfair Drive | June 1972 | 734 | ----- | ----- | Do. |
| 889 | Pittsburgh Avenue west of Sorrell Avenue | do | 675 | ----- | ----- | Do. |
| 890 | Monroe Avenue at North 28th Street | do | 705 | ----- | ----- | Do. |
| 917 | Country Club Drive north of Westdale Drive | October 1973 | 1,867 | 1,736 | "1,500-foot" sand | |
| 918 | Witter Lane at Ward Creek | December 1973 | 1,871 | 1,834 | do | |
| 936 | North 40th Street north of Zion Street | June 1974 | 719 | ----- | ----- | Do. |
| 1000 | U.S. Highway 61 near Maryland Tank Farm | December 1977 | 3,036 | 2,926 | "2,800-foot" sand | |
| | | WEST BATON ROUGE PARISH | | | | |
| WBR-121 | West bank of Mississippi River at I-10 bridge | March 1971 | 740 | 562 | "600-foot" sand | Plugged after test. |
| 146 | Louisiana Highway 415 at Plantation Avenue | November 1977 | 785 | 472 | "400-foot" sand | |
| 147 | Port Allen docks west of grain elevators | do | 1,451 | 1,292 | "1,000-foot" sand | South of fault. |
| 148 | I-10, 4.0 mi west of Louisiana Highway 415 | March 1978 | 2,988 | 1,304 | "1,200-foot" sand | |