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Rehabilitation of a Brine-Polluted Aquifer

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REHABILITATION OF A BRINE-POLLUTED AQUIFER

By

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Project 14020 DLN

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Prepared for

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ABSTRACT

A detailed investigation was made of one (among several noted) incident where a fresh-water aquifer has been polluted by accepted disposal of oil-field brine through an "evaporation" pit (an unlined earthen pit) and later a faulty disposal well. The present extent of the brine pollution is one square mile; however, it will spread to affect 4 1/2 square miles and will remain for over 250 years before being flushed naturally into the Red River. Detailed chemical analyses show changes in relative concentrations of constituents as the brine moves through the aquifer.

Several rehabilitation methods are evaluated in detail, including controlled pumping to the Red River and deep-well disposal. None of the methods that are both technically feasible and permissible show a positive public benefit-cost ratio.

Although real economic damage both present and future results from this brine pollution, rehabilitation is not now economically justified. The report emphasizes that greater effort is needed to prevent such pollution, which not only affects ground-water resources but also affects water quality in interstate streams.

This report was submitted in fulfillment of Grant No. 14020 DLN under the partial sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.

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SECTION I

CONCLUSIONS

1. Improper oil-field brine disposal, first from an "evaporation" pit (an unlined earthen pit) and later from a faulty disposal well, caused pollution of one square mile in a shallow alluvial aquifer.

2. The polluted area will spread downstream to contaminate 4 1/2 square miles of ground water before discharging naturally into the Red River and will affect water quality in the area for over 250 years.

3. Two other polluted areas have been outlined by test drilling, and four more areas of high chlorides have been found by testing private wells in Miller County.

4. Dilution of metals and other chemical parameters in the brine was observed to be not always in proportion to the dilution of chlorides as the brine moves through the aquifer.

5. Of the numerous rehabilitation methods examined, pumping into the Red River and deep-well disposal are the most feasible solutions of those that are technically practical. However, none of the methods are economically justified at this time.

6. Because of the extremely long-term effect of ground-water pollution and its eventual discharge into interstate waters, considerably more effort is justified to insure that such pollution is completely stopped.

7. State agencies responsible for controlling pollution caused by brine disposal should enact and <u>enforce</u> stringent pollution control regulations.

SECTION II

RECOMMENDATIONS

Although the original objective of this project was to demonstrate the feasibility of rehabilitating a brine-polluted aquifer, it now appears that none of the rehabilitation methods that are technically sound and permissible are economically justified at this time. However, the long-term economic damage caused by such ground-water pollution, its effect on interstate waters, and the widespread occurrence of brine pollution are justification for greater participation by the responsible state and federal agencies.

Therefore, it is recommended that EPA formulate brine handling and disposal guidelines in cooperation with the oil producing states. For example, the standards should outlaw brine disposal into unlined "evaporation" pits, except in the rare cases where it's positively established that no water pollution will result under guidelines approved by EPA. Furthermore, the standards should require the use of injection tubing and a monitored fluid-filled annulus for disposal wells. Such regulations should apply to all brine handling systems, not just to future construction, because of the relatively high incidence of pollution caused by older installations. Furthermore, because of the cost of policing and effectively enforcing such regulations, some form of federal assistance to the responsible state agencies may be justified. The overall enforcement costs could be partly offset by a system whereby noncompliance with the regulations would result in a substantial fine to the offending party.

It is further recommended that additional observation wells be constructed as required, and a continuing monitoring program be established for this project area. The objectives of such a program would be: (1) to observe the continuing distribution of the brine in space, time, and concentration as it spreads in the aquifer; (2) to warn downstream irrigators and potential irrigators of the impending brine encroachment; and (3) to observe the actual lag in brine movement compared with natural ground-water flow as an aid in evaluating the natural flushing process. Such a continuing program based on this well-documented incident will benefit not only the immediate ground-water users but will also provide a sound basis for evaluating the long-term effects of all similar ground-water pollution.

In addition, it is recommended that all other areas where similar ground-water pollution exists be sufficiently outlined by test drilling and sampling to describe their extent and chloride concentration. The objectives of this program would be: (1) to warn ground-water users and potential users near the polluted areas of the impending danger; (2) to locate pollution incidents where early rehabilitation would be technically feasible and economically justified before further spreading of the brine occurs; and (3) to form an inventory of first-choice water sources for oil-field water flood operations.

SECTION III

INTRODUCTION

General

Activities related to alleviating pollution of our ground-water resources may be divided into two categories: (1) those activities designed to stop pollution now taking place, and (2) those activities to rehabilitate ground-water reservoirs which have already become polluted. Although this project deals primarily with rehabilitation, it is hoped that the costs of the remedial measures presented and the real economic damage caused by such pollution will stimulate considerably greater efforts by state and federal agencies in the preventive category.

This project deals with the pollution of a valuable shallow ground-water aquifer by the disposal of oil-field brine through first an unlined "evaporation" pit and later through a faulty disposal well. Although the use of unlined "evaporation" pits (which should be called seepage pits) is now outlawed in some states and some rules have been adopted regarding salt-water disposal wells, still considerable pollution is taking place because of the lack of sufficient surveillance and enforcement. This report examines in detail a singular occurrence of such pollution and the costs involved in rehabilitation. If rehabilitation steps are not undertaken, the polluted ground water will spread and eventually discharge into the Red River, an interstate stream.

Location

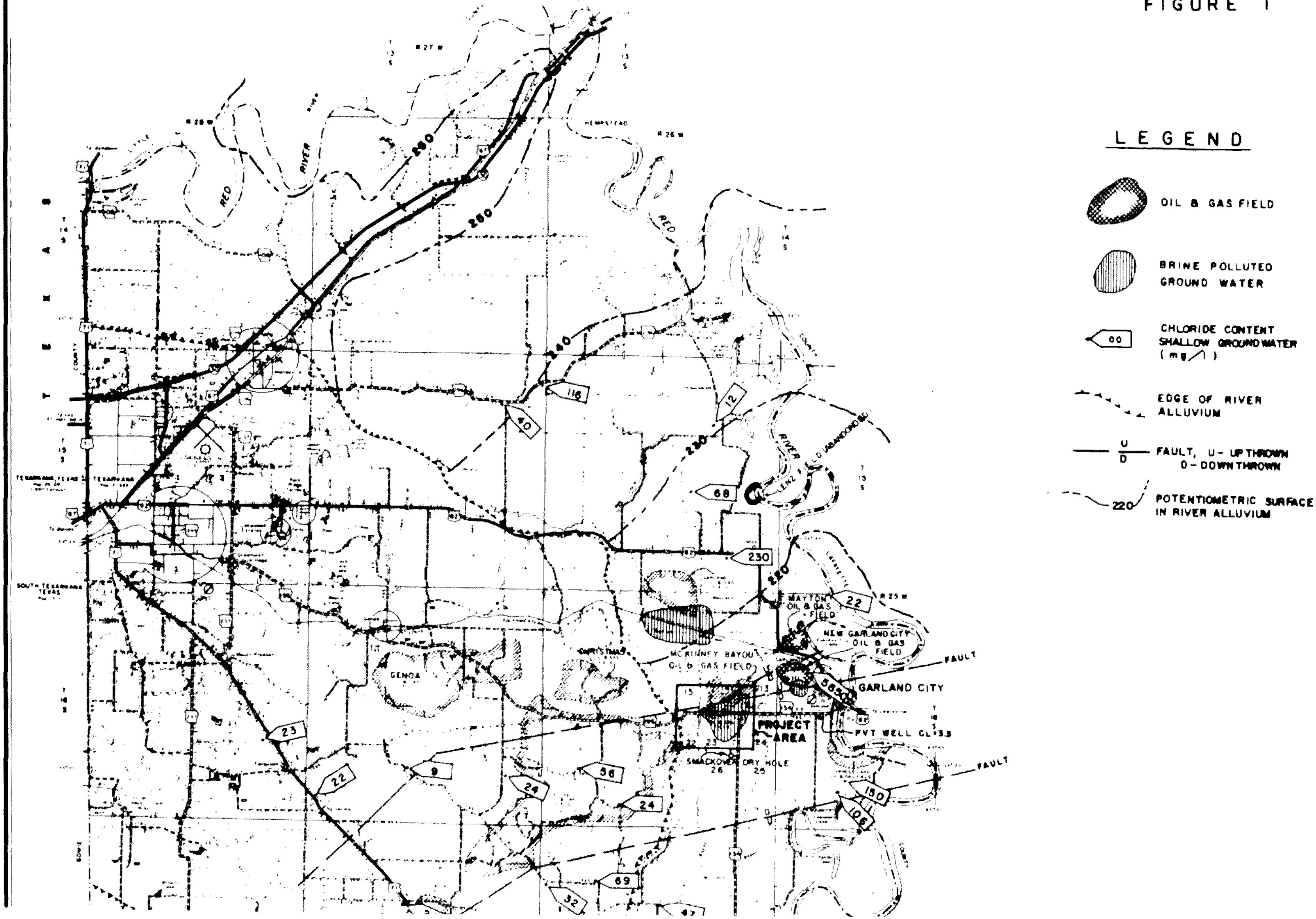
The project is in Miller County in the southwest corner of Arkansas, see figure 1. The sources of the brine pollution are a disposal pit and a disposal well located in the SW 1/4 of the SE 1/4 of Section 14, Township 16S, Range 26W, which is about 2 1/2 miles southwest of the town of Garland City and 2 1/2 miles west of the Red River.

This particular polluted area occupies about one square mile and affects the west half of that part of the alluvial floodplain on the west side of the Red River. The floodplain is flat, productive farmland, which lies 222 feet above sea level at the project area.

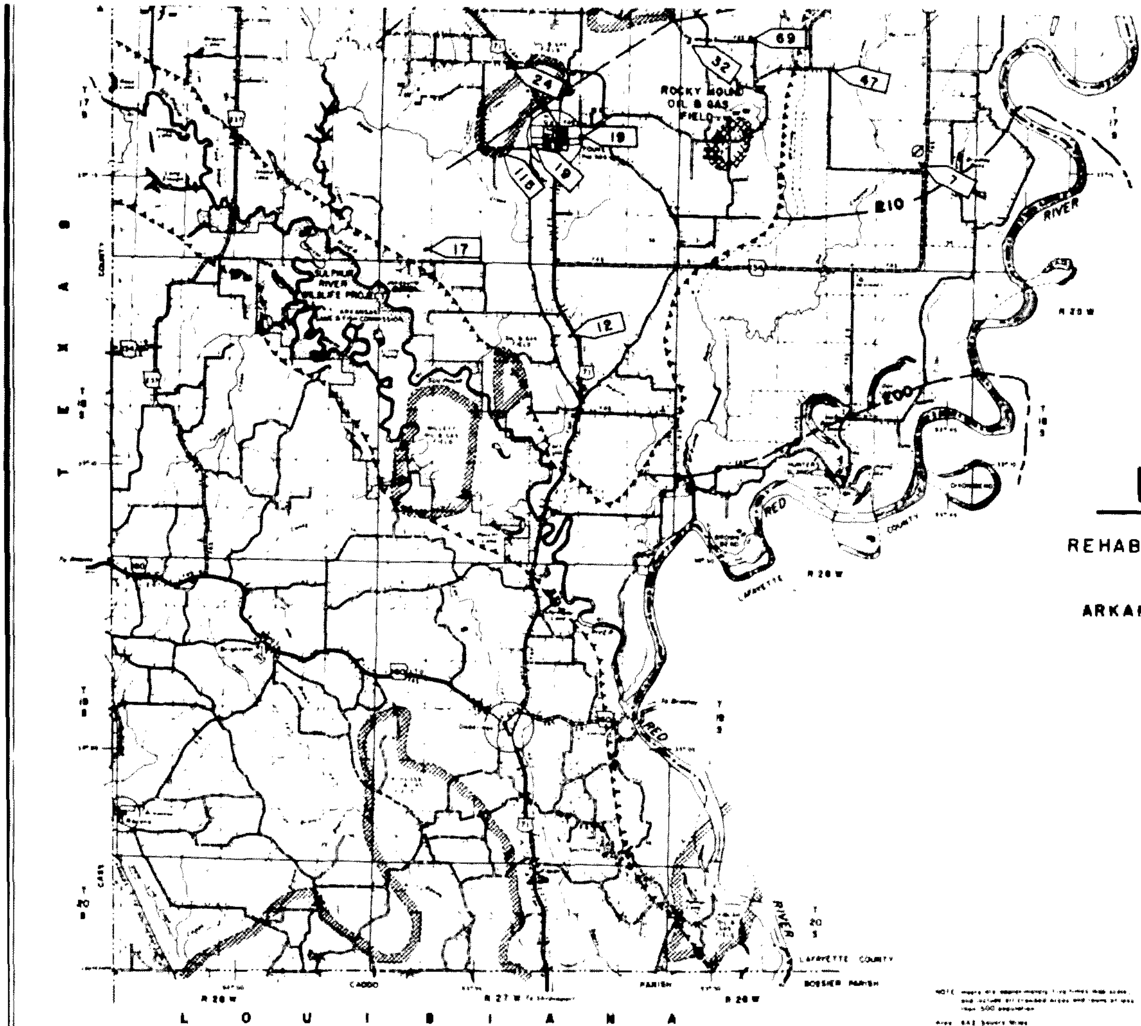
Objective

The original objective of this project was to develop selective pumping techniques whereby a fresh-water aquifer, which had become contaminated by brine from oil-field practices,

FIGURE 1



LEGEND
OIL & GAS FIELD
BRINE POLLUTED GROUND WATER
CHLORIDE CONTENT SHALLOW GROUNDWATER (mg/l)
EDGE OF RIVER ALLUVIUM
FAULT, U - UP THROWN D - DOWN THROWN
POTENTIOMETRIC SURFACE IN RIVER ALLUVIUM
TEXAS
RED RIVER
HEMPSTEAD
R 27 W
R 28 W
R 26 W
R 25 W
GENOA
MAYTON OIL & GAS FIELD
NEW GARLAND CITY OIL & GAS FIELD
MC KINNEY BAYOU OIL & GAS FIELD
GARLAND CITY
PROJECT AREA
SMACKOVER DRY HOLE
PVT WELL GL-33
FAULT
280
260
240
230
220
116
40
12
68
230
22
5650
23
9
22
56
24
24
150
106
69
32
47



LOCATION MAP

REHABILITATION OF A BRINE POLLUTED AQUIFER

EPA PROJECT 14020 DLN

ARKANSAS DIVISION OF SOIL & WATER RESOURCES

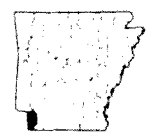
BASED ON
GENERAL HIGHWAY MAP

MILLER COUNTY
ARKANSAS

PREPARED BY
ARKANSAS STATE HIGHWAY DEPARTMENT
DIVISION OF PLANNING AND RESEARCH
IN COOPERATION WITH
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

MILES

1967



could be rehabilitated. Because of problems arising from disposal of the salt water to be pumped from the aquifer, actual rehabilitation is not now considered feasible.

The present objectives of this report are the comprehensive technical evaluation of the brine contamination, the technical and the economic evaluation of various disposal methods, and the relationship of this singular incident to the general pollution problem. In addition, the severity of ground-water pollution as herein presented will hopefully lead to greater state and federal action to prevent such pollution.

Scope

The following areas are herein examined:

1. A history of the pollution.

2. A technical description of the polluted aquifer.

3. A discussion of the value of the water that was polluted.

4. Technical evaluation of several possible methods of rehabilitating the aquifer and attendant costs.

5. Private and public benefit-cost ratio analysis of the rehabilitation methods presented.

Project History

In 1967 a farmer brought to the attention of the state agencies that his irrigation well had turned salty. This 1,000 gpm (gallons per minute) well was located in the NW corner of Section 24, about 2,500 feet southeast of the subject disposal pit. Analyses of water samples from this well showed an increase in chlorides from 900 to 1,100 mg/l (milligram per liter) over the two weeks before the well was shut down.

During the summer of 1967 the Arkansas Soil and Water Conservation Commission, along with the Arkansas Geological Commission, the Pollution Control Commission, and the Oil and Gas Commission conducted an investigation to determine the source of the pollution. This investigation consisted of auguring holes through the alluvium and sampling the water-sand mix as it was brought to the surface. These test hole samples suggested that the disposal pit was the source of pollution to that farmer's well. In addition, under a reconnaissance study being conducted simultaneously by the U. S. Geological Survey, samples were obtained from existing domestic and irrigation wells and other test holes over a

20-square mile area. This more general survey delineated two other polluted areas where chlorides exceeded 500 ppm. All three of these areas are at or just down gradient (south) of producing oil fields and are shown as "brine polluted ground water" on figure 1.

In May 1968 efforts were initiated to obtain a federal grant to rehabilitate the aquifer at the project area, and in June 1969 the demonstration grant was awarded to the Arkansas Soil and Water Conservation Commission. The grant was divided into two phases. The object of Phase I was to delineate the problem and establish in detail the best solution. Upon approval of the proposed solution, Phase II, the construction of rehabilitation facilities, would then be authorized. Field work was started by personnel of that agency in November 1969.

During the latter part of 1969 and the first half of 1970, 28 ground-water sampling sites were established in the project area to delineate the extent of the pollution. Upon analysis of this data a Phase I Report, entitled "Rehabilitation of a Brine-Polluted Aquifer," was submitted to EPA in December 1970. This report stressed the feasibility of disposing of the polluting salt water into the Red River; however, this solution was not acceptable to EPA, and Phase II was not authorized.

In January 1972, EPA authorized the Arkansas Division of Soil and Water Resources (previously the Arkansas Soil & Water Conservation Commission) to finalize the project by submitting a more detailed summary of the problem and work performed. This report constitutes that summary and was prepared for the Division of Soil & Water Resources by Engineering Enterprises, a consulting firm specializing in ground water, assisted by personnel of the Division of Soil & Water Resources.

SECTION IV

GEOLOGY & HYDROLOGY

General

The floodplain of the Red River is about nine miles wide in this area and is characterized by oxbow lakes, cut-off meander scars, and poorly drained bayous, typical of a mature meandering agrading river. Clean, highly permeable sand was deposited by the river during much of its early depositional stage. Later deposition has consisted predominately of silts and clays which form a blanket of variable thickness overlying the alluvial sand bodies.

In the project area, which is only about one mile from the west side of the floodplain, the alluvium extends to about 40 feet; however, depths up to 90 feet are known according to Ludwig. With water levels only 5 to 20 feet below land surface, these readily rechargeable alluvial sands form an important fresh-water aquifer. The extent of the alluvium is shown on figure 1.

Much of the upland area is also covered by unconsolidated sand and silt as terraces deposited by the Red River in earlier times. These terrace deposits also constitute an important source of fresh water to private wells and, as in the case of the alluvium, are also easily polluted.

The Sparta sand of Tertiary age underlies the terrace deposits and shallow alluvium in the general vicinity, but it has been eroded away beneath the project area. Ludwig describes this formation as a fine-to-medium sand, brown and gray sandy clay, and lignite. This extensive formation is also an important fresh-water aquifer in southwestern Arkansas and northeastern Louisiana. Water levels and chemical analyses of samples from the Sparta sand suggest that the salt-contaminated alluvial water will not contaminate the Sparta aquifer.

The Cane River formation underlies the Sparta sand and is the primary source of domestic water where the shallower alluvium and terrace deposits are absent or polluted. Yields from the Cane River are too small for irrigation however. The Carrizo sand lies below the Cane River and is the lowest known fresh water aquifer in the central part of Miller County. The town of Fouke, about eight miles southwest of the project, obtains its supply of nearly 0.23 mgd from a 600-foot well completed in the Carrizo.

Figure 2, "Geologic Column," shows the sequence of formations and approximate depths at the project area. These formations dip southward at about 30 feet per mile. The north edge of a northeast trending fault zone and a splinter fault lie directly under the project area, as shown on figure 1. The main fault plane dips southward 45 degrees in the shallower sediments and steepens to about 60 degrees with depth. Because of continued vertical movement along the fault through geologic time, the deep formations are displaced over 500 feet; the Annona chalk is displaced about 300 feet; but relatively little displacement can be observed in the formations of late Eocene time.

Precipitation in southwest Arkansas averages 48 inches per year. Although rainfall distribution is fairly uniform throughout the average year (August and September having the least precipitation), nevertheless during the dry springs and summers (of years of below average rainfall) many farmers must irrigate in order to produce a good crop. The average annual pan evaporation is 57 inches at Hope, Arkansas, which is about 25 miles from the project area.

The average flow of the Red River at Fulton, Arkansas, is 17,600 cfs (cubic feet per second). The flow duration curves for this stretch of the Red River are shown on figure 3. Figure 4 shows the chloride concentration at various flows. In general the water in the Red River is high in hardness, chlorides and sulfates, and without extensive treatment is unsuited for many uses, including irrigation of some crops according to Ludwig.

According to Ludwig about 80 percent of the total water use in southwest Arkansas is derived from ground water and only one municipality, Texarkana, uses surface water. In 1965, 6.89 mgd (million gallons per day) was used for irrigation, nearly all of which was derived from alluvium in the Red River Valley. Boisier City, which is 57 miles south of the project area in Louisiana, is the closest downstream user of Red River water.

Extent of Ground-Water Pollution in Miller County

In order to obtain information on the natural (unpolluted) chloride content of the water in the alluvial and terrace sands, 25 additional water samples were obtained throughout the county in January 1972. Locations of these water samples and the chloride content are shown on figure 1. These data show that the unpolluted water contains chlorides ranging from 7 to about 50 mg/l.

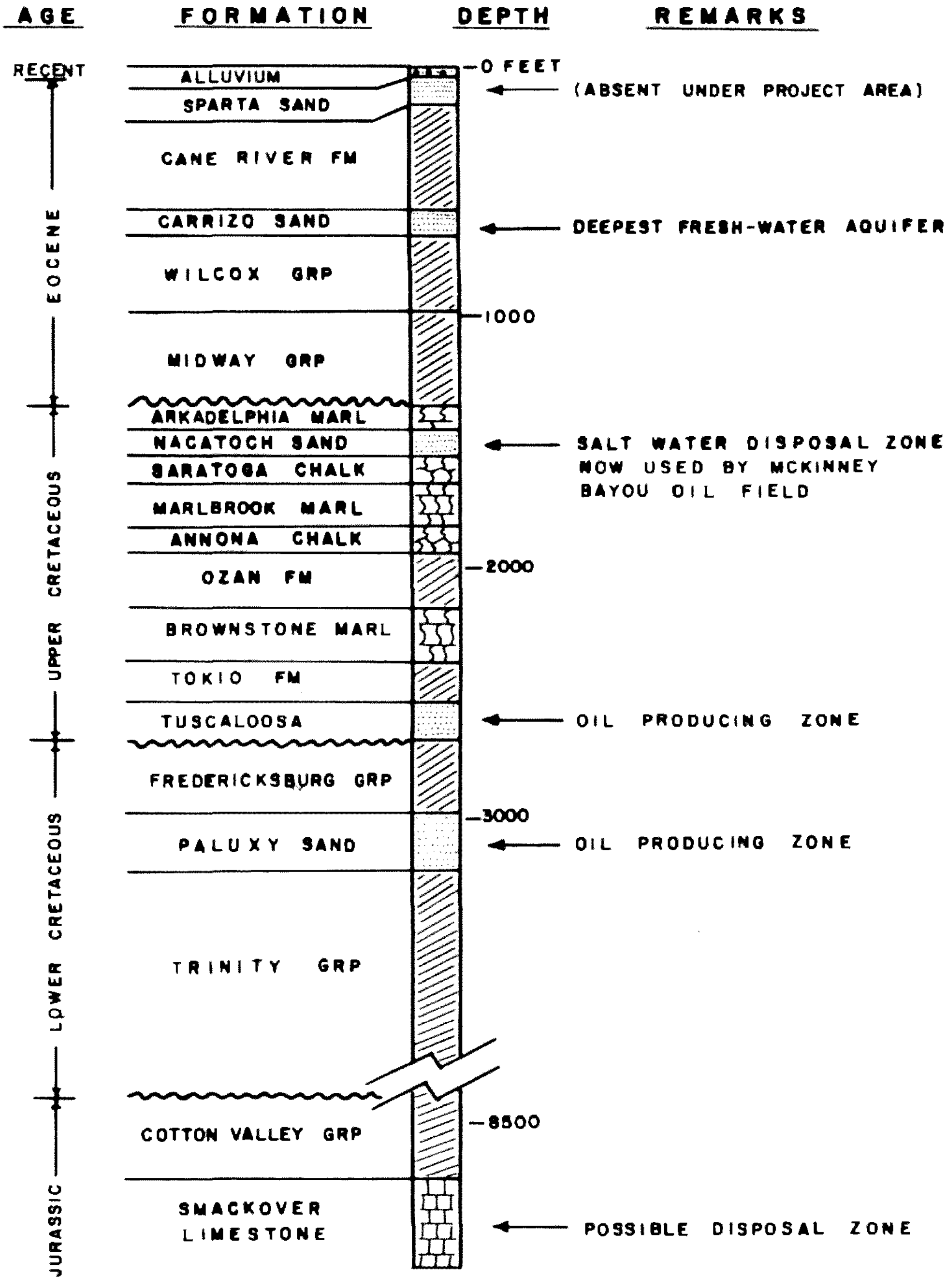


FIGURE 2

GEOLOGIC COLUMN

AT PROJECT AREA

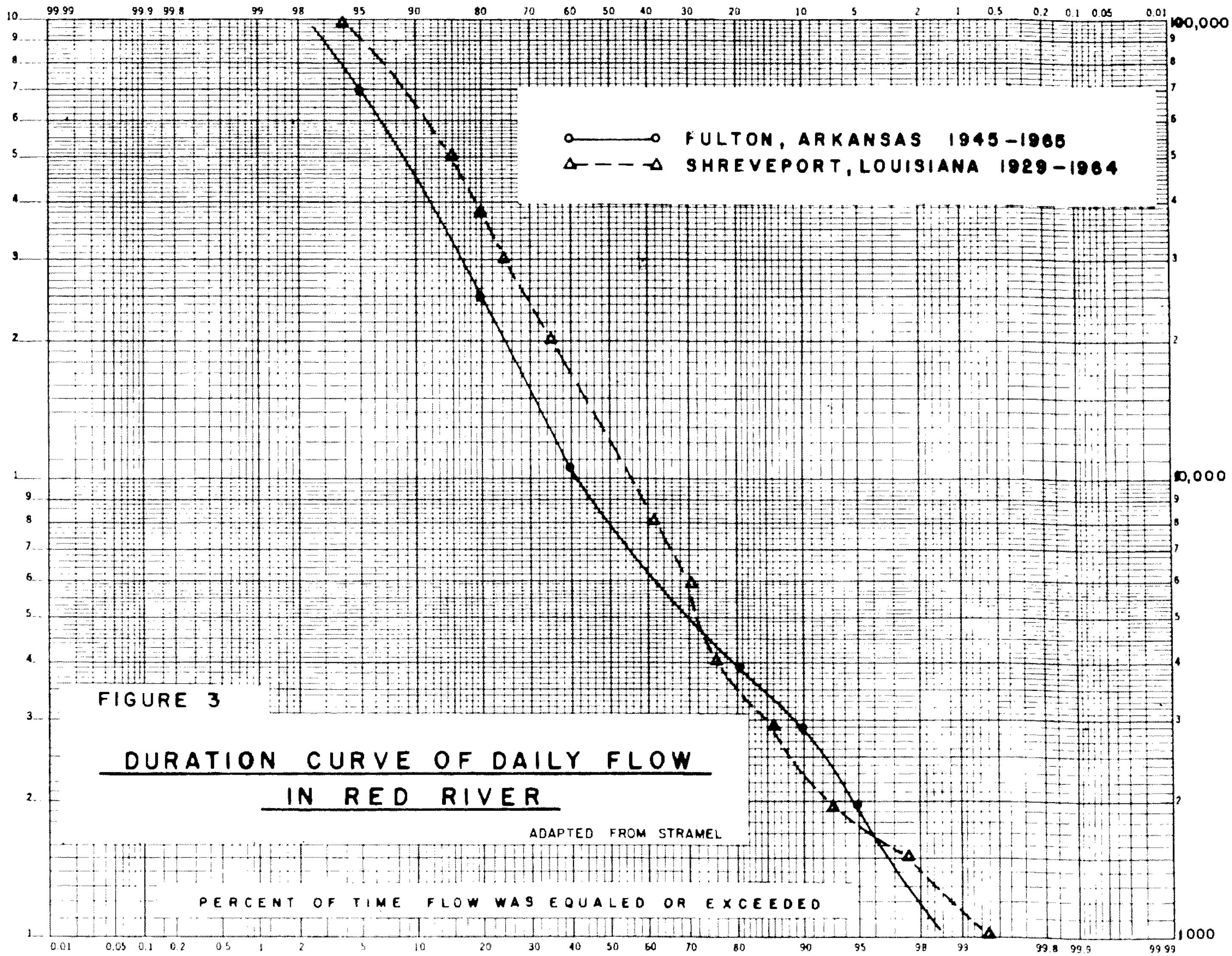


FIGURE 3

DURATION CURVE OF DAILY FLOW IN RED RIVER

ADAPTED FROM STRAMEL

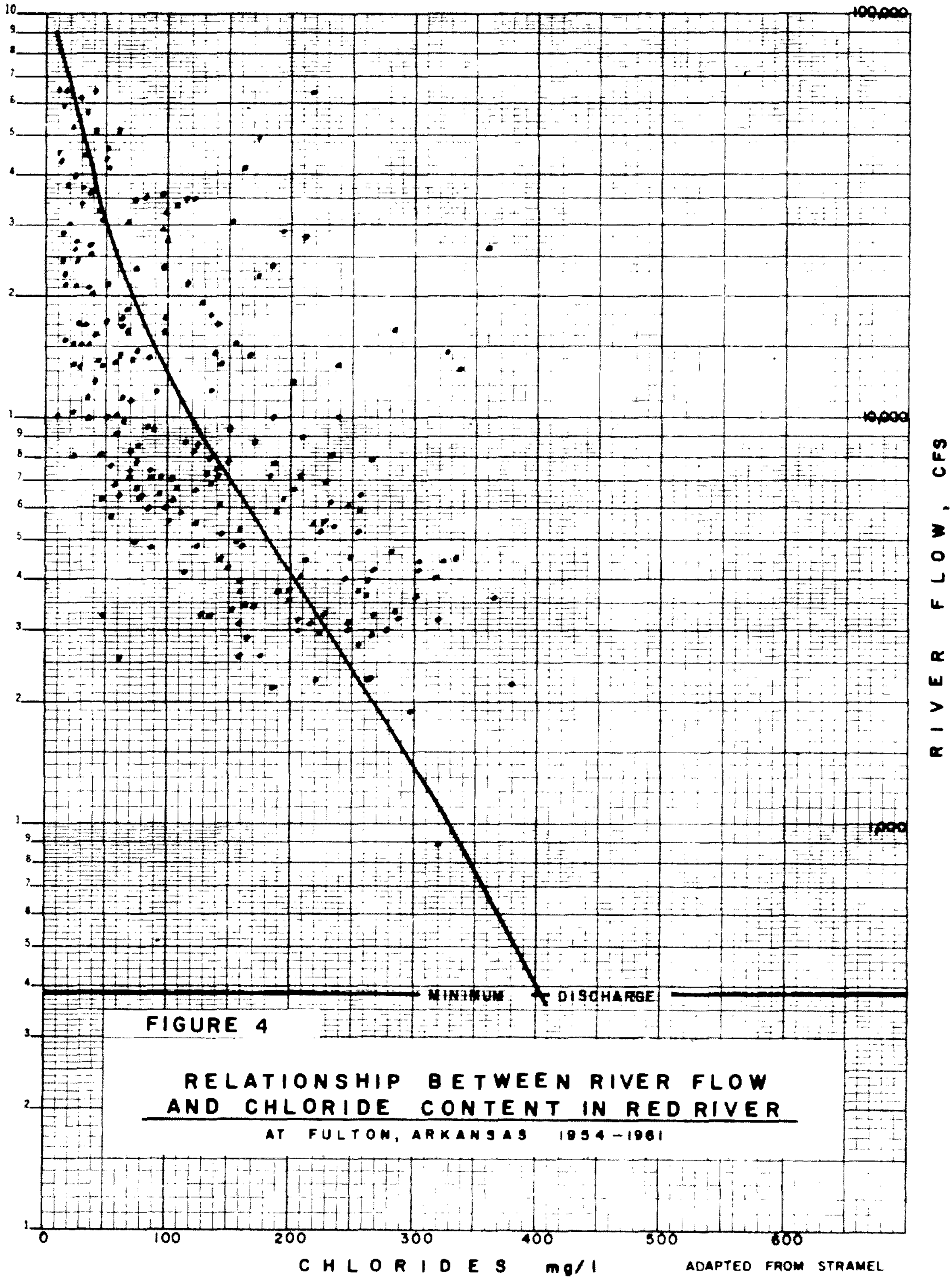


FIGURE 4

RELATIONSHIP BETWEEN RIVER FLOW AND CHLORIDE CONTENT IN RED RIVER

AT FULTON, ARKANSAS 1954-1961

Notable exceptions to the natural chloride concentrations are as follows:

1. Sec 35, T 15S, R 26W; chlorides = 230 mg/l. The source of the chlorides is probably 1 1/2 miles upstream at the Lenz oil field which has been abandoned but reportedly produced considerable salt water which was disposed of through pits.

2. Sec 7, T 16S, R 25W; chlorides = 5,650 mg/l. The chlorides in this sample could be related to pits in either the New Garland City oil field to the west, or the Mayton oil and gas field to the north.

3. Sec 32 and 29, T 16S, R 25W; chlorides = 150 and 160 mg/l. The two irrigation wells from which these samples were obtained were used to irrigate rice. However, after losing one-half of the rice crop in 1971 due to high chlorides, they are now abandoned. The source of the chlorides is probably from old pits in the Cypress Lake oil and gas field, which is located one-half mile to the north. The chloride content was reportedly much higher when the wells were in operation than at the time these samples were taken.

4. Sec 21, T 17S, R 27W; chlorides = 115 mg/l. The moderately high chloride content in this well is probably related to operations in the South Fouke oil and gas field.

5. Sec 1, T 15S, R 27W; chlorides = 116 mg/l. The source of the moderately high chloride content in this well is not apparent.

The samples obtained from wells in sections 30 and 32 in T 16S, R 26W, were expected to be high in chlorides because of their location in the Fouke oil and gas field. However, the reason no pollution was observed may be because of insufficient sampling points or because the operators in this oil field have been more careful with their brine disposal.

In addition to the three brine-polluted areas outlined on figure 1, this general survey using only existing private wells shows that there are at least four other areas in Miller County where the shallow fresh-water aquifers have been polluted by brine-disposal practices of oil-field operations. Further pollution could undoubtedly be delineated by a wide-ranging test drilling and sampling program.

Although the present use of "evaporation" pits is somewhat regulated, the practice is not specifically outlawed in Arkansas. Furthermore, enforcement suffers due to the lack of personnel and the lack of fines or other deterents to violators.

SECTION V

VALUE OF WATER POLLUTED

The ground-water area polluted by the brine is about one square mile. Under the natural ground-water gradient in the alluvium of 1.4 feet per mile (figure 1) and assuming a permeability of 1500 gpd/ft^2, (Ludwig) the natural rate of ground-water movement is about 100 feet per year. The direction of movement is south-southeast and eventually, after flowing about 4 1/2 miles, the salty water will be slowly discharged into the Red River which is the natural discharge avenue for all ground water in the area. At the estimated rate of movement, the salty water will not reach the river for approximately 250 years.

It could be concluded, then, that ground-water occupying at least one square mile (but not necessarily the same square mile) will remain polluted for at least 250 years. It is this author's opinion that because of dispersion, adsorption and vagarious characteristics of the aquifer, the entire 4 1/2 mile-long path of this one-mile wide body of salt water will remain contaminated for a much longer period than 250 years. This view is shared by others (Collins).

The damage that has already taken place because of this particular pollution incident consists of the loss of a high capacity irrigation well valued at $4,000 and the partial loss of one year's rice crop on 120 acres valued at $36,000, for which water from the well was a necessity.

The future monetary loss which will result because of the pollution is of course impossible to evaluate accurately. Nevertheless, the following figures are presented to establish an order-of-magnitude value. All of the estimates conservatively assume that only one square mile of irrigible land is removed from irrigation.

<u>Rice</u> - At $150/acre profit over 640 acres for 250 years = $24,000,000 loss in profit income. (Irrigation is mandatory for rice farming.)

<u>Cotton</u> - At $35/acre difference in profit between irrigated and non-irrigated cotton for 250 years over 640 acres = $5,600,000 loss.

<u>Soybeans</u> - At $20/acre difference in profit between irrigated and non-irrigated soybeans for 250 years over 640 acres = $3,200,000 loss.

Furthermore, _if_ the pollution had affected a municipal water supply and _if_ that town were forced to construct a surface supply to replace the lost ground-water source, then the difference in water cost to the town would be about 20¢/1000 gallons. Assuming that the square mile allowed production of 1 mgd on a sustained yield basis, then the added cost to the town would be $73,000 per year to replace the lost water source, and over 250 years would total $18,250,000.

It is fully recognized that value projections such as in the above examples are not meaningful in any exact sense. Although the real value loss to the national economy resulting from this singular incident is not now significant, ground-water pollution is highly significant considered on the large scale and in time. On the other hand, the real value loss does have present-day significance to the property owners affected. Furthermore, with time the total area affected will probably increase fourfold and the value loss due to non-irrigibility will also increase.

SECTION VI

DELINEATION OF POLLUTION

History of Pollution in Project Area

Since 1955, when the McKinney oil field was discovered, a total of 46 test holes and wells, 15 of which are still producing, have been drilled primarily into the Paluxy sand. Salt water was produced along with the oil starting in 1957 and has increased substantially as the field approaches depletion.

According to records of the Arkansas Oil and Gas Commission the following amounts of salt water have been produced by the field.

Year	Total Barrels Produced	Disposal Method
1957	22,200	Pit
1958	49,700	Pit
1959	78,000	Pit
1960	114,500	Pit
1961 (June)	118,500	Pit
June 1961-1970	3,828,803	Combination pit and disposal well.

Between July 1961 and August 1967 the Parks #1 disposal well adjacent to the pit was in operation; however, the water was stored in the pit before injection into the well. It is considered likely that most of the produced brine seeped through the pit during this period. In August 1967 after the initial study was made of this problem, tanks were provided for storage and the pit was no longer used. All of the water was injected into Parks #1 disposal well under pressure.

During the course of the field work on this project, a hydrograph from observation well #6, about 500 feet from the disposal well, showed a marked relationship between the water level in the alluvial aquifer and the periods of operation of the pump on the disposal well. An investigation of the disposal well showed that the injection pressure was zero, whereas when the well was first put into operation 300 to 400 psi was required to pump the brine into the disposal formation, the Tokio formation.

The overall conclusion was that the casing of the disposal well had indeed corroded through and the brine was escaping into the alluvial aquifer. By December 1970, a new disposal well was completed (Parks #3), and the old well was abandoned and plugged.

It is not possible, based on the available records, to accurately calculate the quantity of brine that seeped or was injected into the alluvial aquifer. However, this quantity of brine is estimated to be about 2,700,000 bbls based on the amount of salt in the aquifer. Using this figure as the amount of brine soaked or injected into the aquifer, and knowing the approximate quantity that soaked through the "evaporation" pit, it may be estimated that the disposal well had been injecting into the alluvium at highly reduced pressures for approximately 1 1/2 years before detection.

If this disposal well had been constructed using injection tubing and a fluid-filled annulus the chances for pollution through corroded casing would have been greatly minimized, and detection would have been much easier. However, this safeguard is not required by Arkansas.

Test Drilling and Sampling

The nature and extent of the pollution in the project area has been determined by the construction of 36 permanent test wells at 28 locations most of which were drilled during 1969-70. The locations of the test wells are shown on figure 5.

The following procedures were used in the construction and sampling of these test wells.

1. A 3-inch hole was augured through the 9 to 15 feet of surface soils and clay.

2. A 2 1/2-inch pipe was driven through the sand to the shale at the bottom of the aquifer. Driving was stopped at various depths, and samples of the water were obtained as this pipe was installed.

3. The permanent 2-inch diameter, 2 1/2-foot long plastic well screen was installed to the desired depth inside the 2 1/2 inch pipe, and the pipe was pulled back to expose the screen.

4. At all locations the primary well point was set just above the shale. At some locations additional well points were installed in adjacent holes to provide permanent sampling wells at higher elevations.

5. Initial and subsequent water samples have been obtained by pumping each test well using a vacuum pump for 5 to 10 minutes in order to obtain representative formation water samples.

Table 1 shows the elevation and depth of the well points for each location and lists the chloride content and temperature for all the samples that have been obtained from each test well, including those samples that were taken during construction and subsequent samples.

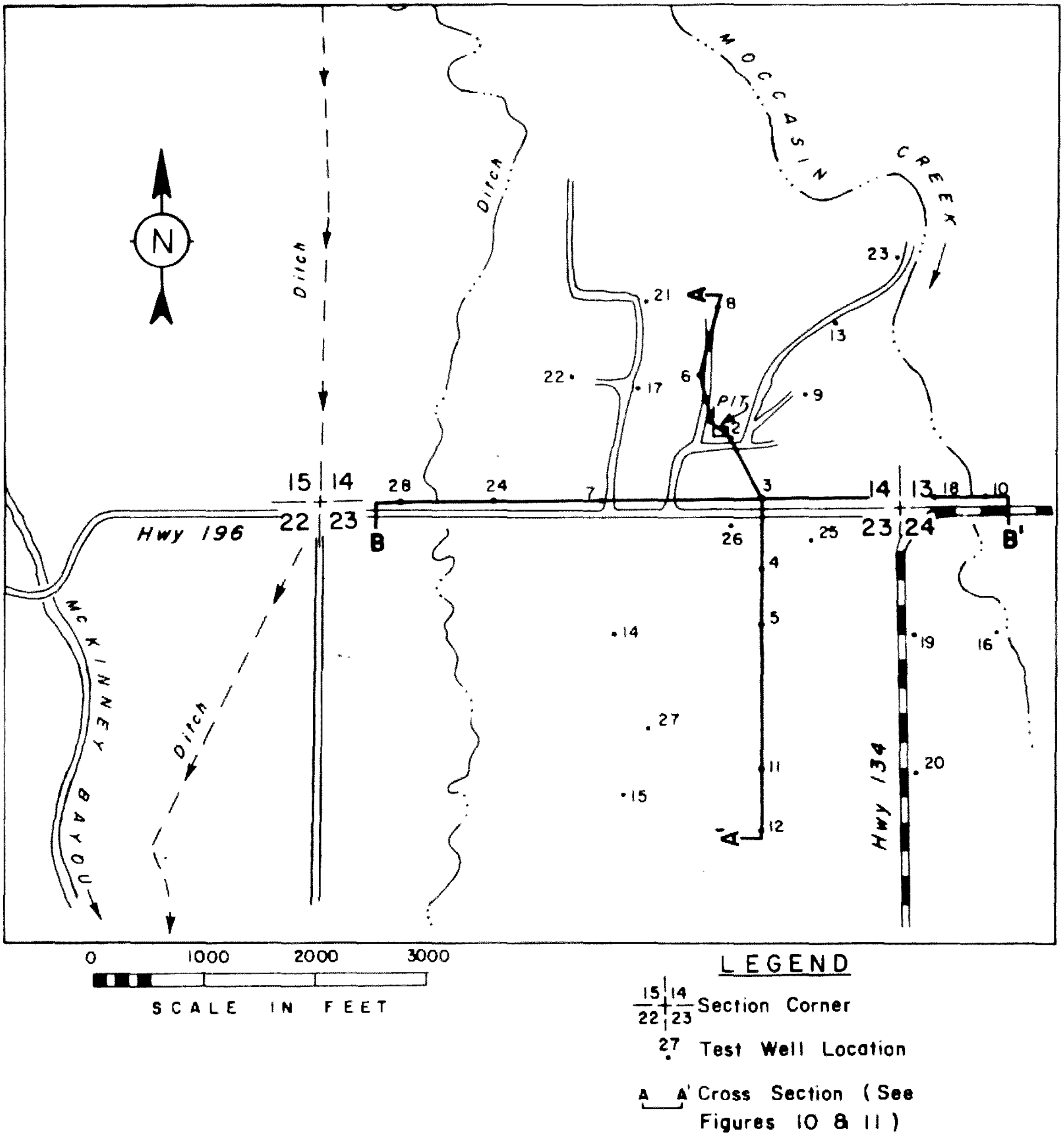


FIGURE 5

LOCATIONS OF TEST WELLS AND SECTIONS

TABLE 1

CHLORIDE CONTENT AND TEMPERATURE
OF SAMPLES FROM TEST WELLS

Well No.	Elev. Sample	Depth	11/69-4/70 mg/l	°F	12/70 mg/l	2/71 mg/l	°F	8/71 mg/l	°F	1/72 mg/l	°F
1	206	16	1,060								
	191	32	45,000								
	185	38	47,000	92	59,000	51,500	84	48,800	84	45,000	
1a	202	24			17,500	2,150	83	980	79	950	
2	192	30	49,500								
	186	36	56,500	98	55,000	49,500	92	47,800	84	48,000	
2a	205	20			27,500	13,500	90	12,470	80	11,000	
3	208	14	300								
	196	26	4,700								
	187	35	47,500								
	182	40	48,000	65	55,000	50,500	65	45,520	66	47,500	
3a	198	26			10,000	8,000	65	4,840	66	3,900	
3b	206	17			285	280	64	249	66	240	
4	207	15	160								
	192	30	13,500								
	178	44	47,500	65	54,000	47,000		44,000	66	49,000	
5	192	30	13,500								
	182	40	39,000		49,000	45,000		40,200	65	44,000	
5a	197	27			7,000	4,000	65	2,450	65	2,600	
6	213	10	680								
	193	30	45,500								
	185	38	46,500	68	55,000	48,000	68	45,560	67	45,000	64
7	212	10	1,000								
	192	30	1,200								
	187	35	12,700	66	17,500	14,500	66	15,940	66	13,000	66
7a	201	22			750	600	64	525	66	600	66
8	194	30	600								
	189	35	625	65	1,150	1,050		790	68	800	64
9	193	30	19,500								
	188	35	39,500	64	41,000	36,000		28,440	65	25,500	65
10	206	15	1,300								
	191	30	800								
	179	42	575		800	600	65	520	66	550	65
11	207	15	300								
	195	27	250								
	181	41	3,775	66	7,470	9,500	64	10,210	66	13,500	
12	191	30	500								
	183	38	525	66	800	400	64	535	65	690	
13	194	30	475								
	184	40	29,000	64	38,000	33,000	66	29,360	65	28,500	65
14	212	9	2,225								
	192	30	2,700								
	188	34	14,100		23,000	22,500	64	22,500	65	24,000	

(Continued)

TABLE 1 (Continued)

CHLORIDE CONTENT AND TEMPERATURE
OF SAMPLES FROM TEST WELLS

Well No.	Elev. Sample	Depth	11/69-4/70 mg/l	°F	12/70 mg/l	2/71 mg/l	°F	8/71 mg/l	°F	1/72 mg/l	°F
15	192	30	650								
	187	35	610	64	825	1,050	64	922	65	1,200	
16	190	30	235								
	178	42	260	65		1,000	64	327	65	300	65
17	195	30	18,500								
	185	40	50,000	65	47,000	45,500	64	42,000	65	43,500	65
17a	203	20			1,000	700	64	680	66	530	66
18	206	15	1,830								
	191	30	490								
	183	38	3,850	66	4,300	4,000		1,930	66	3,000	65
18a	203	20			550	440		416	66	450	65
19	192	30	1,175								
	182	40	8,550		10,400	11,500	65	1,900	66	12,000	65
20	209	12	745								
	191	30	415								
	181	40	375	66		1,695	65	2,543	65	3,700	
21	193	30	600								
	188	35	500	65	590	530	66	494	66	550	
22	212	10	4,000								
	192	30	500								
	189	33	500		570	505	66	478	64	480	65
23	196	30	4,500								
	186	40	1,500		450	405		366	65	385	65
24	193	30	2,050								
	183	40	2,750		2,750	4,000		2,110	66	2,050	66
25	183	42			53,000	47,000	65	42,320	66	45,000	
26	184	39			57,000	49,500	67	45,120	67	47,500	
27	194	28			1,280						
	189	33			9,800	11,500		11,380	64	12,500	
28	199	25			3,250						
	191	33			5,350	5,500	68	5,300	66	4,600	66

Physical Delineation

Figure 6 shows the chloride concentrations at the bottom of the alluvium as determined by samples taken from those test wells positioned just above the clay. From this plan view of the polluted area it is notable that the salty water has spread generally southward in the direction of ground-water flow. The irregular shape of the polluted zone may be attributed to variations in permeability within the aquifer and to irregularities in the top surface of the shale.

Figure 7 shows the contours on top of the shale based on the test-well construction data. It should be noted that a shallow valley extends to the northeast and southwest just north of the disposal pit. The orientation of this valley corresponds generally with the northeast-southwest orientation of the polluted water observed on figure 6. Because the salt water is heavier than the fresh water, it settles to the bottom of the aquifer; hence, its movement is somewhat controlled by the topography of the underlying shale.

Table 2 lists all of the water-table elevations as measured in the test wells throughout the monitoring period.

Figure 8 shows the contours on the water surface as determined by water-level measurements made on June 22, 1970, when the faulty salt-water disposal well was still in use. A water-level mound is evident surrounding the disposal well which was located adjacent to the pit. Also notable from this figure is the water-surface depression south of the disposal well.

In January 1972, water levels were again measured resulting in the contours shown on figure 9. The mound is absent indicating that disposal into the aquifer has been stopped. However, the water-surface depression south of the pit is even more pronounced than in figure 8. This depression is caused by the difference in density between the salt water and the fresh water.

The density of the brine was determined to be 1.057 g/ml. Assuming the density of the fresh water to be 1 g/ml, the following may be calculated based on data at TW 4.

$h_s = \frac{h_f}{D_s}$ where h_s = theoretical height of salt water

h_f = height of fresh water = 32 feet (Figure 10)

D_s = density of salt water = 1.057 g/ml

$$h_s = \frac{32 \text{ feet}}{1.057} = 30.3 \text{ feet}$$

Then the theoretical difference in height of the salt water and fresh water is 32 - 30.3 = 1.7 feet.

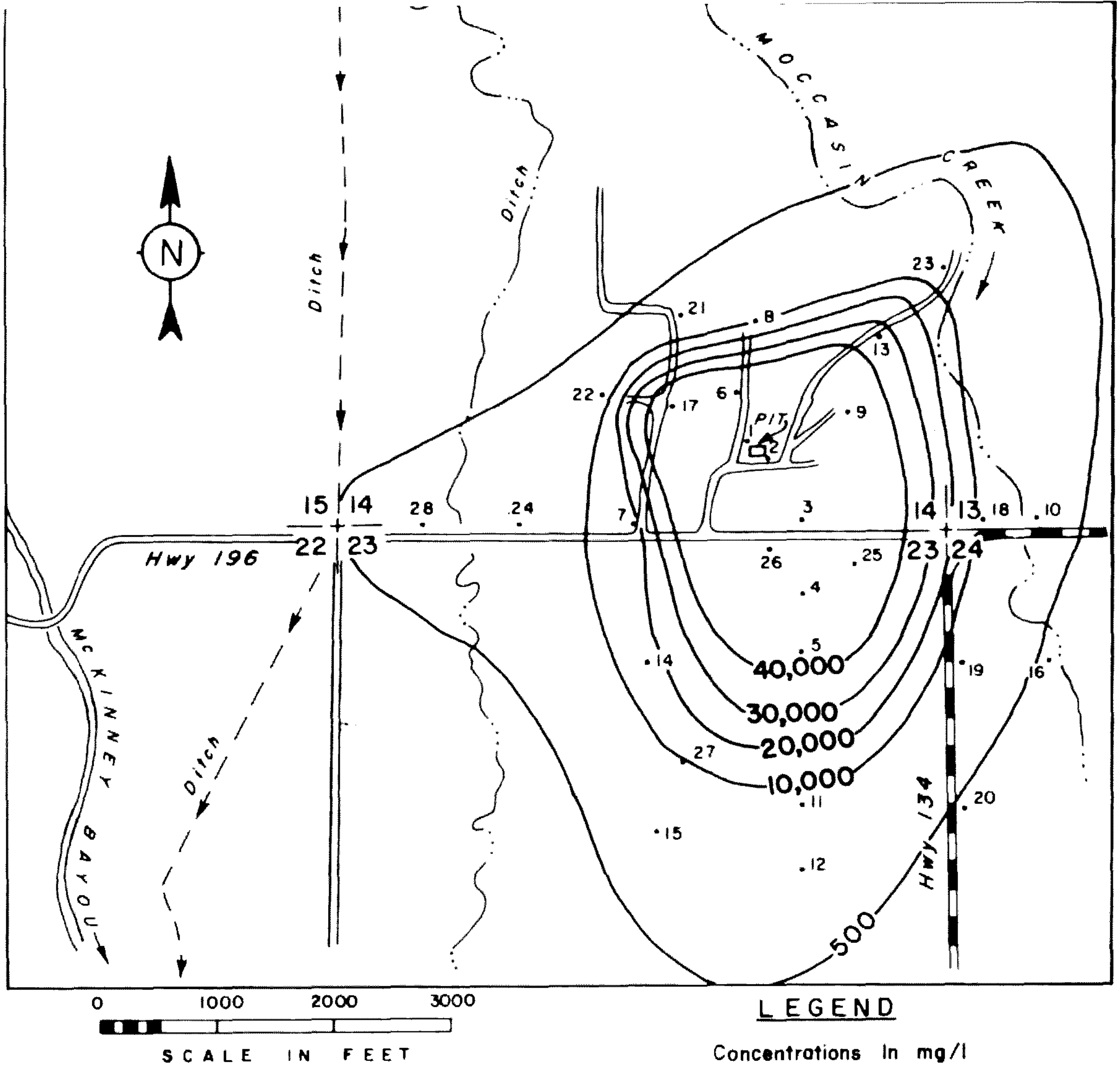


FIGURE 6

CONTOURS OF CHLORIDE CONCENTRATION AT BOTTOM OF ALLUVIUM

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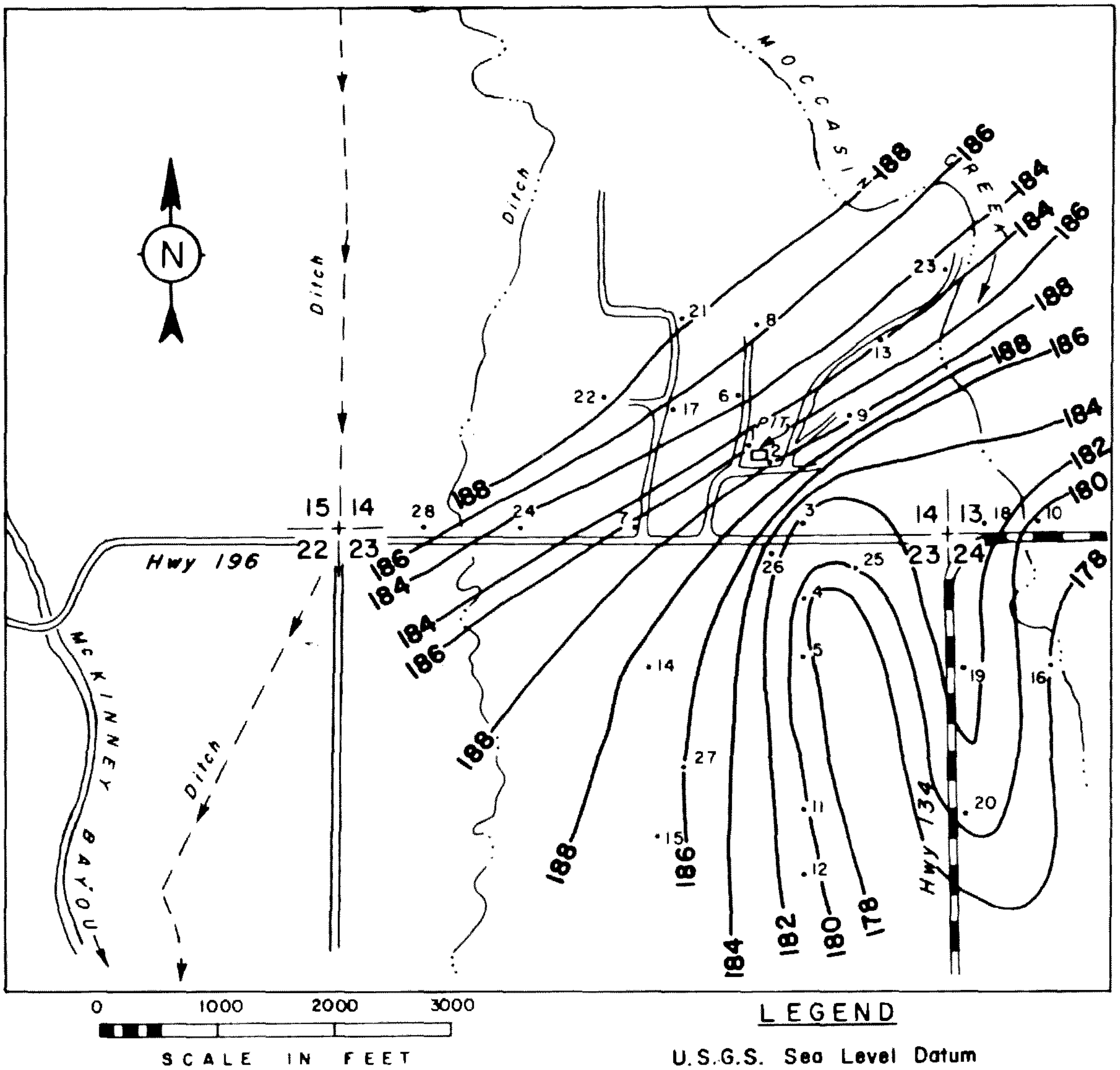


FIGURE 7

CONTOURS ON TOP OF SHALE

(BOTTOM OF ALLUVIAL AQUIFER)

ADAPTED FROM STRAMEL

TABLE 2

SUMMARY OF WATER LEVEL ELEVATIONS

E L E V A T I O N S
(In Feet Above Mean Sea Level)

Test Well	4/22/70	12/70	2/71	8/71	1/72
1	214.23	211.70	212.26	211.68	212.05
2	215.35	211.63	212.13	212.23	212.01
3	213.47	211.26	211.71	212.01	211.56
4	213.29	211.18	211.63	211.75	211.35
5	213.17	211.20	211.54	211.61	211.36
6	213.89	211.90	212.18	212.61	212.15
7	214.44	211.08	212.65	212.74	212.97
8	214.96	212.82	213.28	213.43	213.39
9	213.90	211.96	212.45	212.84	213.04
10	214.58	212.61	213.05	213.08	212.94
11	213.76	211.81	212.22	212.19	211.96
12	213.72	211.63	212.31	212.26	212.08
13	214.20	212.37	212.66	212.90	212.88
14	214.02	211.70	212.15	212.11	212.54
15	213.74	211.48	212.15	212.28	212.22
16	214.16	212.13	212.65	212.46	212.75
17	213.56	211.43	211.95	212.11	212.09
18	214.36	212.33	212.81	213.22	212.91
19	213.92	211.94	212.40	212.49	212.45
20	213.87	211.82	212.42	213.35	212.25
21	214.89	212.83	213.32	213.49	213.47
22	214.79	212.47	213.00	213.10	213.78
23	215.27	213.28	213.69	213.78	213.90
24		211.94	312.56	212.47	213.20
25		212.27	211.74	211.77	211.53
26		210.75	211.27	211.31	211.35
27		212.17	212.28	211.23	212.22
28		211.88	212.49	212.50	213.14

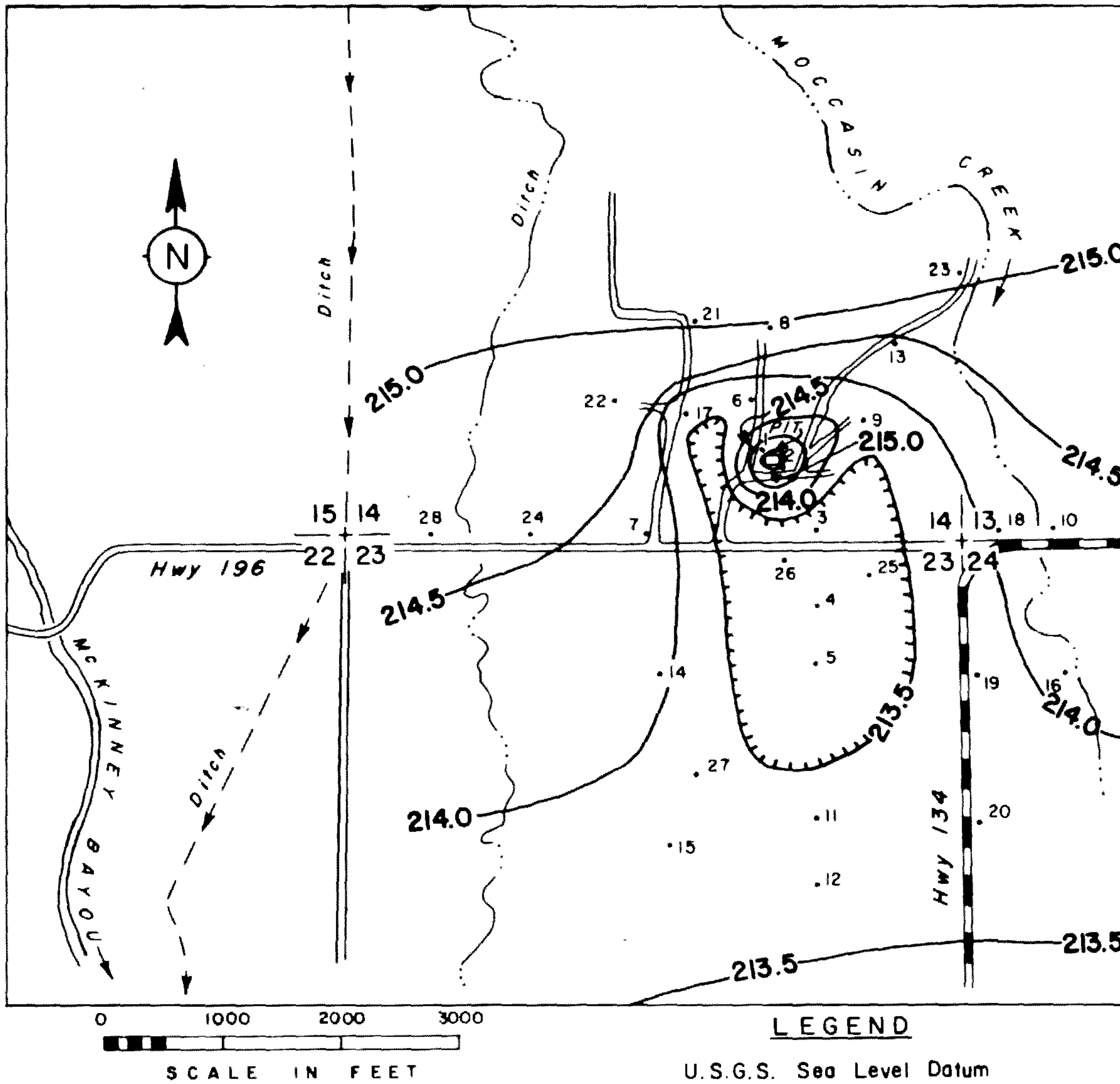


FIGURE 8

WATER LEVEL CONTOURS

JUNE 22, 1970

ADAPTED FROM STRAMEL

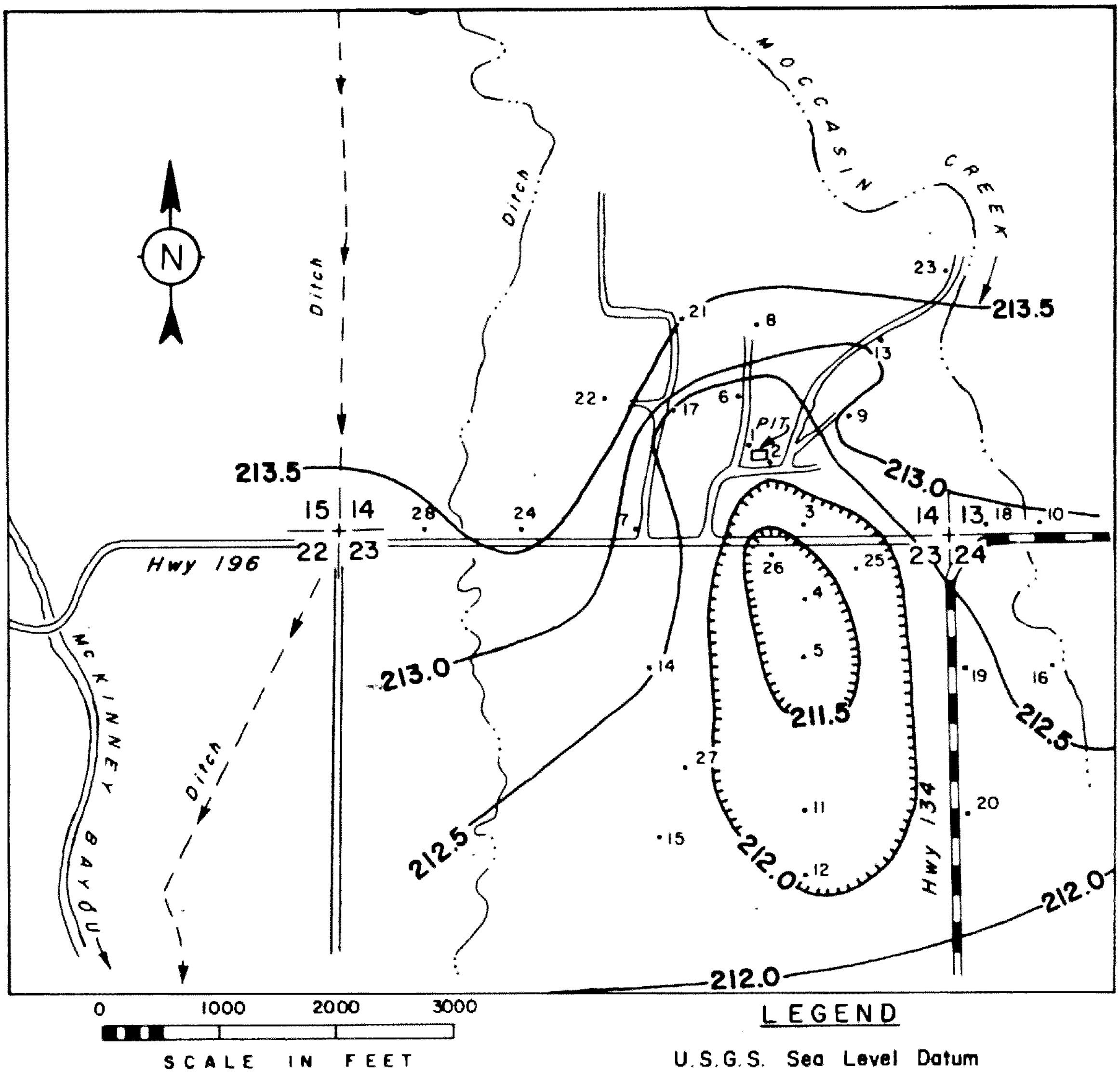


FIGURE 9

WATER LEVEL CONTOURS

JANUARY 12 - 13, 1972

The actual difference in water-surface elevations is 213 - 211.5 = 1.5 feet as determined by the measured water-level elevation in TW 4 and the extrapolated 213-foot water-surface contour line shown on figure 9. This close agreement between the calculated and observed water levels indicates that the depression in the water surface south of the pit is caused by the density difference.

The distortion of the water-level contours around the body of salt water, as evident in figure 9 one year after injection into the aquifer was stopped, may be attributed to the slightly higher viscosity and higher density of the polluted water which condition would tend to make the polluted water flow more slowly than the fresh water.

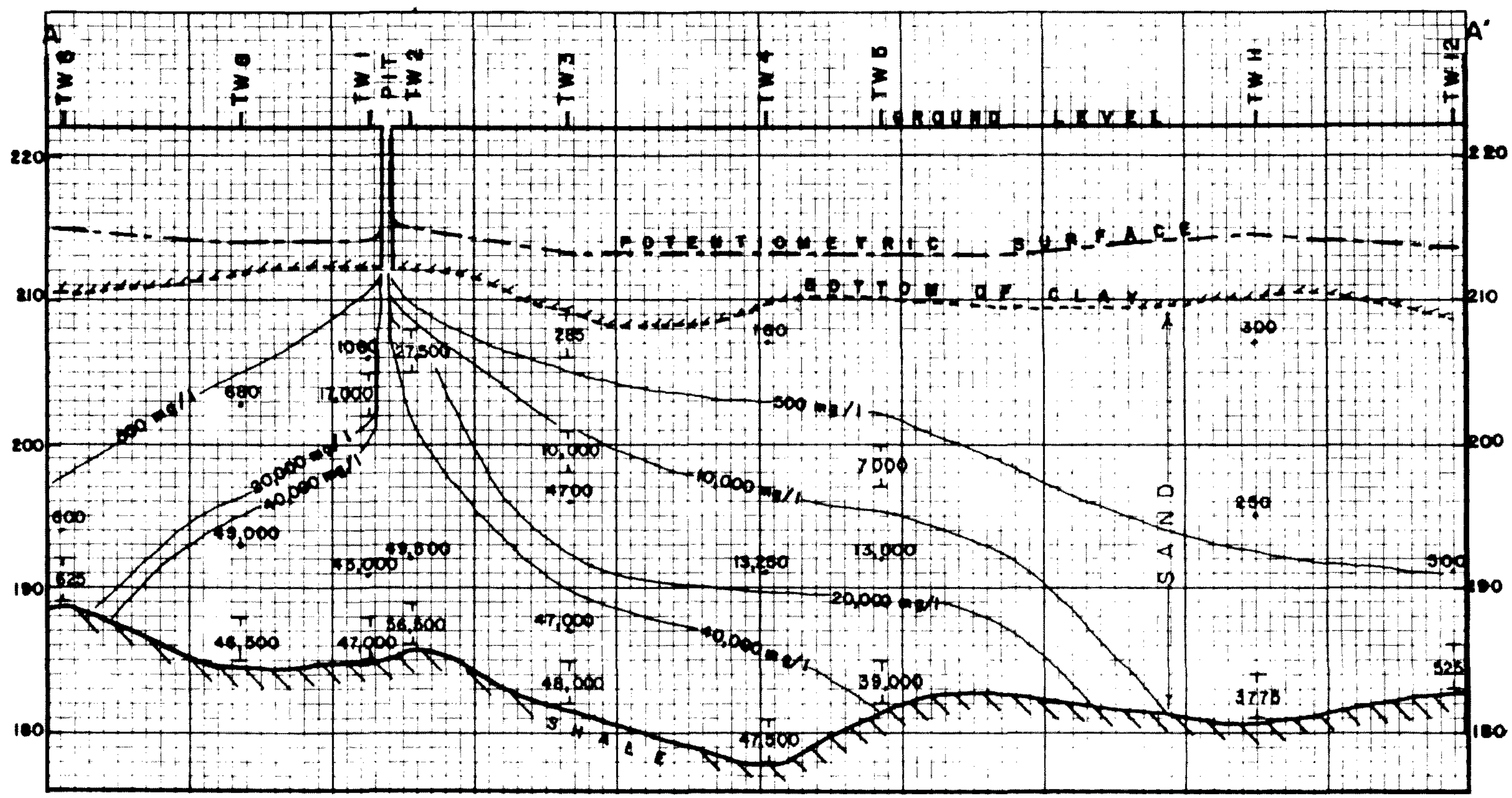
Figure 10 is a north-south cross section through the pit and disposal well showing the vertical distribution of salty water along the section. (See figure 5 for location of sections.) It should be noted from this figure that the source of brine appears to be very high in the alluvium even though the pit was not in use at the time the data were taken. Apparently the break in the casing of the faulty disposal well, which was then in use, was in the top half of the sandy part of the alluvium. Also note that the salt water sinks rapidly and flows along the bottom part of the aquifer.

Figure 11 is an east-west cross section located 600 feet south of the pit and disposal well. The concentrated brine continues to sink and is spreading laterally as shown by this section.

Two rather anomalous conditions are also evident from figure 11 The high chlorides near the top of the sandy part of the alluvium at the east end of the section probably result from brine having been dumped into Moccasin Creek and seeping into the ground. The other anomaly is that the chlorides in TW 28 (west end) are higher than in TW 24 even though TW 24 shows a topographic low in the shale. There is an abandoned oil well in the NE corner of section 22 about 1,500 feet from TW 28. It is possible that this old well is purging salt water into the alluvium thereby causing the apparent anomaly. However, it may also be explained by differences in permeability. A highly permeable sand streak at TW 28 could result in more of the brine flowing past that test well than would flow past TW 24. Another possible explanation is that the drainage ditch west of TW 28 had also been used for salt-water disposal, and residual salt is still leaching downward into the aquifer.

Chemical Delineation

All of the chloride determinations that have been made on samples taken at different times are listed on table 1. A partial record of temperatures is also shown on that table.



000 CHLORIDES IN mg/l 11/69 – 4/70

• SAMPLE TAKEN DURING DRILLING

┬ PERMANENT SAMPLING POINT
┴

SCALES

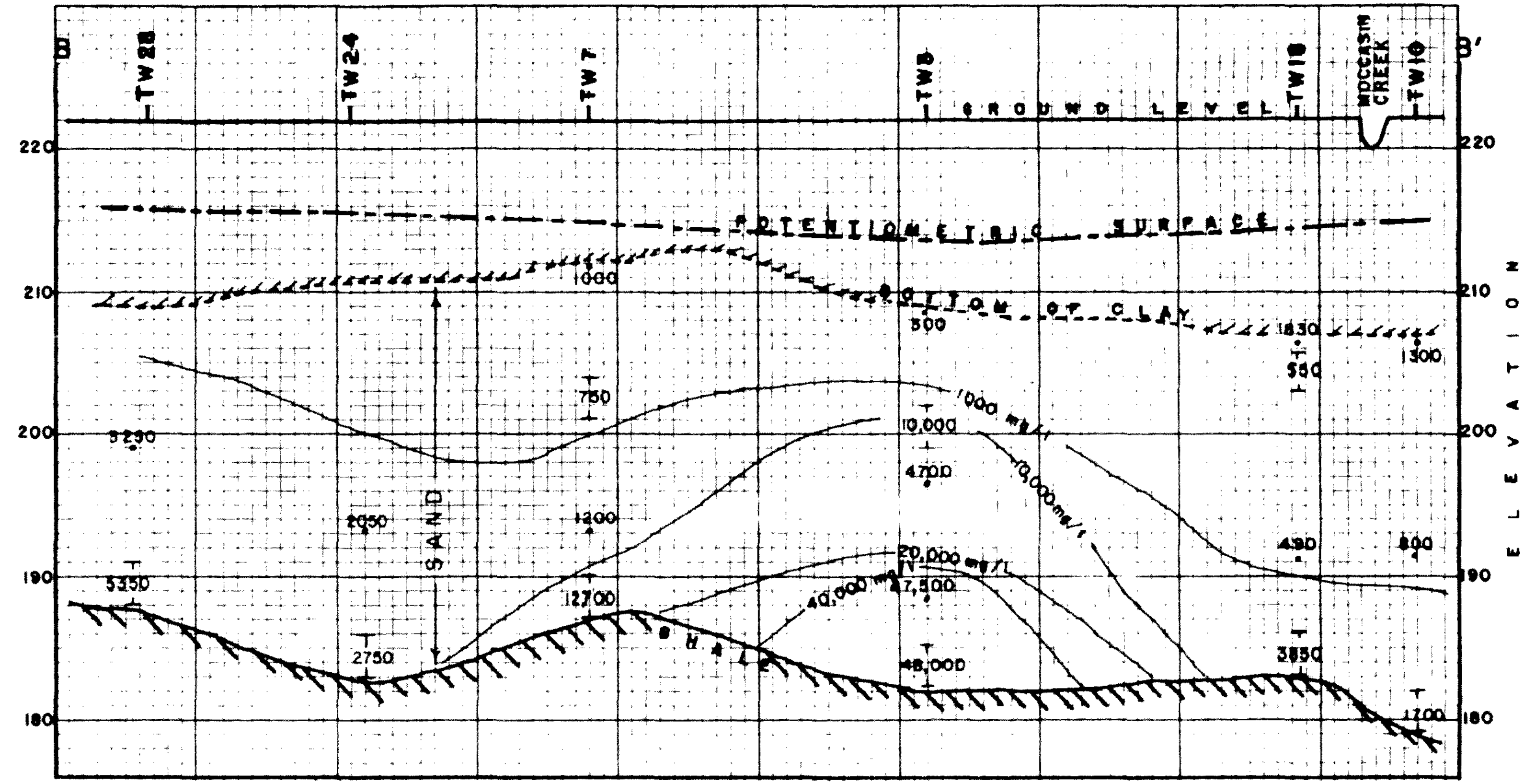
HORIZONTAL: 1" = 500'

VERTICAL : 1" = 10'

FIGURE 10

← NORTH – SOUTH →

SECTION SHOWING BRINE DISTRIBUTION



000 CHLORIDES IN mg/l 11/69 — 4/70

• SAMPLE TAKEN DURING DRILLING

┬ PERMANENT SAMPLING POINT

┴

SCALES

HORIZONTAL: 1" = 600'

VERTICAL : 1" = 10'

FIGURE II

← WEST — EAST →

SECTION SHOWING BRINE DISTRIBUTION

It may be noted that the highest temperature, 98°F, was recorded in November 1969 on a sample taken from TW 2 just south of the pit and near the faulty disposal well. The most recent available temperature from the same test well shows that the temperature has dropped to 84°F. In general the temperature of the warm injected brine appears to be absorbed by the sand and fresh water rather rapidly away from the injection point. However, once the sand is warmed, the temperature dissipates slowly with time.

In January 1972 samples were obtained of the brine, from key test wells progressively farther from the brine source, and from an uncontaminated private well, located 1 1/2 miles east of the project (see figure 1). Relatively complete analyses were performed on these samples to determine the changes in chemical characteristics of the brine as it flows through the alluvium and is mixed with the fresh water. The results of these analyses are shown on table 3.

In order to better visualize the chemical changes as the brine becomes progressively diluted, comparative graphs were prepared of key constituents. The graphs are shown on figure 12.

The chloride graph on figure 12 may be taken as the standard, considering that chlorides should not precipitate nor the concentration otherwise change except in direct ratio with the degree of dilution. Inspection of the graphs for dissolved solids and calcium show that these constituents are diluted in the same general ratio as chlorides. The dilution of several other constituents such as bromide, flouride, lead, strontium, manganese, nickel, and aluminum, although not exactly proportional to chlorides, may not be related to extraneous factors considering the accuracy of quantitative analysis at low concentrations.

The pronounced decrease in barium may be explained by its precipitation as barium sulfate, noting the presence of sulfate in the native ground water but the absence of sulfate close to the injection point. Strontium also appears to have been precipitated, probably as a sulfate, as the brine mixed with the native water. Both strontium and barium are more soluble in brines than in fresh water (Davis and Collins) which also may explain their abrupt decrease in concentration. Although boron shows a similar concentration decrease, its precipitation would not be anticipated, and the reason for its similar pattern is not known.

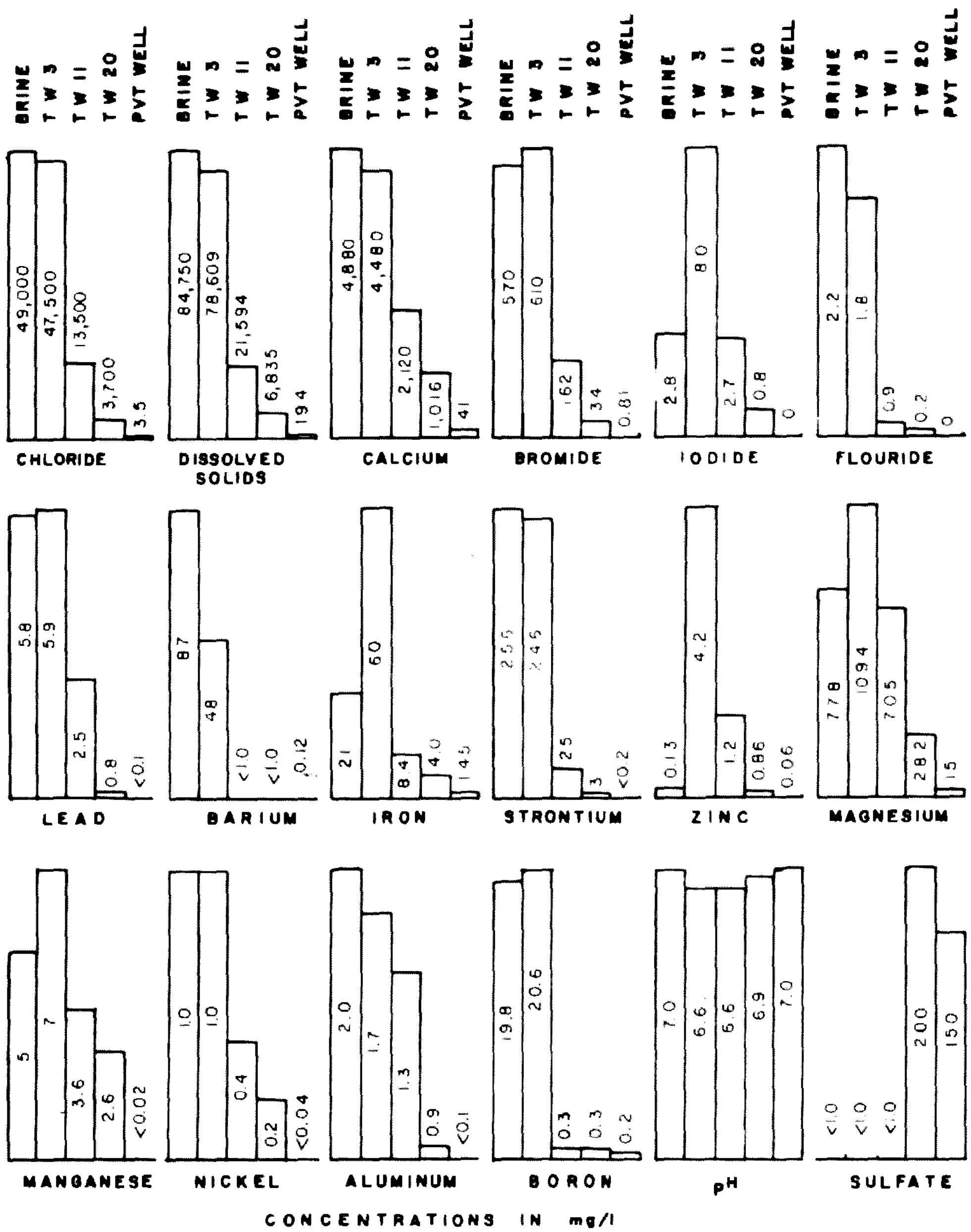
Other constituents such as iodide, iron and zinc are noteworthy in that the concentrations of these elements at TW 3 are significantly higher than in the brine. Three explanations may be offered to explain these anomalous concentrations. (1) These elements may combine with anions that adhere loosely to the sand grains and do not move far from the point of

TABLE 3

CHEMICAL ANALYSES OF SAMPLES
FROM SELECTED SOURCES

Samples Taken 1/12 - 13/72
Concentrations in mg/l unless otherwise indicated

	Brine	Well #2	Well #3	Well #11	Well #20	Private Well
Distance from Pit	0	20 ft	650 ft	3000 ft	36000 ft	12,000 ft
Relationship to Flow		← Directly in line →			Offset	Offset
(Arkansas Pollution Control Lab)						
Spec Cond mmhos	111,000	111,000	111,000	33,300	12,200	333
Chlorides	49,000	48,000	47,500	13,500	3,700	3.5
pH	7.0	6.5	6.6	6.6	6.9	7.0
Sulphates	1	1	1	200	150	1
Nitrate NO_3	← Chloride Interference →					1.7
Total Solids	84,770	79,728	80,313	21,784	6,877	207
Diss Solids	84,750	78,622	78,609	21,594	6,853	194
Susp Solids	20	1,106	1,703	190	24	13
Total Hardness	15,400	14,800	15,700	8,200	3,700	162
Ca Hardness	12,200	11,100	11,200	5,300	2,540	102
Calcium	4,880	4,440	4,480	2,120	1,016	41
Magnesium	778	889	1,094	705	282	15
Methyl Orange Alk	110	71	103	328	383	120
Bromide	570	560	610	162	34	0.81
(USGS Lab Ark)						
Iodide	2.8	7.4	8.0	2.7	.8	.0
Flouride	2.2	2.2	1.8	0.9	0.2	0.0
Potassium	160	140	150	20	8.7	0.8
Phenols	00	-	-	-	-	-
(EPA Lab Ada)						
Iron	21.0	58.0	60.0	8.4	4.0	1.45
Barium	87.0	76.0	48.0	1.0	1.0	0.12
Strontium	256	248	246	25	3	0.02
Zinc	0.13	8.4	4.2	1.2	0.86	0.06
Lead	5.8	5.8	5.9	2.5	0.8	0.1
Manganese	5.0	6.0	7.0	3.6	2.6	0.02
Nickel	1.0	1.1	1.0	0.4	0.2	0.04
Aluminum	2.0	1.5	1.7	1.3	0.90	0.10
Boron	19.8	20.4	20.6	0.3	0.3	0.2



SAMPLE SOURCE	BRINE	TW 3	TW 11	TW 20	PVT WELL
DISTANCE FROM PIT	0	650'	3,000'	3,800'	12,000'
RELATIONSHIP TO FLOW	—	IN LINE	IN LINE	OFF SET	OFF SET

FIGURE 12

RELATIONSHIPS BETWEEN DISTANCE FROM PIT AND CONCENTRATIONS OF SELECTED CHEMICAL PARAMETERS injection. This explanation applies particularly to iodide which may be adsorbed by the sand. (2) The injected brine may have contained higher concentrations of these elements in the past than it now contains. Although no chemical records are available, all of the brine has been derived from the same general formations now producing; therefore, this explanation is considered unlikely. (3) It should be noted that the pH decreases significantly then increases again with greater distance from the pit. The lower pH may dissolve iron coating the sand grains in the alluvium resulting in the increased iron concentrations. Carbonates in the alluvium would also be dissolved by the lower pH which would explain the observed increase in alkalinity (table 3) and the subsequent increase in pH. As the pH increases again toward the outer fringes of the brine, the dissolved iron reprecipitates. The initial decrease in pH is not explained, but it may be related to complex changes in the bicarbonate-carbon dioxide balance in the native water and the sodium-calcium ratio in the injected brine. The samples were not analyzed in the field; hence, the pH as determined in the laboratory may not accurately reflect the field conditions. These complex relationships may help explain the iron concentration pattern, but it is difficult to include the similar zinc pattern under this explanation because zinc would probably not be found as a coating on the sand grains as would iron. The adsorption theory may better explain the zinc concentrations.

It may be concluded from the comparative dilution of these chemical parameters that few elements remain in solution in the exact ratio of the chlorides and that considerable care must be exercised in using ratios as a "finger printing" tool for identifying brine sources. It is apparent that considerably more research is needed in this area of geochemical reactions of brines polluting fresh-water aquifers.

SECTION VII

REHABILITATION METHODS

General

In reviewing possible rehabilitation methods, it is necessary to consider the degree of rehabilitation desired. For instance, it would be possible to contain the water in place thereby preventing the future contamination of an additional 3 1/2 square miles of aquifer. On the other hand, by physically removing the contaminated water, all of the aquifer could be restored to beneficial use.

Another consideration affecting the selection of the rehabilitation method is the present and most probable future use of the water and the attendant quality requirements. The water could be used for some purposes, such as washing sand and gravel, as is; and, even though the tail water would require a disposal system, the income from such a beneficial use could partially offset the cost of disposal. Another example is treatment or blending of the water for irrigation use which would be less critical, hence less costly, than treatment for domestic use. Of all the possible treatment methods and degrees of rehabilitation, only those that could possibly apply to this project are discussed in this report.

Rehabilitation methods are herein grouped under four general headings which are: (1) containment, (2) accelerated discharge, (3) use, and (4) deep-well disposal. Under each of these general categories both the technical feasibility and economics are discussed for each of the methods which could apply to this project. Emphasis is placed on discussion of those methods that initially appeared most feasible even though most of these methods are necessarily discarded for one reason or another.

Containment

Bentonite Wall: Rather than allowing the salty water to spread and move downstream thereby polluting over four times the area now affected, it would be possible to contain it by constructing an impermeable underground wall across the east, west and downstream (south) sides. Such a bentonite cut-off wall would cost on the order of $7,000,000 as estimated in the Phase I report.

Accelerated Discharge

If the polluted water is allowed to remain, it will not only move downstream and contaminate an additional 3 1/2 square miles of ground-water for an estimated 250 years but will also eventually discharge into the Red River under natural ground-water flow conditions. The objectives of an accelerated discharge rehabilitation system would be: (1) to limit the time period that the pollution is present, and (2) to limit the area affected. Any method of getting the polluted water into the Red River faster than will occur under natural conditions could be considered accelerated discharge. One such method is to force the polluted ground water to the river underground, and another method is to pump the water to the river above ground. Both of these methods are herein discussed but with emphasis on above ground discharge.

Water Drive: This method would employ recharge wells positioned west of the polluted zone through which imported fresh water would be pumped. This "water drive" would cause the polluted water to move eastward through the aquifer and discharge into the Red River in much less time than will be required under the natural ground-water flow rate. The result would be faster removal of the polluted water, and pollution under less area than will occur under natural conditions. Of course the quality of water in the Red River would deteriorate somewhat as the salty ground-water flows into it. Cost of such a system was estimated to be $1,264,000 in the Phase I report.

Pumping to Red River: A system whereby the polluting brine would be pumped from the aquifer and discharged into the Red River is discussed in detail in the Phase I report. Although it was recognized that discharging a pollutant into a surface stream is against established policy, it was argued that the discharge would be regulated so that the chloride content of the Red River would never be increased by more than 10 mg/l - an insignificant amount to pay considering the benefit derived from rehabilitating the aquifer. Surface discharge has been disallowed, but the technical considerations are herein summarized for comparison with the alternate methods.

Examination of figure 3, Daily Flow Duration Curves - Red River, shows that 50 percent of the time the flow exceeds 10,000 cfs in the Red River. Figure 4 shows that although the chloride content of the river varies rather widely as a function of flow, a general relationship is present as shown by the average chloride - flow curve. Figure 13 shows the average monthly discharge which would affect the timing of brine discharge. These data establish the physical parameters of the Red River which affect its ability to receive additional salty water.

Because the rate of discharge into the Red River is not as limiting a factor as the rate of injection into a disposal well system, the pumping rate for removing salt water from the aquifer can be relatively high. A practical rate would be 300 gpm

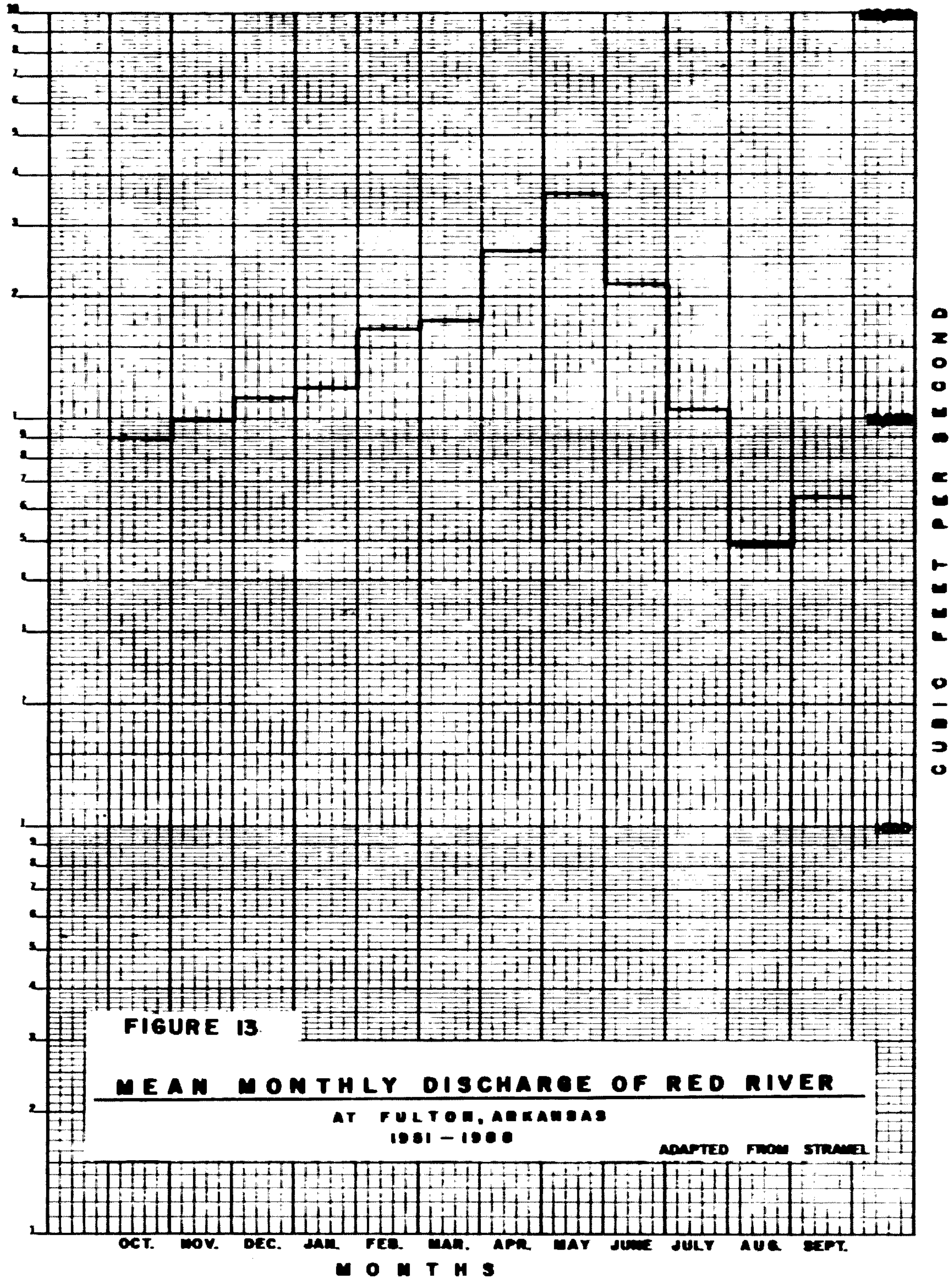


FIGURE 13

MEAN MONTHLY DISCHARGE OF RED RIVER
AT FULTON, ARKANSAS
1951 — 1966

ADAPTED FROM STRAMEL

to be pumped from each of four wells so that the discharge rate to the river would be 1,200 gpm (2.67 cfs). At this rate of pumping it would only take 2.8 years to pump out the 5,400 acre feet estimated amount to be removed. It is somewhat arbitrarily estimated that three times the volume of polluted water will have to be removed to effectively flush the aquifer. The wells would be positioned as shown in figure 14, which also shows the water-level contours and flow directions that would result from the pumping.

The chloride content of the pumped water is, of course, an important factor in determining the resulting chloride increase of the river. Generally, the chloride content would be close to 40,000 mg/l initially but would decrease probably within a few months to perhaps 10,000 mg/l and continue to decrease even more gradually throughout the pumping period. It would be necessary to monitor the chloride content of the pumped water and regulate the discharge as necessary depending on river stage in order to avoid a mixed water chloride increase greater than some limit such as 10 mg/l.

Figure 15 is presented as a graphical aid in determining that minimum river flow at which it would be safe to discharge 1200 gpm of water with a known (by observation) chloride content and not increase the chloride content of the mixed water by more than 10 mg/l. For instance, figure 15 shows that if the observed chloride content is 40,000 mg/l in the water pumped from the aquifer, then the river flow would have to equal or exceed 11,000 cfs to stay within the 10 mg/l limit increase. Because the river flow exceeds 10,000 cfs only about half the time according to figure 3, the discharge of the alluvial salt water should be started in about February, according to figure 13, in order to discharge the most concentrated water during the period of maximum river flow. By monitoring both the river flow and the chloride content of the produced water it would be possible to stop pumping at any time that the chloride increase would exceed 10 mg/l; however, it is doubtful that such curtailment to pumping would be necessary.

Costs for construction and operation of the Red River discharge system were estimated in the Phase I report. These costs are summarized as follows:

<u>Estimated Costs - Red River Disposal System</u>

Wells, pumps and power	$ 39,000
Pipeline from wells to river	69,000
Maintenance	10,000
Personnel, supervision and operation	63,000
	$181,000

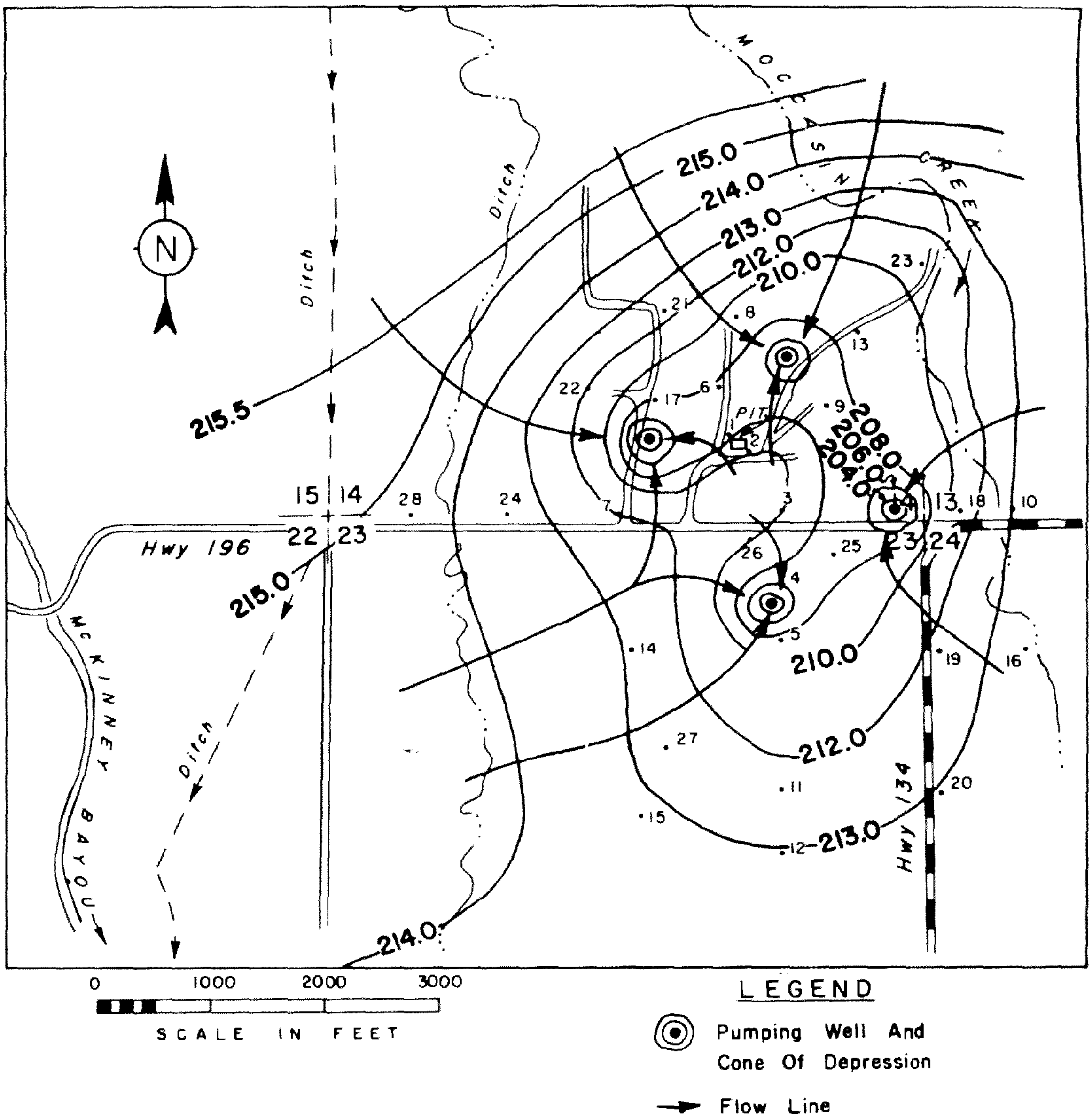


FIGURE 14

CALCULATED WATER TABLE CONTOURS AROUND FOUR PROPOSED PRODUCTION WELLS PUMPING 300 GPM FOR 100 DAYS

ADAPTED FROM STRAMEL

BASED ON EQUATION

$$C_w F_w + C_r F_r = (C_r + 10)(F_r + F_w)$$

WHERE: C_w = mg/l CHLORIDES IN WELL WATER
C_r = mg/l CHLORIDES IN RIVER WATER
F_w = FLOW FROM WELLS = 2.67 CFS
F_r = FLOW IN RIVER

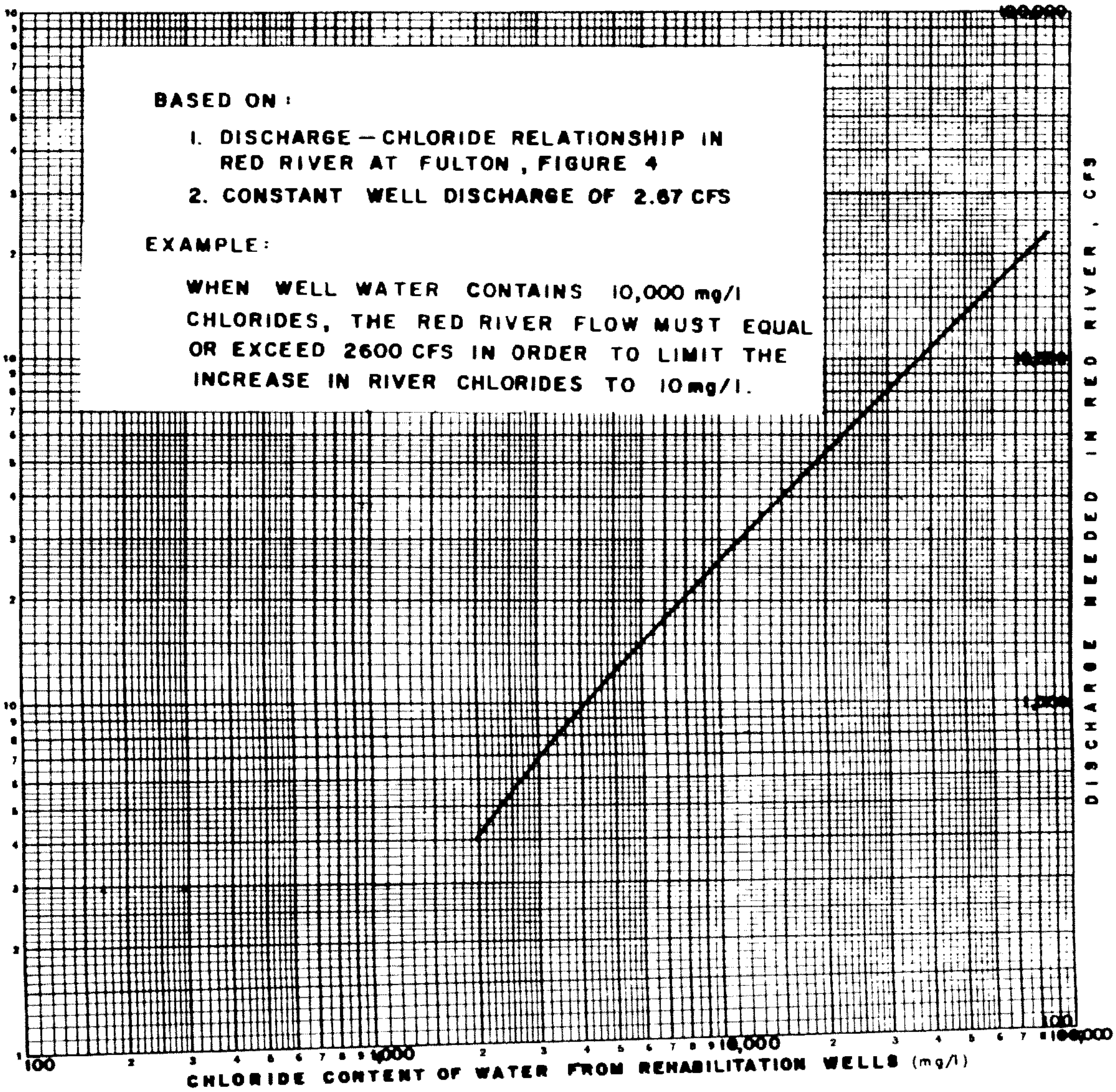


FIGURE 15 REVISED FROM STRAMEL

NOMOGRAPH: TO DETERMINE FLOW REQUIRED IN RED RIVER THAT WOULD LIMIT THE CHLORIDE INCREASE TO 10mg/l AT ANY PUMPED WATER CONCENTRATION

Although disposal into the Red River is technically sound and less costly than other methods, it is not permissible because of its violation, however slight, of the very principle it is intended to enhance. The final justification for the rehabilitation of this brine-polluted aquifer is economic gain through agricultural production. Similarly the production of oil, and its attendant brine waste problem, is for economic benefit. In neither case should further pollution be allowed.

Use

Rehabilitating the aquifer by pumping the water out and putting it to some beneficial use would be an ideal solution, and in some cases might be practical. Three possible uses which could apply to this project are described, each use requiring a different level of treatment.

Secondary Recovery: Oil fields are often repressurized by water to increase oil production. This water flooding operation sometimes requires fairly large quantities of makeup water in addition to the water produced with the oil. If the polluted water in the aquifer could be used for this purpose, no treatment would be necessary. Inquiries were made to all the nearby oil field operators; however, none expressed a need for additional water. If such a need existed, the cost for a pumping system to deliver the polluted alluvial water would be about $80,000 plus the cost of the pipeline to the point of use and power costs which could be paid for by the user.

The rehabilitation approach has been successful in other areas, according to McMillion, and has threefold benefits in that the aquifer is reclaimed, the contaminated water is used beneficially, and fresh water that may have been used for water flooding is available for other purposes. This ideal rehabilitation method should be actively pursued whenever possible.

Blending for Irrigation: An intermediate degree of treatment is dilution of the high chloride water with unpolluted fresh ground water which could enable the blend to be used for irrigation. The clayey soil in the river bottom where the irrigation would take place is a limiting factor, however. A high sodium content in irrigation water tends to cause clayey soils to become very tight and difficult to farm. A blended water containing only 1,000 mg/l of chlorides would have a calculated SAR (sodium adsorption ratio) value of 4.4 and a conductivity of about 5,000 mmhos. This combination establishes a medium salinity hazard which, for the clayey soils involved, would be the maximum recommended limit.

The ratio of fresh water to salty water in order to limit the chlorides to 1,000 mg/l in the resulting blend is 40.2 to 1 when the salty water contains 40,000 mg/l chlorides, and 9.3

to 1 when the salty water contains 10,000 mg/l chlorides. For example, if 1,200 gpm (capacity of well that was destroyed) were being used for irrigation, then only 30 gpm could be pumped from the salty part of the aquifer when the chlorides were in the 40,000 mg/l range.

In order for a blending-use system to be effective in preventing the further spread of the polluted water, 323 acre-feet per year (average 200 gpm) of salty water would have to be pumped out. At the 10,000 mg/l chloride range, this would require 3,000 acre-feet of fresh water for dilution resulting in 3,323 acre-feet of blended water per year for irrigation. If rice could be grown with this water, then about 1,100 acres could be irrigated. However, if more salt-tolerant crops such as bermuda grass or cotton were grown, then at least 1,700 acres under irrigation would be needed. In practice this would require exchanging both good and bad quality water between several farms. Farmers owning land overlying good quality water could object to using the blended water with the resultant increase in costs caused by the salt build-up and other harmful results to their soil and crops.

Furthermore, such a system in effect is pollution of the blended fresh water to some degree by the addition of the salty ground-water and is analogous to pumping the water to the Red River. In fact, the results would be even less desirable and the system much more difficult to administer than pumping directly to the river. The cost of a well, pumping system, power, and supervision is estimated to be about $200,000 plus pipeline costs of about $100,000 to various irrigation users for a total of $300,000.

Desalinization: The final degree of treatment of the polluted water to permit its direct use would be removal of all the contaminants. If there were a sufficiently dire need for the water, desalinization would be considered. It was estimated in the Phase I report that construction and operation of a desalinization plant would cost about $2,000,000.

Deep Well Disposal

General: An apparently attractive solution is to dispose of the polluting brine into deep formations already containing salt water. In examining the technical considerations involved in pumping the polluted water out of the fresh-water aquifer and disposing of it through disposal wells, there are two limiting and opposing factors. The rate of pumping out of the aquifer should be maximized in order to effectively capture all of the polluted water and not allow any of the water to bypass the pumping well and to do this in the shortest time possible. On the other hand, the rate of injection of the water into the disposal zone should be minimized in order to operate under reasonable injection pressures. This problem is resolved by establishing the smallest quantity that can be pumped from the aquifer and be effective, and then designing the disposal system to accommodate that quantity.

In order to establish the smallest effective quantity that can be pumped, it is necessary to examine the hydraulic properties of the aquifer. Figure 16 shows the shape and extent of the cones of depression around a pumping well at different rates of pumping under the hydrologic conditions assumed for this aquifer. Under natural conditions the aquifer is confined by the shallow clay layer; however, as the aquifer is dewatered by pumping, the hydraulic characteristics change from a confined to a water-table condition. That part of the distance-drawdown curve below the confining layer will reflect water-table characteristics (large values for the coefficient of storage, S), whereas that part above the confining clay will reflect confined (very low S value) characteristics. The proportion of the curve below the clay is primarily a function of the pumping rate and secondarily a function of time. The theoretical distance-drawdown curves, shown on figure 16, take into consideration this estimated resulting change in the value of the coefficient of storage. The curves are intended to show the most probable drawdown conditions under the known and assumed aquifer parameters. Based on an examination of these curves, the pumping rate of 200 gpm is (somewhat arbitrarily) selected as the minimum rate that will be effective in pumping out all of the salt water. This pumping rate causes about two feet of drawdown at a radius of 2,000 feet which should result in effective movement of the water toward the well from the perimeter of the polluted area.

Based on the hydraulic gradient and permeability, the natural flow through a cross sectional area one mile long is about 30 gpm. Therefore, if a system of closely spaced wells were installed all across the downstream side of the polluted area, the absolute minimum pumping rate would be 30 gpm to capture the polluted water. Such a system would have to be operated for over 100 years, however, in order to drain all of the salt water. Because fewer wells and higher pumping rates are more practical, the production system chosen for deep-well disposal employs one pumping well for which the minimum pumping rate is 200 gpm.

The position of the production well relative to the direction of movement of the main body of salt water and relative to the configuration of the underlying shale surface is critical in the successful removal of the polluted water. The well should be located just downstream (south) from the main body of polluted water, and the well should be located in a topographic low of the shale surface in order to allow the high-density salt water to flow toward the well. Furthermore, the production

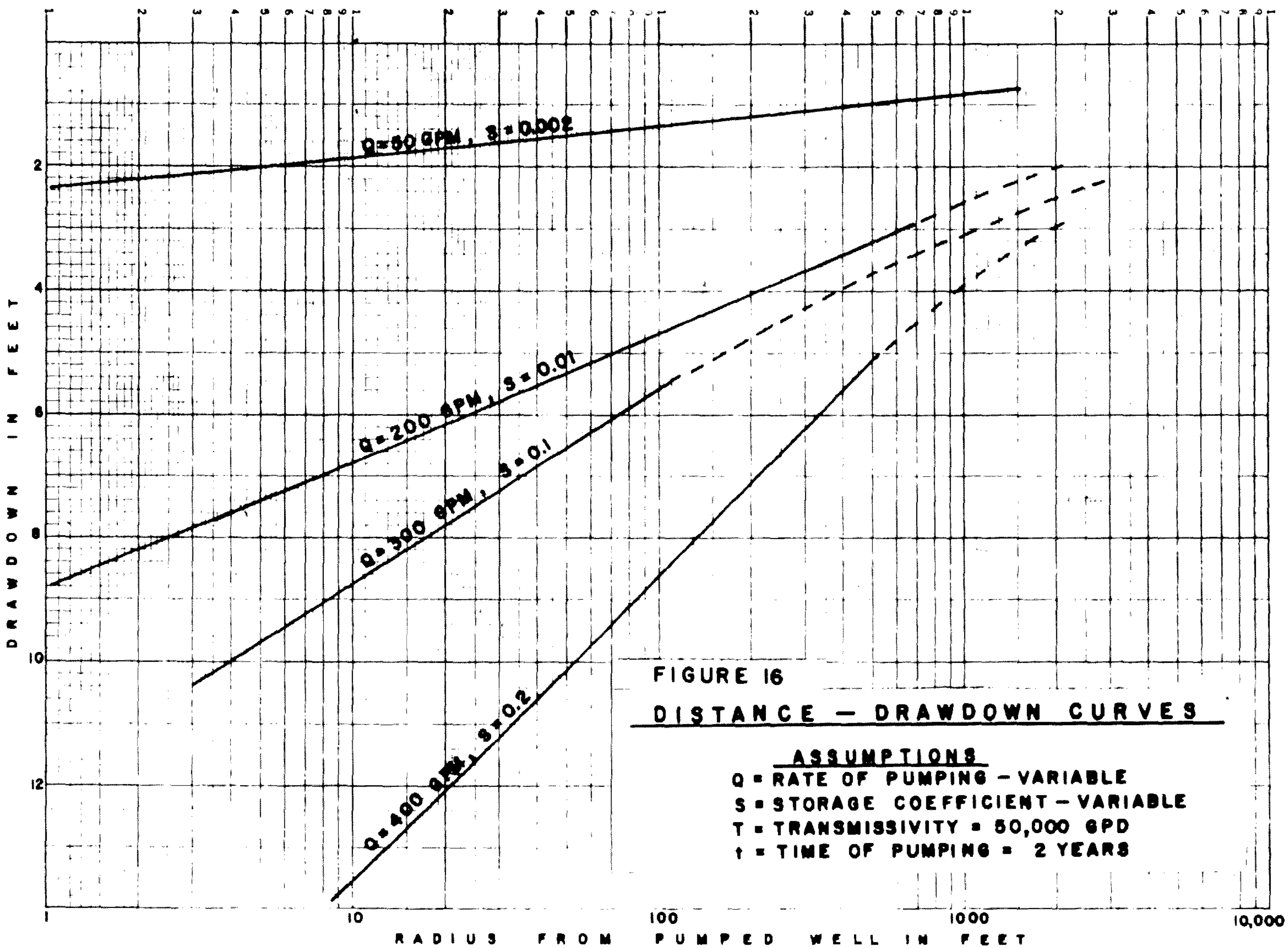


FIGURE 16

DISTANCE — DRAWDOWN CURVES

ASSUMPTIONS

Q = RATE OF PUMPING — VARIABLE
S = STORAGE COEFFICIENT — VARIABLE
T = TRANSMISSIVITY = 50,000 GPD
t = TIME OF PUMPING = 2 YEARS

well should be constructed using about five feet of hydraulically efficient well screen set as low as possible in permeable material just above the shale in order to concentrate on the dense salt water. Additional test-hole drilling would be recommended to locate the best position for the production well if the rehabilitation should be carried out.

Nacatoch Disposal Well: The Nacatoch sand in this area is non-oil-bearing, contains salt water, and is sufficiently permeable to be used as a disposal zone. In fact, the salt-water disposal well now in operation in this field is completed in the Nacatoch at a depth of 1,466 to 1,496 feet. This well disposes daily of about 1,500 barrels of brine in about 17 hours of operation, which is an average pumping rate of 82 gpm. The pressure developed by the pump ranges from 200 to 400 psi. When the pressure gets high, a detergent is added to the brine causing the required pressure to decrease. Because of mutual pressure interference between wells and constant injection, it is estimated that 50 gpm per well would be the maximum practical injection rate for a multi-well disposal system.

It has been estimated that the aquifer contains 14 million barrels (1,800 acre-feet) of salty water. However, because of lag time and the nonhomogeneity of the aquifer, it is estimated that three times the original volume would have to be pumped to effectively flush the salt out of the aquifer. This would require nearly 17 years at the 200 gpm pumping rate.

Although only one production well would be required to produce 200 gpm, four disposal wells would be necessary in order to inject the water within reasonable pressure limits. A system could be designed using one production well in the center with pipelines in four directions leading to the four disposal wells 1,000 feet away from the production well. Such a system would space the disposal wells about 1,400 feet apart which, within practical limits, would minimize mutual pressure interference. In order to minimize costs, the system could be operated by a single pump -- the production pump would develop the pressure required for injection into the disposal wells.

Estimated costs for constructing and operating a rehabilitation system using disposal wells completed in the Nacatoch formation are summarized as follows:

Estimated Costs - Nacatoch Disposal System

Four disposal wells, 1,500 ft deep..............	$160,000
One production well............................	6,000
Pump and motor.................................	6,000
Pipeline from production well to disposal wells.	16,000
Controls, valves, meters, etc..................	12,000
Contingencies..................................	30,000
Total Hardware.........................	$230,000

(Estimated Costs Continued)

Estimated Costs (Continued)

Total Hardware (Previous Page)........	$230,000
Design and construction supervision.............	15,000
Operation and maintenance for 17 years..........	102,000
Power costs for 17 years........................	103,000
Total Estimated Cost...................	$450,000

Disposal into the Nacatoch, however, has disadvantages that render this alternative undesirable. One disadvantage is the presence of faults in the immediate area. These faults could form relatively impermeable barriers to the lateral flow of the injected brine thereby causing a gradual but highly significant increase in the pressure required to inject the required 200 gpm. If, on the other hand, the faults were more permeable than the undisturbed formations, then the fault planes could provide a conduit for the upward migration of water injected into the pressurized Nacatoch formation thereby creating another pollution hazard.

Another significant disadvantage is the presence of so many oil wells and test wells drilled within 1 1/2 mile radius. Of the 46 holes drilled, none set surface casing below the Carrizo sand - the lowest fresh water. Furthermore, according to Oil and Gas Commission records, of the 31 wells that have been plugged, only in 8 wells was casing left in the hole extending below the Carrizo. These old holes could allow brine to migrate from the Nacatoch into any or all of the fresh water-bearing formations, if the pressure in the Nacatoch were raised high enough and if some of the old holes should form conduits. The Arkansas Oil and Gas Commission has witnessed the plugging of all wells since 1961. Many of these wells and test holes were plugged prior to that time, however, and the adequacy of the plugs is questionable.

Smackover Disposal Well: The Smackover formation is predominately a limestone of Jurrasic age (Vestal). This formation underlies most of southern Arkansas and not only produces considerable oil but also produces brine from which bromide is extracted. In the northern part of the project area the depth to the top of the Smackover is estimated to be between 8,200 to 8,700 feet. One mile south of the project area a Smackover test well was drilled in the fall of 1971. This well reached the top of the Smackover at 9,570 feet; however, that location is both down-dip and on the downthrown side of the fault. Although no oil was encountered in the well, the drilling reports did indicate that there are high permeabilities in the top 100 feet of the Smackover. The bottom-hole pressure was not measured in this test hole, but based on other data in the area, the static fluid level is expected to be between 500 and 1,000 feet below land surface. This existing well could be re-entered and completed as a disposal well.

The Ethyl Corporation at their bromide plant near Magnolia, Arkansas (about 30 miles east of the project) produces brine from the Smackover through 22 production wells and injects about 195,000 bbl/day back into the formation through seven disposal wells - an average of 815 gpm per well. In the Magnolia area the static fluid level is about 3,000 feet below ground level. Based on information developed from the Ethyl Corporation records and the permeability estimated from electric logs in the Smackover test well one mile south of the project, it is estimated that the injection specific capacity should be on the order of 0.2 gpm per foot of head increase. This suggests, then, that a Smackover disposal well should take 200 gpm under vacuum (no surface pressure required) if the static fluid level is 1,000 feet below ground level. On the other hand, 500 feet (217 psi) of surface pressure would be required to inject 200 gpm if the static fluid level is only 500 feet below land surface.

The experience of operators in the area indicates that there should not be an excessive problem of plugging of the formation due to mixing incompatible waters provided that a buffer zone is established and that the injected water is not exposed to air.

Two possible systems, one using the existing test well and the other drilling a new well, could be used to dispose of the polluting brine into the Smackover formation. Estimated costs for each system considering injection pressure requirements are presented for comparison.

Estimated Costs - Smackover Disposal Well System
Using Existing Well Located One Mile South of Project Site

Disposal well (casing, tubing and other conversion costs)	$130,000
Production well	6,000
Pipeline	34,000
Pump (combined production and injection)	5,000
Controls and fittings	10,000
Contingencies	20,000
Total Hardware Costs	$205,000
Design and supervision	15,000
Operation and maintenance	102,000
Power costs for 17 years	83,000
Total (assuming injection pressure required)	$405,000

The above cost estimate assumes that the static fluid level is 500 feet below the surface and that 217 psi injection pressure will be required to dispose of the 200 gpm. If the static fluid level is 1,000 feet below land surface and no injection pressure is required, then power costs can be reduced substantially and the pipeline cost can reflect less pressure requirements, thereby reducing the total cost to $337,000.

Estimated Costs - Smackover Disposal Well System
Drilling a New Well Near the Production Well

Disposal well	$180,000
Production well	6,000
Syphon system	4,000
Controls and fittings	3,000
Contingencies	17,000
Total Hardware Costs	$210,000
Design and supervision	15,000
Operation and maintenance	65,000
Total (assuming no injection pressure required)	$290,000

This design is based on the assumption that the static fluid level is on the order of 1,000 feet below ground level and that the 200 gpm injection rate would not require surface pressure. Under these circumstances, a syphon system could be used to transfer the water from the production well into the disposal well, thereby eliminating power costs.

If this system were to be constructed, the disposal well would be constructed first. By conducting injection tests, the rate at which the well would receive water under vacuum could be determined. The production well system would then be designed to furnish water at the rate of acceptance of the disposal well. If this rate should be less than 200 gpm (but greater than 100 gpm), then more than one production well would be necessary in order to spread the pumping over a wider area so that none of the polluted water would flow past the production system.

If the rate of injection under gravity should be less than 100 gpm, pressure injection would be required in order to dispose of the water in a reasonable time and to insure against salty water passing the collection system. Under these circumstances requiring a pump and power consumption, the total cost of a new Smackover well disposal system is estimated to be $375,000.

The well design used for all disposal-well cost estimates incorporates important safeguards against further pollution. First, surface casing should be set and cemented below the lowest fresh water. Then, the production casing should be set to the disposal zone and cemented. Next, the injection tubing should be set with a packer just above the disposal zone. The annulus between the tubing and production casing should be filled with a non-corrosive fluid, and the salt water would be pumped through the tubing. If a leak should develop in the tubing or packer, it would be detected immediately by the change in pressure in the annular fluid, and injection would be stopped until the leak was repaired. The safeguard supplied by using tubing and a fluid-filled annulus is not now required by the State of Arkansas.

There is no oil or gas production from the Smackover formation closer than four miles, and none of the nearby existing wells penetrated to that depth. Therefore, there are no technical disadvantages or dangers connected with using the Smackover as a disposal zone. The only disadvantage is its great depth and the resulting high cost of a disposal well.

SECTION VIII

BENEFIT-COST RATIOS

In the preceding sections the technical details of this pollution incident and the possible rehabilitation methods have been discussed. Finally, it is necessary to decide which rehabilitation method is most feasible and whether or not that method is justified. The most direct means of evaluating the feasibility of this type of project is an economic evaluation based on the benefit-cost ratio. The determination of costs is fairly straightforward, but the determination of the money value of benefits is more difficult and subject to varying approaches. The following discussion is hopefully explained in sufficient detail to allow the reader to follow the calculations step by step and form his own opinion as to their appropriateness.

As stated in Section V, the long-term value of water contaminated ranges from $3,200,000 to $18,250,000 based on present-day crop values and potential use. In order to grow rice, for instance, water is mandatory, whereas for cotton and other crops water just adds to the quantity that can be harvested per acre. In order to establish reasonable benefit-cost ratios for this report, the difference in profit between irrigated and nonirrigated cotton is chosen as a realistic use. It is further stated in Section V that the pollution will eventually affect 4 1/2 square miles; however, to be conservative it is assumed that only two square miles will be polluted at any one time throughout the 250-year natural flushing period.

Using the above assumptions, it is possible to arrive at the annual difference in profit (not total income) that may be gained if the aquifer is rehabilitated and used to irrigate cotton. At $35 per acre difference in profit over 1,280 acres (2 square miles) the difference in profit is $44,800.

In order to compare benefits spread over 250 years and costs, part of which are spread over 17 years, it is necessary to reduce all values to present worth. This is accomplished by using the following uniform series present worth factor equation from Taylor.

$$P = R \frac{(1+i)^n - 1}{i(1+i)^n}$$

Where P = Present worth
R = Annual payment (or income)
i = Interest = 6 percent for all calculations
n = Number of years

The present worth (P) is defined as that amount of money deposited now at (i) interest rate in order to withdraw (R) dollars annually as payment for benefits or costs for (n) years. For instance, the present worth of $44,800 per year for 250 years (same for infinite time) is $746,680; or in other words, if $746,680 were deposited at six percent compounded interest, it would be possible to withdraw $44,800 per year for 250 years.

The $746,680 is the present worth of added profit that would accrue to the few landowners involved and is used to establish the private benefit-cost ratio. In order to relate this to public benefit, it is assumed that 25 percent of this added profit would revert to the public as taxes. Therefore, the public benefit is $186,670, which is used for establishing the public benefit-cost ratio. These values ignore the future benefit resulting from preventing discharge of the salty water into the Red River and possible future attendant costs. The public benefit further assumes that irrigation of the full two square miles would actually be done by the private landowners and that cotton would be grown. Rice crops would increase the annual profit considerably over dry-land cotton, hence would increase both the private and public benefit values.

For calculating the worth of rehabilitation costs, it is assumed that the operating and power portions will be spread uniformly over the life of the rehabilitation project. These cost factors are reduced to present worth and added to the initial investment to arrive at the total present worth cost.

Table 4 summarizes the rehabilitation methods discussed and shows the private and public benefit-cost ratios based on present worth for each method. Examination of this table shows that disposal into the Smackover formation is the least expensive method that is both technically feasible and permissible under established policy. Construction of the new well in the project area, as opposed to using the existing test hole, offers the most advantageous range of benefit-cost ratios. This method would be recommended if the project were to continue.

In considering the negative public benefit-cost ratio, however, and the assumed higher priority for funds for preventive measures, rehabilitation of the aquifer does not appear economically justified at this time.

TABLE 4

SUMMARY AND BENEFIT-COST RATIOS OF REHABILITATION METHODS

Method	Years of Operation	Total Cost	Present-Worth Cost	Benefit-Cost Ratio Private	Benefit-Cost Ratio Public	Remarks
1. Containment						
A. Bentonite Wall	Must be maintained forever	$7,000,000	$7,000,000	0.1:1	0.03:1	Only restricts pollution and too costly.
2. Accelerated Discharge						
A. Water Drive	10 years	$1,264,000	$1,194,306	0.6:1	0.15:1	Too costly, benefits too low.
B. Pumping to Red River	3 years	$ 181,000	$ 176,749	4.2:1	1.05:1	Contrary to policy.
3. Use						
A. Secondary Recovery	10 years	$ 80,000	$ 80,000	9.3:1	2.3:1	No market for water use.
B. Blending for Irrig.	17 years	$ 300,000	$ 258,528	2.9:1	0.7:1	Probably not acceptable to users.
C. Desalinization	17 years	$2,000,000	$1,692,410	0.4:1	0.1:1	Too costly, possible uses don't justify.
4. Deep Well Disposal						
A. Nacatoch Formation	17 years	$ 450,000	$ 371,247	2:1	0.5:1	Not recommended because of danger of further pollution.
B. Smackover Formation						
(1) Existing well (using pressure)	17 years	$ 405,000	$ 333,727	2.2:1	0.55:1	Technically feasible and acceptable, not as economical as new well.
(2) Existing well (gravity flow, no pressure)	17 years	$ 337,000	$ 288,634	2.6:1	0.65:1	
(3) New well (using pressure)	17 years	$ 375,000	$ 320,854	2.3:1	0.57:1	Technically feasible and acceptable, highest benefit-cost ratio of feasible methods.
(4) New well (gravity flow, no pressure)	17 years	$ 290,000	$ 265,022	2.8:1	0.7:1	

SECTION IX

ACKNOWLEDGMENTS

The support and continuing interest of Mr. Leslie G. McMillion, EPA Grant Project Officer, is especially noteworthy. Mr. McMillion has been instrumental throughout the project in guiding the work to a conclusion.

This report was prepared by John S. Fryberger, Ground-Water Geologist, with the assistance of John H. Marsh, Civil and Sanitary Engineer, partners in the firm of Engineering Enterprises, Norman, Oklahoma. The work was performed under contract to the Arkansas Division of Soil and Water Resources as authorized by EPA.

The Phase I report, from which considerable information was used in this final report, was prepared by G. J. Stramel, Project Director for this project and Chief Engineer of the Arkansas Division of Soil and Water Resources. Other personnel of this Division contributed as follows: Keith Jackson had overall responsibility for the project; Roy Smith supervised the initial test drilling, and A. J. Bryniarski, J. R. Young, Al Nyitrai, and Larry White performed the field work and water sampling. Dr. Leslie Mack, former Governor's Advisor on Water Resources, assisted in the early planning and in efforts to obtain the EPA Grant.

Other Arkansas state agencies have also contributed significantly. The Oil and Gas Commission took part in the initial investigation and provided records on the oil fields and brine disposal. The Pollution Control Commission has analyzed most of the water samples. And the Geological Commission has provided technical assistance. In addition, the U. S. Geological Survey office in Arkansas provided considerable geologic and hydrologic data including the results of their 1967 reconnaissance, and performed some of the chemical analyses for this report.

Mr. Ernst P. Hall, Program Element Manager, and Dr. James Shackelford, Project Manager, for the Office of Research and Monitoring, EPA, were instrumental in approving the project and revising the project's objectives. Mr. Jack Keeley, Chief, National Ground Water Research Program of EPA, assisted in review, and Mr. Wm. DePrater, Chemist, Robert S. Kerr Research Center, EPA, and A. Gene Collins, Chemist, Bartlesville Petroleum Research Center, U. S. Bureau of Mines, provided valuable assistance in analyzing and interpreting the complex water chemistry.

The cooperation of the landowners in the project area is especially appreciated. Considerable assistance was rendered by Mssrs. Linn Lowe, Glen Price, and Harold Tullos of Garland City, Arkansas.

SECTION X

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REHABILITATION OF A BRINE-POLLUTED AQUIFER,

5. Report Date

6.

8. Performing Organization Report No.

Fryberger, John S.

Engineering Enterprises
under contract to
Arkansas Division of Soil & Water Resources

14020 DLN

13. Type of Report and Period Covered

12. Sponsoring Organization **Environmental Protection Agency**

Environmental Protection Agency report number EPA-R2-72-014, December 1972.

A detailed investigation was made of one (among several noted) incident where a fresh-water aquifer has been polluted by accepted disposal of oil-field brine through an "evaporation" pit (an unlined earthen pit) and later a faulty disposal well. The present extent of the brine pollution is one square mile, however it will spread to affect 4 1/2 square miles and will remain for over 250 years before being flushed naturally into the Red River. Detailed chemical analyses show changes in relative concentrations of constituents as the brine moves through the aquifer.

Several rehabilitation methods are evaluated in detail, including controlled pumping to the Red River and deep-well disposal. None of the methods that are both technically feasible and permissible show a positive public benefit-cost ratio.

Although real economic damage both present and future results from this brine pollution, rehabilitation is not now economically justified. The report emphasizes that greater effort is needed to prevent such pollution, which not only affects ground-water resources but also affects water quality in interstate streams. (Fryberger-Engineering Enterprises)

17a. Descriptors *Ground-water, *Water pollution, *Pollution abatement, *Brine disposal, Water pollution sources, Water pollution control, Water pollution effects, Path of pollutants, Aquifers, Saline water--freshwater interfaces, Arkansas hydrology, Water chemistry, Water conservation, Waste water disposal.

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