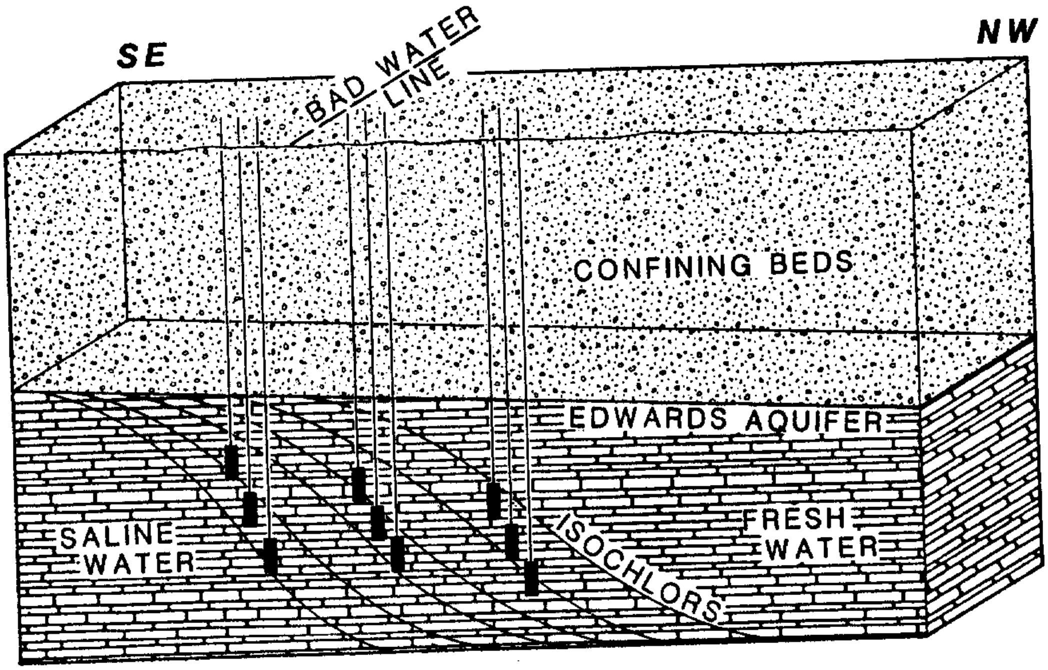
DRILLING, CONSTRUCTION, AND TESTING OF MONITOR WELLS FOR THE EDWARDS AQUIFER BAD WATER LINE EXPERIMENT

CITY WATER BOARD OF
SAN ANTONIO

EDWARDS UNDERGROUND
WATER DISTRICT

TEXAS WATER DEVELOPMENT
BOARD

UNITED STATES GEOLOGICAL
SURVEY



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By

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ABSTRACT

The primary purpose for the Edwards aquifer bad water line experiment is to establish a long-term monitoring system and develop site-specific information at one location along the bad water line. Ongoing analysis of information obtained as a result of this project is expected to help in determining whether encroachment of poor quality water presents a serious problem to maximum use of the aquifer as natural and man-made stresses of the aquifer come to pass, and in determining ways to avoid the problem to the extent it exists.

This report discusses the drilling, construction, and testing of monitor wells along a transect of the Edwards aquifer bad water line and the data that were obtained during those operations. The transect is the first of a number of similar transects that are planned for various locations along the bad water line of the Edwards aquifer in the San Antonio region. It is located near the City Water Board of San Antonio's Artesia Well Field in the eastern part of San Antonio, Texas.

Seven monitor wells were constructed during this part of the Edwards aquifer bad water line experiment. The wells are completed at different depths in the Edwards aquifer at three sites along the transect. Three wells are located at the bad-water zone site, the southernmost site, two are located at the transition-zone site, and two are located at the fresh-water zone site, which is adjacent to the Artesia Well Field and a little more than a mile north-northwest of the bad-water zone site.

Drilling and testing of the monitor wells provides site-specific information about the geology, hydrology, and water quality along the transect. The monitor wells provide a means for monitoring water levels and water quality in the Edwards aquifer along the transect over a period of several decades. This information will be used for determining whether stresses on the aquifer system caused by pumping and/or drought conditions result in a shift of the bad water line, and if they do, how this will affect development of fresh ground water from the aquifer. It should be noted that this transect is only the beginning of a much larger program, and that it provides information for only one point along nearly 200 miles of the Edwards aquifer bad water line in the San Antonio region. Thus, information from other transects that are planned for various locations along the bad water line will also

be needed to determine whether encroachment of poor quality water presents a regional problem to maximum use of the aquifer.

The geologic units along the transect do not appear to be significantly offset vertically, except possibly in the vicinity of the fresh-water zone site which is near the extensively faulted Artesia Well Field. The regional dense member of the Person Formation, located near the middle of the Edwards Group, is readily identifiable and persistent at all three drilling sites. Cavernous conditions were encountered in the upper part of the Edwards at the two northernmost sites, although at the transition-zone site, a large cavity that was present at one well was not encountered in the other well 100 feet away. At the bad-water zone site, the grainstone member of the Kainer Formation, which is present immediately beneath the regional dense member, was more porous than is normally the case in the fresh-water part of the aquifer.

The upper part of the Edwards aquifer is more productive than the lower part. However, information from the tests that were made shows that the productivity of a water-producing zone can change appreciably within a small distance. The aquifer also appears to be more productive in the fresh-water zone than it is in the bad-water zone.

As shown by packer tests and tests of completed monitor wells, the water producing zones are not in direct hydraulic communication vertically at the drilling sites. However, small changes in water levels that occurred with time indicate there is general hydraulic communication between zones throughout the aquifer areally, probably as a result of vertical communication along fault planes. Water levels in wells at all three sites fluctuate in accordance with changes in water levels caused by pumping from the fresh-water part of the aquifer in the San Antonio area.

In general, the quality of the ground water becomes poorer with depth and in a downdip (southeasterly) direction along the transect. Chemical analyses of the initial water samples collected from the completed monitor wells show that the quality of the water in the very upper Edwards aquifer may be slightly better at the transition-zone site than it is at the fresh-water zone site near the Artesia Well Field. This may reflect the fact that initial water samples were collected from the fresh-water zone wells about 4 months after the initial samples were collected from the transition zone wells, and poorer quality water might have moved to the fresh-water zone site if there was a seasonal shift in the bad water line due to pumping. Poor quality water was encountered in the lower part of the Edwards aquifer at the northernmost site. This was unexpected, especially since this site is near fully penetrating production wells in the City Water Board's Artesia Well Field.

As noted earlier, the primary purpose for this project was to establish a long-term monitoring system and develop site-specific information for ongoing analysis. Preliminary assessment of observations and data from the drilling, construction, and testing of monitor wells presented in this report identifies the general geohydrologic framework of the Edwards aquifer along the transect. The U. S. Geological Survey through a cooperative program with the City Water Board and the Edwards Underground Water District is currently making a more detailed analysis of conditions along the transect. This analysis will include microscopic examination of drill cutting samples and detailed study of geophysical logs, bore hole surveys, and geochemistry. Long-term monitoring of water levels and water quality will provide information for determining whether the bad water line shifts as a result of stresses imposed on the aquifer, and if so, how this is likely to affect the availability of fresh ground water.

In view of the presence of poor quality water in the lower part of the Edwards aquifer at the northernmost drilling site, it will be desirable to extend the transect northward into and beyond the Artesia Well Field to find out if poor quality water is present in the lower part of the aquifer in a much larger part of the area. Construction of additional monitor well transects of the Edwards aquifer bad water line will be needed in other areas to better establish how conditions along the bad water line are likely to affect the availability of fresh ground water from the aquifer on a regional basis.

Consideration needs to be given to constructing a transect of the bad water line in the New Braunfels or San Marcos areas to the north, and another one in the D'Hanis or Uvalde areas to the west. The bad water line in the areas to the north may be related to faulting, whereas in the areas to the west, it may be related to rock permeabilities. These areas are in or near major ground-water flow paths. Therefore, the information obtained from these transects also will contribute to a better understanding of regional hydrology.

INTRODUCTION

The primary purpose for the Edwards aquifer bad water line experiment is to establish a long-term monitoring system and develop site-specific information at one location along the bad water line. Ongoing analysis of information obtained as a result of this project is expected to help in determining whether encroachment of poor quality water presents a serious problem to maximum use of the aquifer as natural and man-made stresses on the aquifer come to pass, and in determining ways to avoid the problem to the extent it exists.

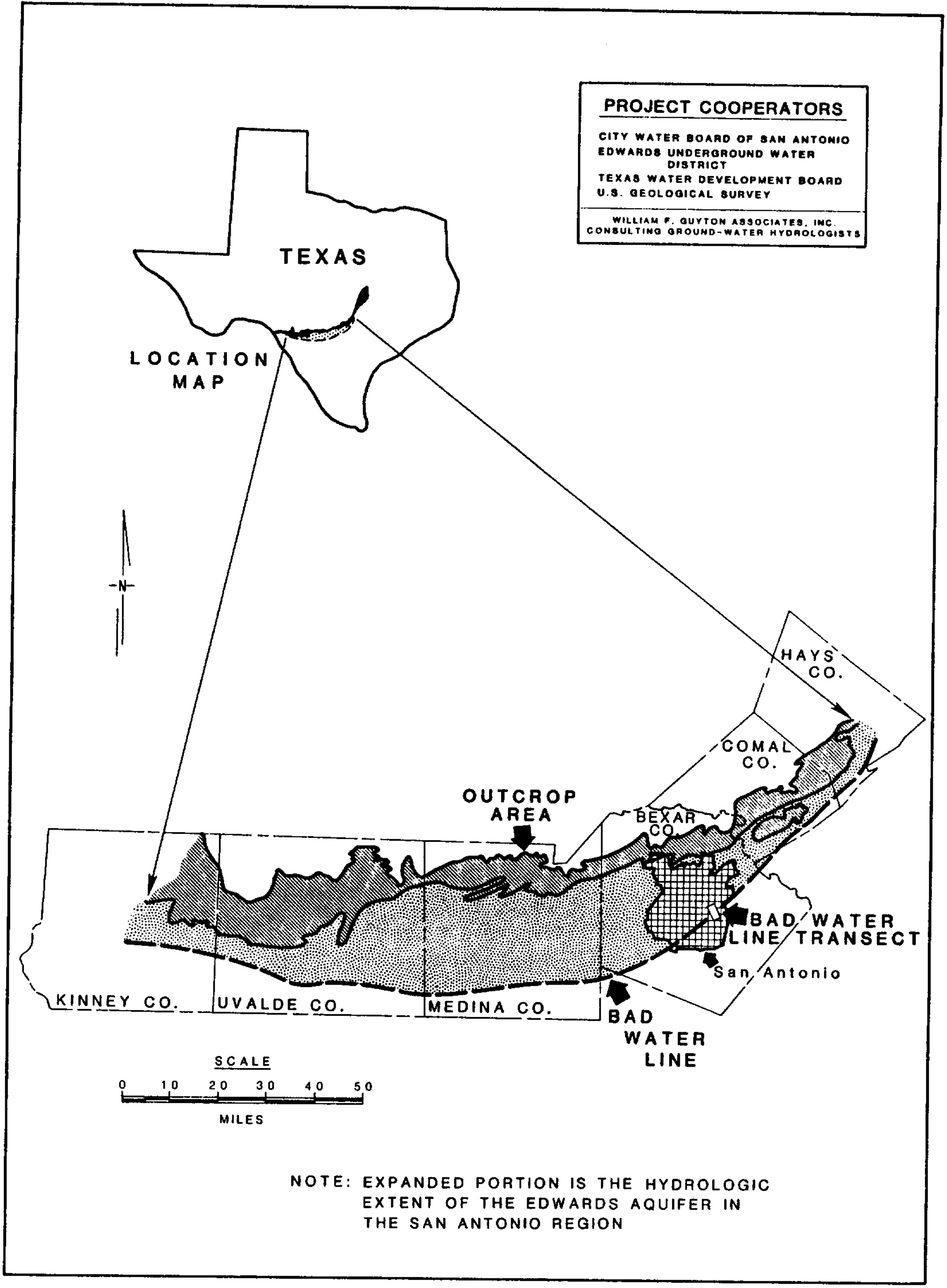
This report discusses the monitoring well transect that has been constructed to determine site-specific conditions across the Edwards aquifer bad water line near the City Water Board of San Antonio's Artesia Well Field and to provide a means for identifying changes in water quality that may occur in the aquifer with time as a result of hydrologic stresses that are imposed on the aquifer system in the area. These stresses on the aquifer occur as water levels are lowered by pumping and by droughts that regionally reduce recharge to the aquifer and, at the same time, result in increased withdrawals from it.

The Edwards Aquifer

The Edwards aquifer is a series of carbonate rocks that extends eastward from the Rio Grande near Del Rio on the west to San Antonio, and then generally northeastward to near Salado about 50 miles north of Austin.

The general position of the San Antonio bad water line transect in relation to the Edwards aquifer is shown on Figure 1. As shown by the expanded portion of the aquifer on Figure 1, the Edwards aquifer in the San Antonio region extends hydraulically from Brackettville near the middle of Kinney County on the west to near Kyle in Hays County to the northeast. The Edwards Underground Water District, one of the cooperators on this project, occupies all of the Edwards aquifer in the San Antonio region except for the portion of the aquifer that is in Kinney County.

The Edwards aquifer has been designated a sole source aquifer. It supplies water for more than one million people in the San Antonio and surrounding area. It also supplies potable water and water for irrigation, industry, and recreation throughout an 8,000 square mile area of south-central Texas. Most of the



PROJECT COOPERATORS

CITY WATER BOARD OF SAN ANTONIO
EDWARDS UNDERGROUND WATER DISTRICT
TEXAS WATER DEVELOPMENT BOARD
U.S. GEOLOGICAL SURVEY

WILLIAM F. GUYTON ASSOCIATES, INC.
CONSULTING GROUND-WATER HYDROLOGISTS

NOTE: EXPANDED PORTION IS THE HYDROLOGIC EXTENT OF THE EDWARDS AQUIFER IN THE SAN ANTONIO REGION

LOCATION OF BAD WATER LINE TRANSECT

Figure 1

withdrawals for irrigation occur in the western part of the region, and most of the natural discharge, which occurs through springs and supports recreational activities, occurs primarily in the eastern part of the region. Withdrawals for municipal and industrial use are centered generally in Bexar County. Recharge of the aquifer to sustain man-made withdrawals and natural discharge is from infiltration of rainfall on the outcrop area and from streams which drain large areas to the north before crossing the outcrop area where they lose a large portion of their flow to the aquifer.

The southern edge of the aquifer is physically a fluid boundary, commonly referred to as the bad water line, which separates fresh ground water from poor quality saline ground water. This boundary is not fixed, and maximum development or use of the aquifer as a reservoir depends upon the extent to which the water levels may be drawn down within the reservoir without causing major encroachment of poor quality water. The extent to which the reservoir can store water in wet times and deliver the water in dry times will play a significant part in the management and conservation of the overall water resources of the area as regional water use approaches the limits of the resources available. Thus, site-specific and long-term monitoring information obtained from the bad water line transects is to be used for determining whether the saline water can be forced to move toward and into the fresh-water part of the aquifer as a result of pumping stresses that have been accumulating since man began using the aquifer and natural stresses such as those that occur during droughts when recharge to the aquifer is seriously deficient.

Objective of Bad Water Line Experiment

This bad water line experiment is designed to help define the location of the subsurface interface between fresh and poor quality water at one location along the bad water line, to obtain estimates of the properties required for prediction of movement of the interface, and to provide a long-term, carefully controlled monitoring system for the interface as natural and man-made stresses come to pass. It includes monitor wells in the bad-water zone, the transition zone where the quality of the water goes from bad to good, and the fresh-water zone. Information obtained from the experiment is expected to help in determining whether encroachment of poor quality water presents a serious problem to maximum use of the aquifer and in determining ways to avoid the problem to the extent it exists. The present transect of monitor wells is but the first of a number of such transects that are expected to be required along the nearly 200-mile length of the bad water line that forms the southern boundary of the Edwards aquifer in the San Antonio region.

Selection of Site for Bad Water Line Transect

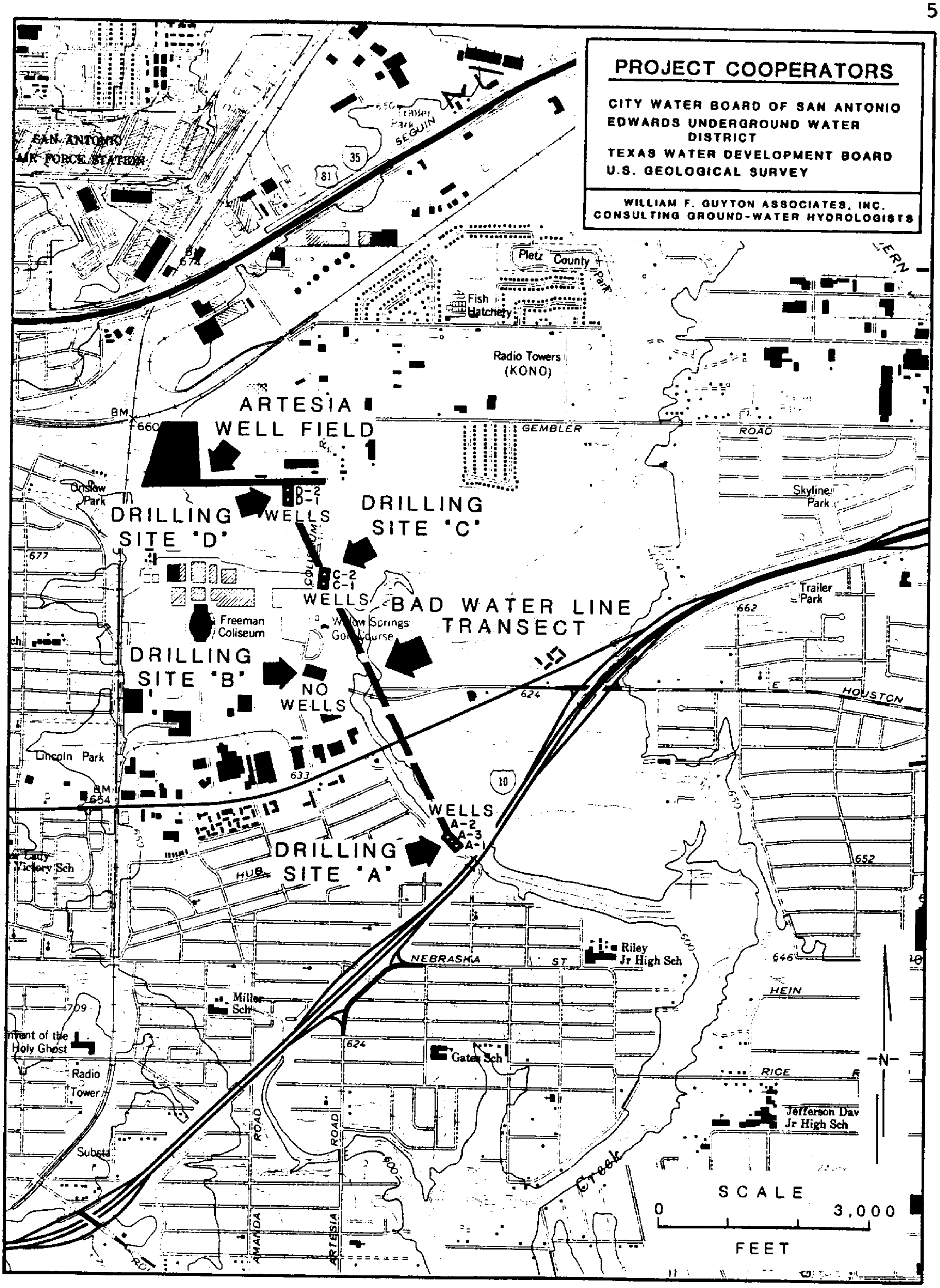
Several factors were considered in the selection of the site for the first bad water line transect. These factors included: (1) the site should be located where there was a reasonably good definition of the position of the bad water line, (2) the geology should be relatively simple in terms of faulting so as not to complicate evaluation of data, (3) the transect should be located near a pumping center which provided a reasonably large controllable and measurable hydrological stress on the aquifer system, and (4) because of the total cost of the experiment, land for construction of the monitor wells comprising the transect and access for long-term monitoring (up to 50 years) should be available at minimal cost. The site selected for the transect is near the City Water Board of San Antonio's Artesia Well Field in the eastern part of San Antonio as shown on Figure 1. A more detailed map showing the locations of the drilling sites and monitor wells associated with the development of this transect is shown on Figure 2.

Data initially available indicated the bad water line (transition from bad water to good water) in this area trended in a general southwest-northeast direction and passed through the southwestern part of Willow Springs Golf Course near drilling Site B.

The only known faults in the vicinity of the transect pass in a general southwest-northeast trending direction through the Artesia Well Field area just north of drilling Site D.

Pumping from the Artesia Well Field provides a means for stressing the system to change hydraulic heads (water levels) and possibly cause the bad water line to shift. Average monthly pumpage from the well field during recent years ranged from as little as 3-1/2 million gallons per day (mgd) during the winter months to more than 20 mgd during the summer months. While pumping from some of the other well fields within the City is greater, the geology associated with those stations generally is more complex. In addition, land for construction of a bad water line transect was not as readily available in the vicinity of those well fields.

The City of San Antonio provided City park property for construction and long-term monitoring of monitor wells at no cost to the project. Site A located in the bad-water zone is at the southern end of Dafoste Park, and Sites B and C, originally



LOCATIONS OF DRILLING SITES AND MONITOR WELLS

Figure 2

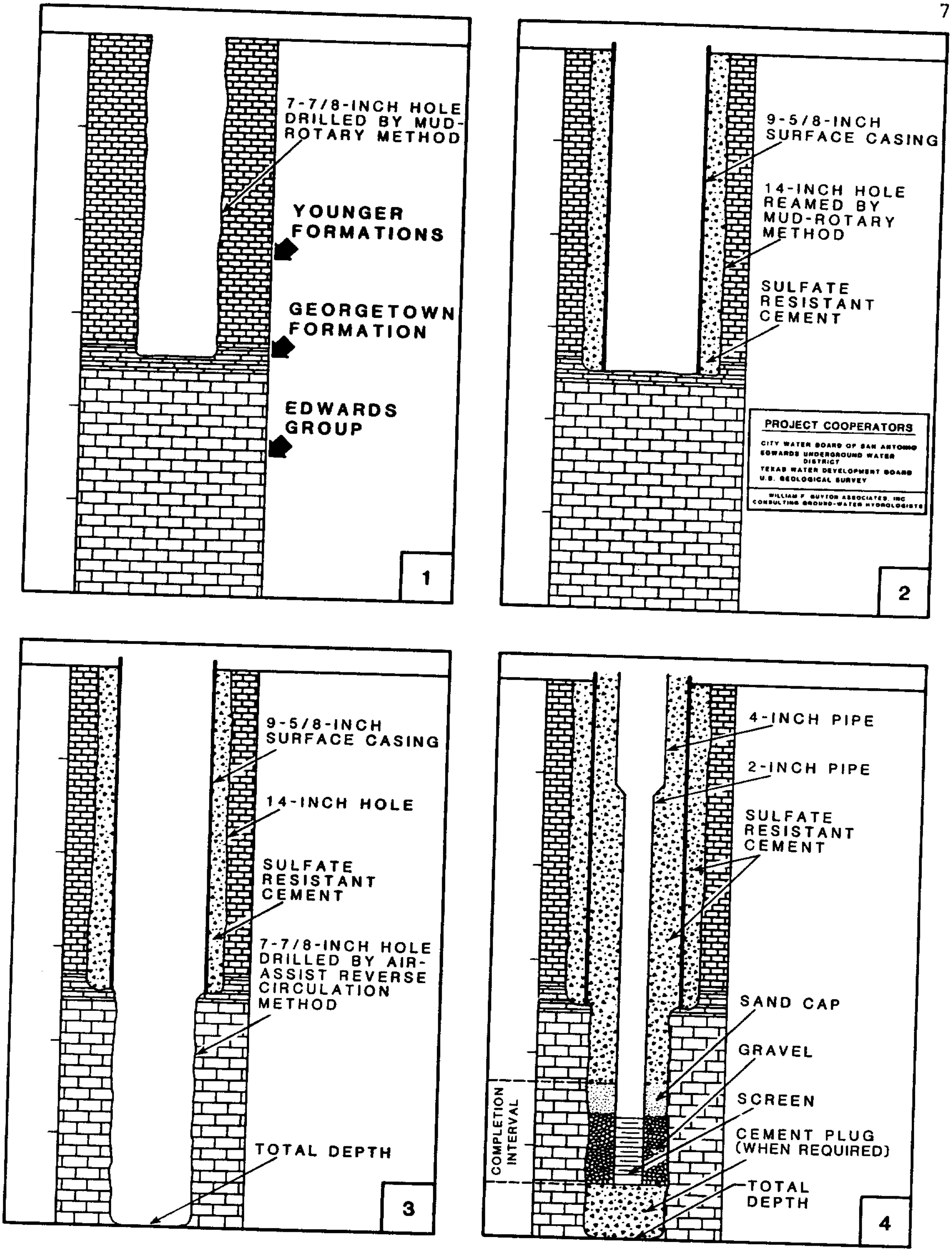
planned for the transition zone and fresh-water zone monitor wells, respectively, are located along the western edge of the Willow Springs Golf Course. It was initially anticipated that these three sites would suffice for the transect. However, while preparing to move the drilling equipment from Site A to Site B, a member of the City Parks Department reported that poor quality water had been produced from a well located between Site B and Site C when he lived in the area as a boy. While this well had apparently been abandoned many years ago and there are no factual data available for it, this firsthand eyewitness report of poor quality water indicated the transition zone was located farther north in the vicinity of Site C rather than Site B. Subsequent drilling and testing at Site C showed this was the case, and as a result, no drilling was conducted at Site B. The transect was then extended farther north by obtaining Site D to provide for monitor wells in the fresh-water zone. Site D is located on property belonging to Bexar County. Authorization to construct monitoring wells at this site with permission for monitoring during a minimum of 50 years was obtained for a nominal sum through negotiations with the Bexar County Coliseum Advisory Board, the agent for Bexar County.

Work Performed

A total of seven monitor wells was constructed along the transect of the bad water line. Three of the monitor wells were completed at Site A, two at Site C, and two at Site D. The wells at each site were completed at different depths to provide monitoring control for determining whether water levels and water quality at different levels in the Edwards aquifer reacted differently to stresses imposed on the aquifer system.

The initial work at each site involved drilling a primary test hole through the Edwards Group and into the underlying Glen Rose Formation. Information obtained from the primary test hole was used to select the depths at which monitor wells were to be constructed at the site with one of the monitor wells being constructed in the primary test hole. The four sequential steps involved in drilling and constructing each monitor well are shown on Figure 3. Completion data for the seven monitor wells that were constructed are presented in Table 1.

Drilling began at Site A on June 27, 1985 and final testing of Well D-2 at Site D was completed on May 7, 1986. The progress of monitor well drilling and construction is shown by the chart on Figure 4.



SEQUENCE OF DRILLING AND CONSTRUCTION

Figure 3

TABLE 1. MONITOR WELL COMPLETION DATA

Monitor Well Number		Ground Elevation, Feet	Total Depth, Feet	Surface Casing		Completion Interval, Feet 1/		Material Settings, Feet			Date Completed	Rate of Flow, gpm	Static Head, Feet 2/
Project	State			Diameter, Inches	Depth, Feet	From	To	Material	From	To			
A-1	AY-68-37-521	620	1,489	9	965	1,193	1,303	4-inch Pipe	0	200	8-14-85	22	24.0
								2-inch Pipe	200	1,218			
								2-inch Screen	1,218	1,264			
								2-inch Pipe	1,264	1,275			
A-2	AY-68-37-522	620	1,075	9	964	1,001	1,075	4-inch Pipe	0	200	9-17-85	24	29.8
								2-inch Pipe	200	1,014			
								2-inch Screen	1,014	1,067			
								2-inch Pipe	1,067	1,075			
A-3	AY-68-37-523	620	1,175	9	964	1,087	1,175	4-inch Pipe	0	200	10-21-85	35 3/	40.3
								2-inch Pipe	200	1,115			
								2-inch Screen	1,115	1,165			
								2-inch Pipe	1,165	1,175			
C-1	AY-68-37-524	626	1,396	9	832	840	891	4-inch Pipe	0	200	1-31-86	42	46.7
								2-inch Pipe	200	840			
								Open Hole	840	891			
C-2	AY-68-37-525	624	1,150	9	832	1,068	1,150	4-inch Pipe	0	200	1-22-86	28	46.2
								2-inch Pipe	200	1,090			
								2-inch Screen	1,090	1,140			
								2-inch Pipe	1,140	1,150			
D-1	AY-68-37-526	642	1,384	9	854	1,150	1,223	4-inch Pipe	0	200	4- 1-86	7.5	17.3
								2-inch Pipe	200	1,156			
								2-inch Screen	1,156	1,209			
								2-inch Pipe	1,209	1,220			
D-2	AY-68-37-527	641	926	7	874	874	926	Open Hole	874	926	5- 6-86	351	13.2

Footnotes:

1/ - Producing interval considered to extend from top of open hole or bottom of cement cap above sand and gravel envelope to bottom of open hole as drilled or plugged back from a greater drilled depth (as illustrated by part 4 of Figure 3).

2/ - Static head is in feet of water above ground level.

3/ - Pumped by airlift method because of small natural flow rate (13.3 gallons per minute).

EDWARDS AQUIFER BAD WATER LINE EXPERIMENT

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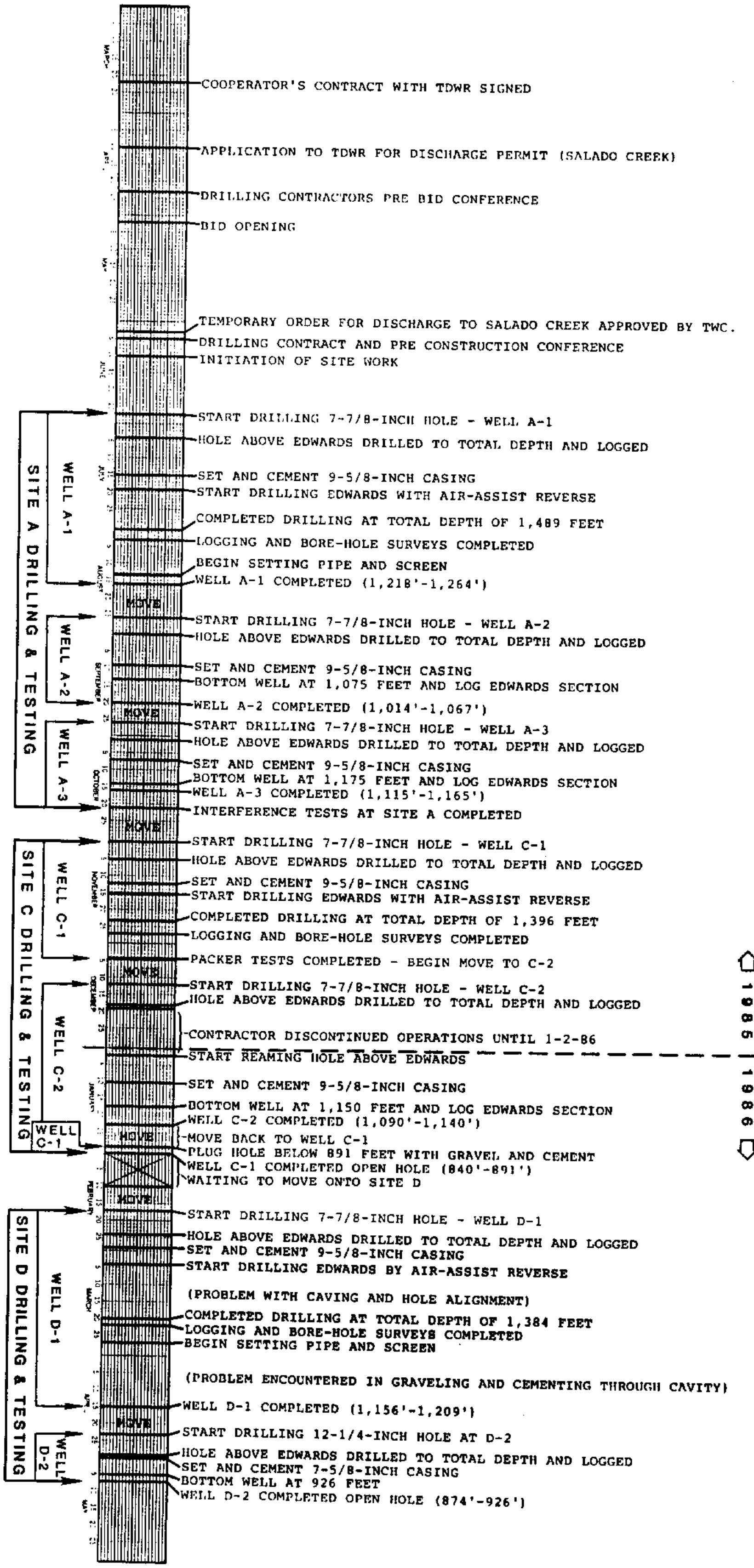


PROGRESS OF MONITOR WELL DRILLING AND CONSTRUCTION

Figure 4

Project Cooperators

The bad water line experiment was a cooperative endeavor entered into by the City Water Board of San Antonio, the Edwards Underground Water District, the Texas Water Development Board, and the U. S. Geological Survey. The City Water Board served as the Project Administrator and Manager to accomplish the project.

As discussed in the following section of this report, funding was provided by the City Water Board, the Edwards Underground Water District, and the Texas Water Development Board. The U. S. Geological Survey provided services in lieu of funds. These services included on-site collection of geohydrologic data, observation of drilling and construction operations, making geophysical logs and bore hole surveys of the Edwards portion of the primary test holes, and making chemical analyses of water samples. Geophysical logs of the section above the Edwards Group as well as the Edwards Group were made by the Texas Water Development Board and the Edwards Underground Water District at no direct charge to the project.

Management representatives for the cooperating agencies were: Mr. Robert P. Van Dyke, General Manager, for the City Water Board; Mr. Thomas P. Fox, General Manager, for the Edwards Underground Water District; Mr. Charles E. Nemir, Executive Administrator, for the Texas Water Development Board; and Mr. Charles W. Boning, District Engineer, for the U. S. Geological Survey.

The firm of William F. Guyton Associates, Inc. provided technical and some administrative services and general field direction of operations during the course of the project. The contractor for drilling, construction, and testing operations was the Layne Texas Company of Houston, Texas.

Technical representatives for the cooperating agencies were: Mr. Royce V. McDonald for the City Water Board of San Antonio, Mr. Robert W. Bader for the the Edwards Underground Water District, Mr. Robert L. Bluntzer for the Texas Water Development Board, and Mr. Charles R. Burchett for the U. S. Geological Survey. Mr. Mervin L. Klug represented William F. Guyton Associates, Inc. and Mr. W. Donald Endebrock was the field representative for the Layne Texas Company. On-site observations and collection of data were performed primarily by Messrs. Theodore A. Small, Paul L. Rettman, and Robert W. Maclay, and Miss Dianne Pavlicek, all of the U. S. Geological Survey.

Project Costs and Funding

Funding for the project was provided through contributions in cash by the City Water Board, Edwards Underground Water District, and the Texas Water Development Board, and through contribution of services by the U. S. Geological Survey. Project costs and funding beginning on March 22, 1985, the date of the contract and agreement between the cooperators, and extending through the preparation and presentation of this report at the conclusion of the project are as follows.

Project Costs

Drilling, Construction, and Testing	$1,411,500
U. S. Geological Survey Services	405,000
Technical and Administrative Services	136,000
Direct Costs and Contingencies	98,500
	$2,051,000

Project Funding

City Water Board (Cash)	$ 420,000
Edwards Underground Water District (Cash)	660,000
Texas Water Development Board (Cash)	566,000
U. S. Geological Survey (Services)	405,000
	$2,051,000

Project work also was done prior to execution of the contract and agreement by the cooperators. This work included preparation of specifications for drilling, construction, and testing of the monitor wells through contract with the Edwards Underground Water District in the amount of $17,500; work on siting the bad water line transect performed by the U. S. Geological Survey in the amount of $25,000 in services; and technical and administrative services related to siting the transect and other matters through contract with the City Water Board and Edwards Underground Water District in the amount of $4,600. Taking these costs into consideration, the total cost of the project was $2,098,100, of which $2,051,000 was funded through the cooperators contract and agreement of March 22, 1985.

Purpose for Report

This report describes the work that was performed, methodology, and preliminary results obtained from drilling, constructing, and testing the seven monitor wells located along the bad water line transect near the Artesia Well Field in the City of San Antonio. It includes a preliminary assessment of conditions along the transect. A detailed study of the geohydrologic data collected during the course of the drilling, construction, and testing is being made by the U. S. Geological Survey. The U. S. Geological Survey also is preparing a complete basic data report that is expected to be published in the near future.

Disposition of Data

A complete record of drilling, testing, and well construction operations was made during the course of the work. This record includes observations of drilling conditions and operations, field descriptions of drill cutting samples, and measurements made and recorded during testing and construction. The original record was retained by the U.S. Geological Survey and a copy was provided for the files of William F. Guyton Associates, Inc. Copies of the field measurements obtained during the drilling, testing, and construction operations were submitted to the Texas Water Development Board and constitute a basic field data file. Parts of the data are summarized in the tables and illustrations which accompany this report. A copy of the completion report that the Layne Texas Company prepared for the monitor wells has been supplied to each of the cooperative agencies.

Copies of geophysical logs and bore hole surveys, with the exception of television and acoustical televiewer surveys, were furnished to each of the cooperating agencies. Video cassettes of the television surveys were retained by the City Water Board of San Antonio and are on file there. Additional copies were purchased by the U.S. Geological Survey and William F. Guyton Associates, Inc. for their records. The acoustical televiewer surveys were retained by the U. S. Geological Survey.

A long-term program has been initated by the U. S. Geological Survey in cooperation with the City Water Board and the Edwards Underground Water District to monitor water levels and water quality at and near the bad water line transect. A current agreement exists that assures the continuity of this program over the next 50 years, and data obtained from this monitoring program will be submitted periodically to the Texas Water Development Board and the other cooperators. In addition, it is expected that reports will be prepared from time to time as data obtained from monitoring water levels and water quality become available and are evaluated.

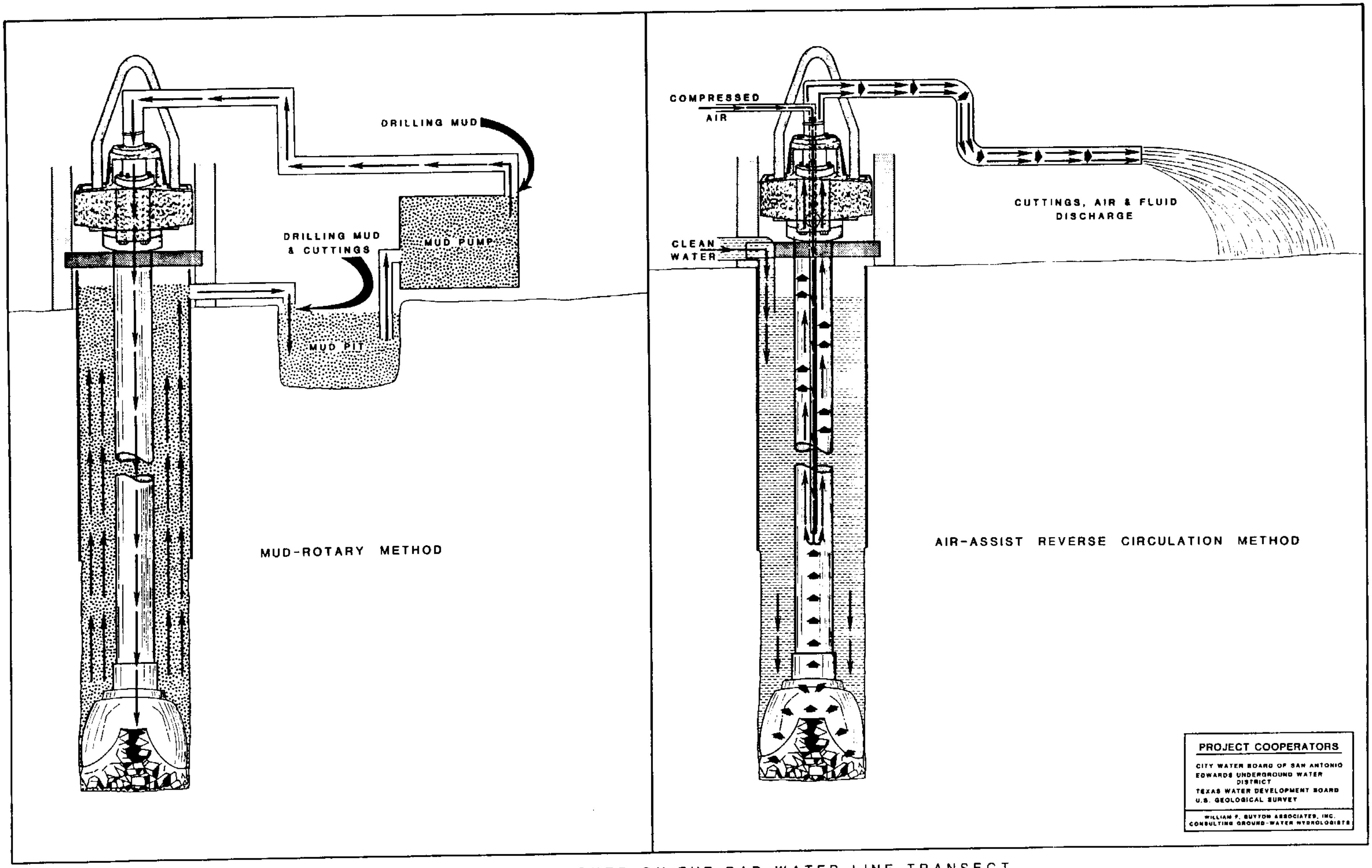
DRILLING METHODS

Two drilling methods were employed in drilling each of the holes in which the monitor wells on the bad water line were constructed. These were the standard mud-rotary method, which was used to drill and ream the portion of the hole generally above the upper part of the Georgetown Formation, and the air-assist reverse circulation method, which was used to drill the remainder of the hole through the Edwards Group and into the underlying Glen Rose Formation. These two methods of drilling are described in the following paragraphs and are shown schematically on Figure 5.

Mud-Rotary Method

The mud-rotary method of drilling was used to drill the hole through the material between the land surface and the depth to which surface casing was set and cemented into the Georgetown Formation just above the Edwards Group. As shown by the schematic drawing on Figure 5, the mud pump picks up the bentonitic mud which has been mixed and placed in the mud pit (in the case of the bad water line wells, above-ground steel mud holding tanks rather than mud pits were used) and then pumps it under pressure down the drill pipe and through ports in the drill bit. As the mud passes through the ports and across the cones in the drill bit, it picks up the rock fragments that have been dislodged from the formation by penetration of the drill bit. These rock fragments, which are commonly called drill cuttings, are then carried with the mud as it circulates back up the annulus between the drill pipe and the wall of the hole to the surface. At the surface the mud and cuttings are discharged into the mud pit or holding tank. The drill cuttings settle out of the fluid and the mud is then picked up again by the mud pump and recirculated through the system. Drilling mud and drill cuttings that collect in the holding tanks are disposed of by trucking them to a licensed disposal site as required by the Texas Water Commission.

The mud-rotary method of drilling was suited to drilling the hole above the Edwards aquifer because lost circulation conditions, which can cause problems, were not expected or encountered. Also the need for clean drill cuttings and preventing the mud from entering the formation were not matters of concern in this portion of the hole. The viscosity of the drilling mud and other mud properties can be controlled to improve the drilling action as materials having different drilling properties are encountered in drilling. Use of drilling mud was of some advantage because the mud cake that forms on the wall of the hole reduces the loss of



DRILLING METHODS EMPLOYED ON THE BAD WATER LINE TRANSECT

Figure 5

cement to the formation when the casing that is set through this section of the hole above the Edwards aquifer is cemented in place.

The mud tanks used to hold the drilling mud during mud-rotary drilling operations at the monitor well sites were equipped with sample collection boxes through which a portion of the drilling mud containing drill cuttings was diverted during drilling. The drill cuttings carried in this portion of the drilling fluid settle out in the sample boxes to provide representative samples of the sections being drilled. Drill cutting sampling procedures are discussed later in this report.

Air-Assist Reverse Circulation Method

The air-assist reverse circulation method was used to drill the portion of the hole below the bottom of the surface casing that had been set and cemented into the Georgetown Formation just above the top of the Edwards Group. Drilling by using this method began after the drilling mud inside the casing had been replaced with clean water. This drilling method is shown schematically in the right-hand part of Figure 5.

The method involves introducing compressed air into the drill pipe through an air line to pump water out of the hole as drilling takes place. As the produced water is drawn into the drill pipe through the ports near the cones on the bit, it draws drill cuttings dislodged during drilling into the drill pipe with it. The drill cuttings are carried up the drill pipe with the water and discharged with the air and fluid into the sample collection box and holding tank. Clean water was introduced at the surface to support the drilling operation until such time as sufficient water was supplied by the formations that were penetrated.

The air-assist reverse circulating method of drilling the Edwards Group had several advantages over the mud-rotary method. Lost circulation problems were avoided when the cavities that are present in the Edwards aquifer were encountered. As soon as the bit passed through the cavity and encountered the bottom, it immediately began drilling a hole. The drill cuttings were drawn into the drill pipe and carried to the surface rather than being forced upward in the hole outside the drill pipe and carried into the cavity with the escaping drilling fluid as would be the case with mud-rotary drilling. Thus, circulated drill cuttings of all the materials penetrated by the bit were available at the surface for collection and examination with the air-assist reverse circulation method of drilling. The cuttings were basically clean and could be readily examined to determine the type of materials that were being penetrated because no mud had been introduced into the hole. The drill cuttings are quickly carried to the surface where they are available for examination because of the small volume of fluid contained in the drill pipe and the relatively large air-lift pumping rate of from 100 to 200 gallons per minute.

Since there is no lost circulation with the air-assist reverse circulation method of drilling, once sufficient water was produced from the Edwards aquifer to support the drilling action, foreign fluids were not introduced into the hole where they could enter the producing zones and affect water quality. Thus, it was possible to check the mineral content of the water discharged at the surface during drilling to provide an indication as to whether changes in water quality occurred with depth as the hole was drilled.

Because water was continuously discharged at the surface during air-assist reverse circulation drilling, it was necessary to provide for disposal of the produced water. Disposal of drilling fluid is not a problem in the case of mud-rotary drilling because the fluid is continuously circulated and the amount of fluid involved is relatively small. Since some of the water produced from the Edwards aquifer was highly mineralized, a temporary permit was obtained from the Texas Water Commission for disposal of the produced water into Salado Creek which passes near the drilling sites. The permit had restrictions with regard to the amount and chemical quality of the water that could be discharged into the creek. Therefore, the quantity of water disposed of and its quality were monitored during drilling to make sure the limits were not exceeded.

DATA COLLECTION

The procedure followed at each of the three monitor well drilling sites was to begin by drilling a primary test hole. This primary test hole was drilled to penetrate the entire section of the Edwards Group. Information from the primary test hole was then used to identify the water-bearing zones in which monitor wells were to be constructed at that site. One of the monitor wells at each site, the deepest one with the exception of Site C, was constructed in the primary test hole. The following paragraphs discuss the collection of data from the primary test holes and from the other holes drilled for construction of additional monitor wells.

Primary Test Holes

Drillers' Logs. A log of the formations encountered in drilling each of the holes was kept by the driller. These logs describe in a very general way the types of materials that were encountered and their depths. Copies of the drillers' logs are included in the field data record books and in the drilling contractor's completion report.

Geolographs. Geolographs were made during all drilling operations in the test holes, both with the mud-rotary method and the air-assist reverse circulation method. The geolographs provide a record of the rate at which the drill hole penetrated the rock strata. Copies of the geolographs are included in the field data record books.

Drill Cutting Samples. Drill cutting samples were collected at each 10-foot interval of depth during drilling of the holes. Samples were collected while drilling by the mud-rotary method and the air-assist reverse circulation method. At each 10 feet of depth, drilling stopped and circulation or air-lift pumping continued until all drill cuttings from the last drilled section had been carried to the surface. A representative portion of the drill cuttings that had been deposited in the sample box were then collected. The sample box was cleaned of all drill cuttings before drilling of the next 10-foot interval was allowed to begin. The drill cutting samples were described in the field in the course of drilling to identify the formations and provide a basis for determining the depth at which drilling should stop for setting surface casing and when the hole had reached its total depth. The descriptions were recorded in field data record books. A summary of the stratigraphic units encountered in each primary test hole based on examination of drill cutting samples and study of borehole geophysical logs is given in Table 2.

Electric Logs Above The Edwards. Upon reaching the depth selected for setting the surface casing, an electric log and/or a gamma ray log was made in the hole prior to reaming it to a larger diameter for setting the surface casing. The electric and/or gamma ray log was studied to confirm that the depth selected for setting casing based on examination of drill cuttings was deep enough to have penetrated part of the limestone of the Georgetown Formation. They also were used in identifying the lithology. The electric and/or gamma ray logs of the hole above the Edwards Group were made by the Edwards Underground Water District and/or the Texas Water Development Board, depending on the availability of personnel and equipment at the time.

TABLE 2. STRATIGRAPHIC UNITS ENCOUNTERED ALONG TRANSECT OF BAD WATER LINE

Stratigraphic Unit	Primary Test Hole, Site A*		Primary Test Hole, Site C*		Primary Test Hole, Site D*		General Description of Lithology
	Depth to Top	Thickness	Depth to Top	Thickness	Depth to Top	Thickness	
Navarro Group	0	390	0	253	0	264	Clay, marl, and limestone
Taylor Group	390	156	253	151	264	176	Marl and calcareous clay
Anacacho Group	546	154	404	148	440	140	Marly chalk
Austin Group	700	112	552	118	580	130	Chalk, marl, and hard limestone
Eagle Ford Group	812	30	670	32	710	32	Shale, siltstone, and limestone
Buda Limestone	842	60	702	58	742	56	Limestone, hard, nodular
Del Rio Clay	902	52	760	60	798	46	Clay
Georgetown Formation	954	28	820	20	844	12	Limestone, dense, argillaceous
Edwards Group	982	507+	840	550	856	506	
Person Formation Undifferentiated	982	182	840	206	856	174	Limestone and dolomite
Regional Dense Member	1,164	22	1,046	24	1,030	11	Limestone, dense, argillaceous
Grainstone Member	1,186	74	1,070	50	1,041	59	Limestone, hard
Kirschberg and Dolomitic Members	1,260	200	1,120	220	1,100	220	Limestone, calcified dolomite, and dolomite
Basal Nodular Member	1,460	29+	1,340	50	1,320	42	Limestone, hard, dense, clayey
Glen Rose Formation	-	-	1,390	6+	1,362	22+	Limestone, dolomite, shale, and marl

* Elevations at land surface are: Site A, +620 Feet MSL; Site C, +626 Feet MSL; Site D, +642 Feet MSL
All depths and thicknesses are in feet.

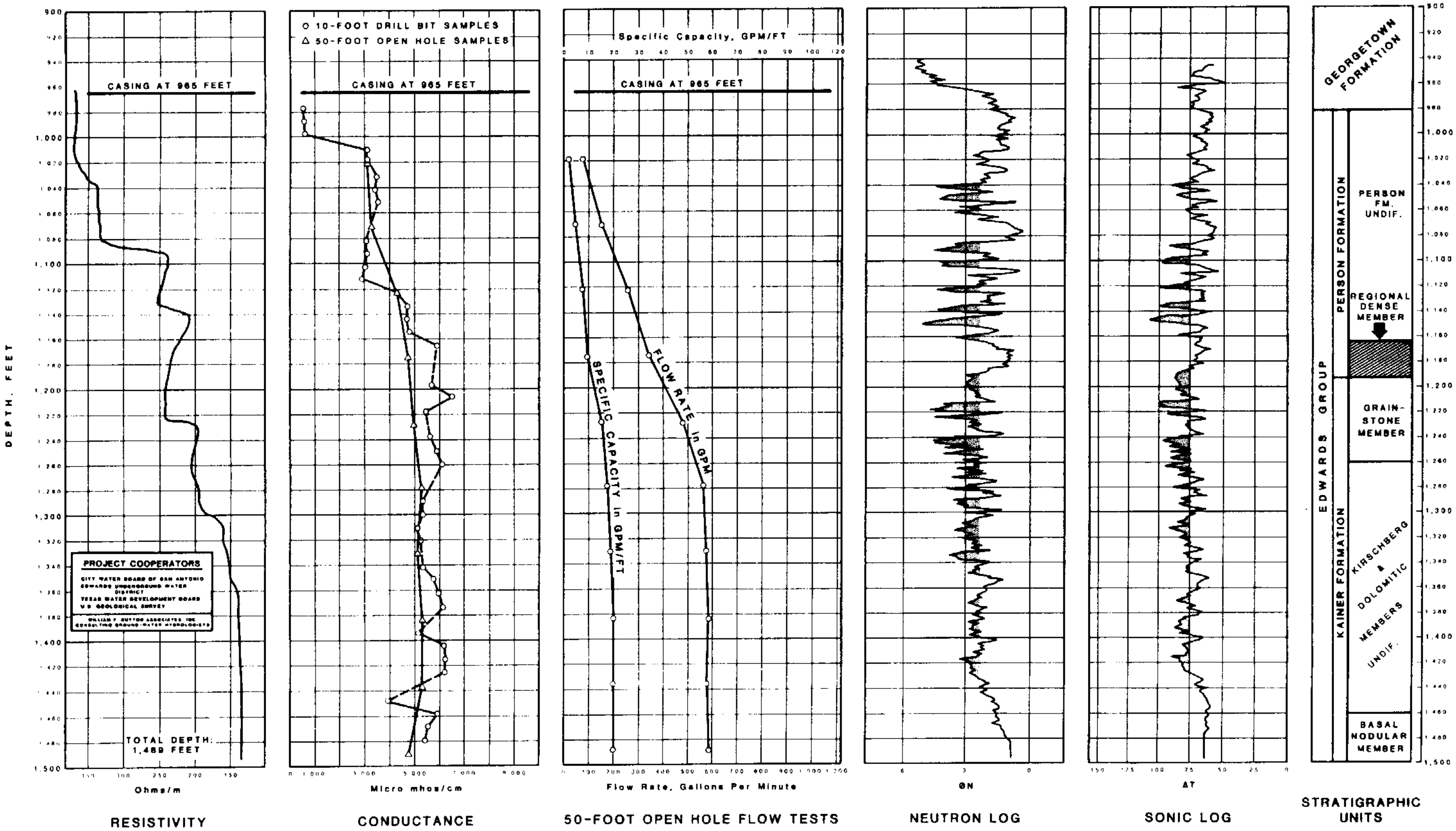
Water Quality Checks. Water samples were collected after drilling each 10-foot section of the Edwards aquifer to check the chemical quality of the water at that depth. A water sample was collected as soon as all drill cutting samples had been circulated to the surface and the produced water was reasonably clear of suspended materials. The conductance of each water sample was measured as it was collected to determine whether a change in quality had occurred. These conductivity measurements, which reflect the quality of the water produced from the full open-hole section between the bottom of the surface casing and the depths at which the samples were collected, were recorded in the field data record books. They also are plotted as part of the information for the primary test holes that is presented on Figures 6, 7, and 8.

50-Foot Flow Tests. At approximately each 50-foot depth of penetration of the Edwards aquifer, a flow test, herein referred to as a 50-foot flow test was made to obtain productivity information and water samples for chemical analysis. The 9-5/8-inch surface casing was equipped at the surface with a rotary drilling head, a blowout preventer, and discharge piping with valving to provide control of the natural flow of water from the hole at all times.

The 50-foot flow test involved stopping the penetration of the bit at every 50 feet of depth and allowing water from the primary test hole to flow to waste for a 1-hour period after the drill cutting samples had been collected from the last drilled 10-foot interval and the water had cleared. Flow was from the entire section of open hole that had been drilled to that depth, and discharge to the surface was through the annulus outside the drill pipe. The rate of flow and the above-ground head were measured periodically during the 1-hour flow period and recorded. At the end of 1 hour, water samples were collected for chemical analysis and the valve on the discharge piping was closed to stop the flow of water from the primary test hole. Water levels were then allowed to recover for a 1-hour period during which time the shut-in head (height of the water level above the land surface) was measured periodically and recorded.

The measurements of flow rates and the changes in head provided information for determining the productivity of the Edwards section that had been penetrated to that depth. It also provided information for determining specific capacity and an indication of the transmissivity of the section that had been tested. Once the 50-foot flow test had been completed, drilling resumed and continued until the depth for the next 50-foot flow test was reached, at which time the testing procedure was repeated.

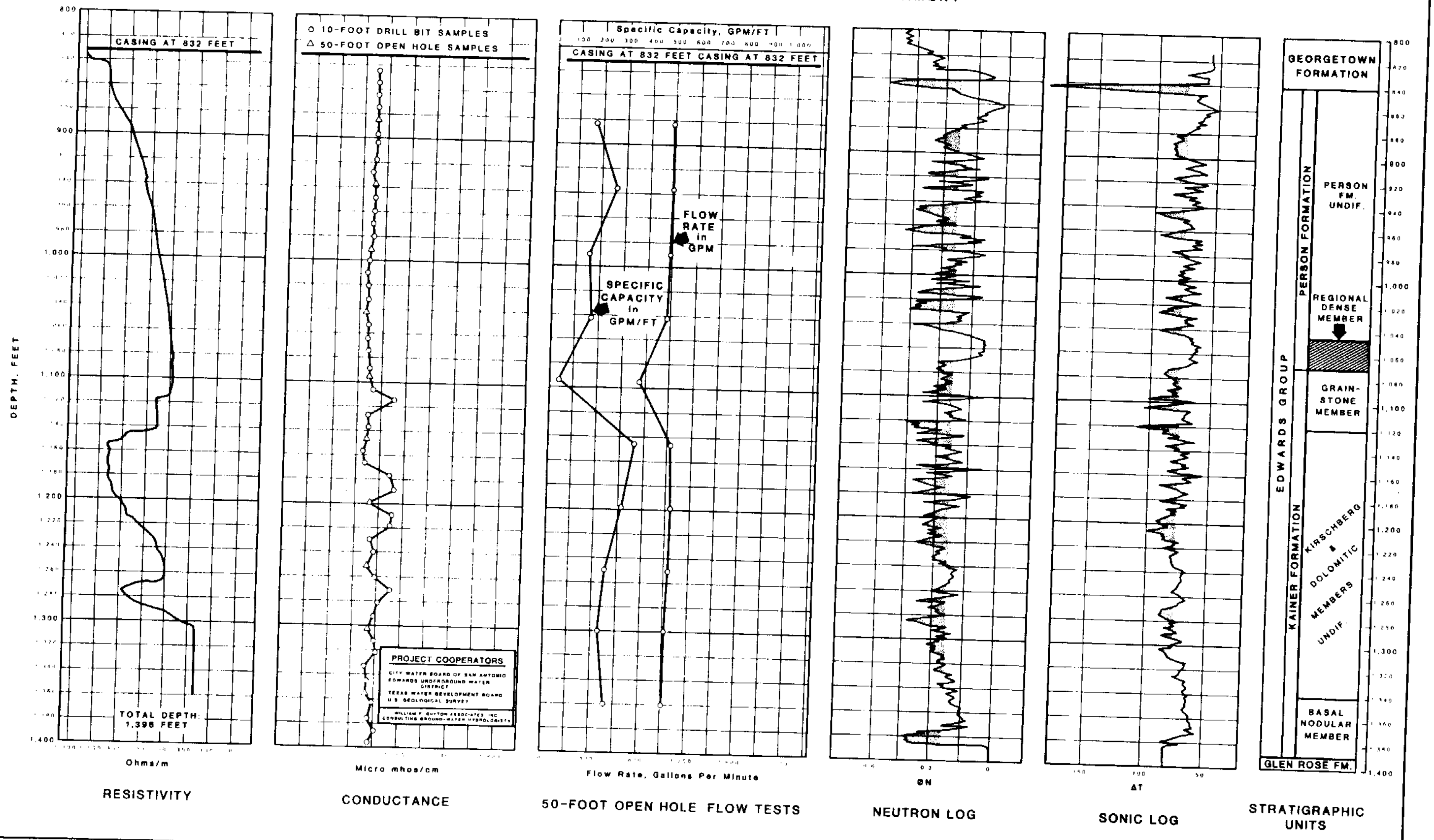
EDWARDS AQUIFER BAD WATER LINE EXPERIMENT



SELECTED INFORMATION FOR PRIMARY TEST HOLE AT SITE A

Figure 6

EDWARDS AQUIFER BAD WATER LINE EXPERIMENT



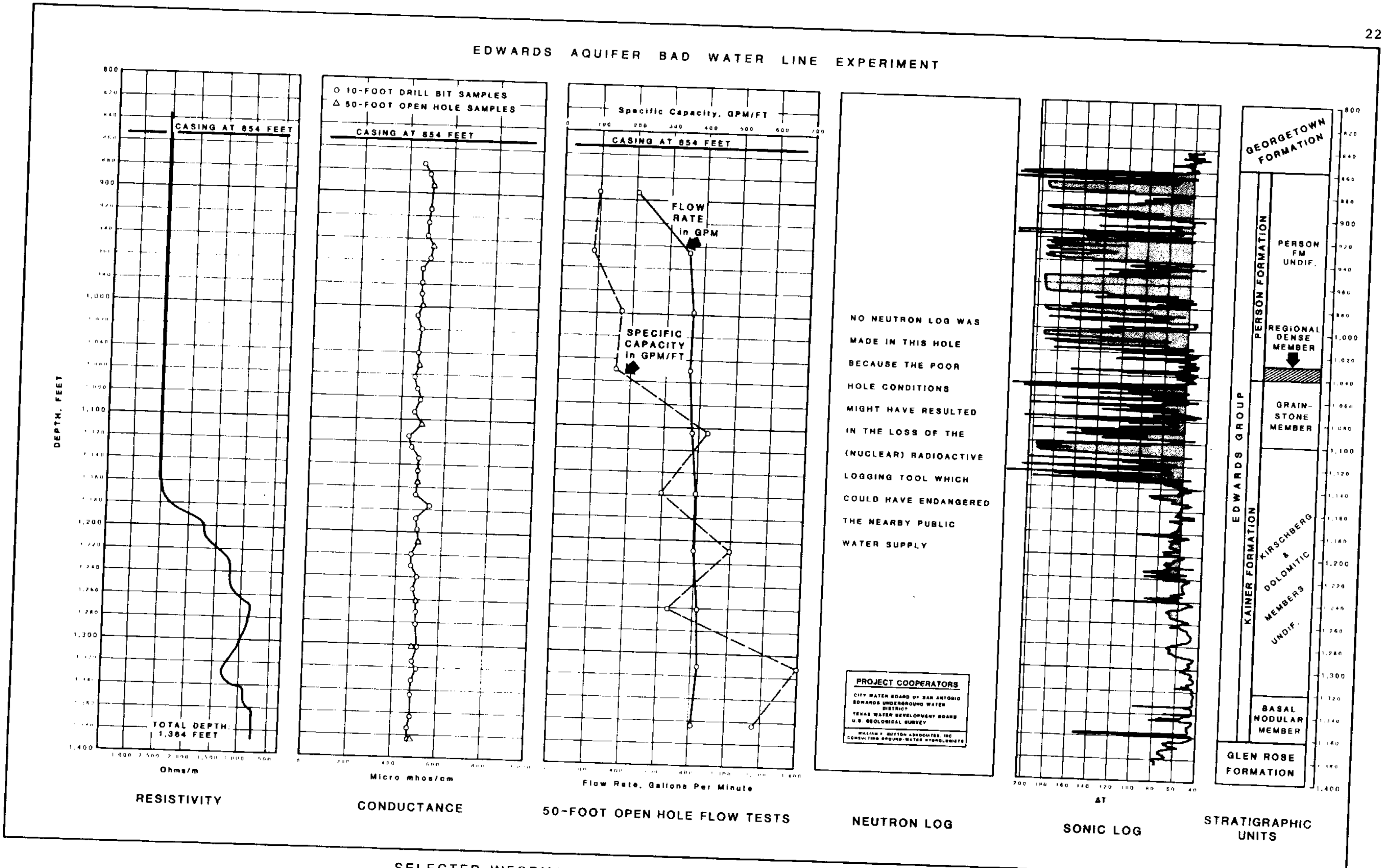
PROJECT COOPERATORS

CITY WATER BOARD OF SAN ANTONIO
EDWARDS UNDERGROUND WATER DISTRICT
TEXAS WATER DEVELOPMENT BOARD
U.S. GEOLOGICAL SURVEY

WILLIAM F. GUYTON ASSOCIATES, INC.
CONSULTING GROUND-WATER HYDROLOGISTS

SELECTED INFORMATION FOR PRIMARY TEST HOLE AT SITE C

Figure 7



NO NEUTRON LOG WAS MADE IN THIS HOLE BECAUSE THE POOR HOLE CONDITIONS MIGHT HAVE RESULTED IN THE LOSS OF THE (NUCLEAR) RADIOACTIVE LOGGING TOOL WHICH COULD HAVE ENDANGERED THE NEARBY PUBLIC WATER SUPPLY

PROJECT COOPERATORS

CITY WATER BOARD OF SAN ANTONIO
EDWARDS UNDERGROUND WATER DISTRICT
TEXAS WATER DEVELOPMENT BOARD
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SELECTED INFORMATION FOR PRIMARY TEST HOLE AT SITE D

Figure 8

Chemical analyses of the water samples collected during the 50-foot flow tests are given in Table 3 and productivity information is included in Table 4. Some of the chemical quality (resistivity and conductance) and productivity (flow rate and specific capacity) information also is plotted on Figures 6, 7, and 8.

Open-Hole Flow Tests. An open-hole flow test was conducted of each primary test hole after the hole had been drilled to its total depth. This test, which was made in lieu of a 50-foot flow test at this depth, involved removing the drill pipe, drill collars, and drill bit from the hole so that the natural flow of the well would not be impeded. After having been shut in for some time the valve on the discharge line was opened and water was allowed to flow from the hole at a reasonably large constant rate for which a positive above-ground head could be maintained during the period of flow. The flow rate was maintained at a constant rate by adjusting the valve on the discharge line, and measurements of flow rate and above-ground head were made periodically throughout the flow period.

Flow times ranged from 4 hours for the primary test hole at Site A to 7 hours for the primary test hole at Site D. The length of the flow periods was determined in large part by how long it took to establish a water-level trend during the flow period. At the end of the flow period the water samples were collected for chemical analysis and the valve on the discharge pipe was closed. Water levels were allowed to recover for a period of 2 hours after the valve was closed. During this 2-hour recovery period the shut-in head was measured periodically and recorded in the field data record book. Measurements made during the open-hole flow tests were used to evaluate productivity, specific capacity, and transmissivity of the Edwards at each drilling site.

Chemical analyses of water samples from the open-hole tests are included in Table 3 and productivity data are included in Table 4.

Geophysical Logs. Geophysical logs were made of the Edwards Group after each primary test hole had been drilled to its total depth. These included logs by Schlumberger Well Surveying Corporation at Sites A and C, by the U. S. Geological Survey at all three sites, A, C, and D, and by the Texas Water Development Board at Sites A and C. The Schlumberger logs included a dual induction spherically focused electric log, a compensated neutron density log with gamma ray, and a sonic/caliper log. The U. S. Geological Survey logs included an electric log, a focused guard log, an acoustic velocity log, a natural gamma log, and except for the primary test hole at Site D, a neutron log and a density log. A neutron log and a density log were not made in the primary test

TABLE 3. CHEMICAL ANALYSES OF 50-FOOT FLOW TEST SAMPLES FROM PRIMARY TEST HOLES
(Analyses by U.S. Geological Survey; results in milligrams per liter except pH and specific conductance)

Depth of Hole, feet	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved Solids	Specific Conductance, Micromhos/cm	Hardness as $CaCO_3$	pH	Temperature, °C
SITE "A", DEPTH TO BOTTOM OF CASING IS 965 FEET.														
1,021	17	320	100	250	16	262	920	440	2.2	2,190	3,200	1,200	6.4	31
1,071	16	280	110	250	15	262	950	450	2.3	2,200	3,320	1,100	6.1	32
1,123	18	460	140	340	20	281	1,300	670	2.5	3,090	4,260	1,700	6.6	32.5
1,180	18	460	160	370	21	284	1,400	760	2.6	3,390	4,550	1,800	6.5	33
1,228	18	480	170	400	23	287	1,500	770	2.7	3,510	4,940	1,900	6.7	33
1,279	17	420	170	380	24	284	1,500	810	2.7	3,500	4,260	1,700	6.7	33
1,331	18	430	180	380	28	289	1,400	750	2.6	3,300	5,080	1,600	6.8	33
1,384	18	430	180	390	26	291	1,500	860	2.7	3,580	5,300	1,800	6.7	33
1,437	18	420	170	440	25	282	1,300	810	2.8	3,306	5,280	1,700	6.5	33
1,489	18	510	180	400	25	283	1,500	840	2.7	3,600	5,230	2,000	6.6	33
SITE "C", DEPTH TO BOTTOM OF CASING IS 832 FEET.														
885	13	80	24	27	2.7	243	87	48	0.8	400	712	300	7	28.5
938	13	82	25	28	2.8	242	92	50	0.8	410	696	310	6.9	28.5
991	13	79	24	26	2.7	242	86	48	0.7	400	672	300	6.8	28.5
1,042	13	80	24	25	2.5	244	77	45	0.7	390	652	300	6.8	28.5
1,095	13	78	23	25	2.6	242	80	42	0.7	380	673	290	6.9	28.5
1,147	13	79	23	25	2.5	240	80	44	0.7	390	680	290	7.1	28.5
1,199	13	81	25	28	2.8	240	93	49	0.7	410	720	300	6.9	28.5
1,251	13	83	25	30	2.8	240	97	51	0.8	420	712	310	7.2	28.5
1,300	13	82	26	31	3.1	243	110	54	0.8	440	732	310	7.1	28.5
1,360	13	83	26	33	3.2	243	110	56	0.8	440	736	310	7.2	28.5
1,396	14	90	29	38	3.4	240	130	66	0.9	490	842	340	7.1	28.5
SITE "D", DEPTH TO BOTTOM OF CASING IS 854 FEET.														
894	12	63	17	10	1.4	240	23	16	0.3	260	511	230	6.9	25
947	12	64	17	10	1.3	242	24	17	0.3	260	520	230	6.8	26.5
999	12	64	17	9	1.3	243	27	16	0.3	-	480	230	6.8	26.5
1,052	12	65	17	10	1.3	244	17	17	0.3	260	475	230	6.9	26.5
1,105	11	64	17	10	1.3	242	17	17	0.3	260	495	230	6.8	26.5
1,157	12	64	17	10	1.3	240	16	17	0.3	-	482	230	6.8	26.5
1,209	12	64	17	10	1.3	234	24	17	0.3	260	495	230	6.9	26.5
1,261	11	64	17	10	1.2	232	23	17	0.3	260	495	230	6.7	26.5
1,312	11	63	16	9.7	1.2	242	18	16	0.3	250	482	220	6.9	26.5
1,384	11	63	16	9.8	1.3	229	23	17	0.4	250	490	220	7.0	26.5

TABLE 4. PRODUCTIVITY TESTS

Well	Interval Tested, Feet From	Interval Tested, Feet To	Date	Flow Rate, gpm	Static Head, Feet 1/	Measured Drawdown, Feet 2/	Adjusted Drawdown, Feet 3/	Specific Capacity, gpm/ft 4/	Approximate Transmissivity, gpd/ft 4/
A-1	50-Foot Flow Tests								
	965	1,021	7-22-85	96	40.0	35.6	35.0	2.7	-
	965	1,071	7-23-85	151	37.6	34.4	33.2	4.5	37,600
	965	1,123	7-24-85	257	37.1	33.8	30.4	8.4	32,500
	965	1,180	7-25-85	341	36.6	33.4	27.4	12.4	48,700
	965	1,228	7-25-85	481	35.2	31.8	20.0	24.0	55,000
	965	1,279	7-26-85	564	35.3	32.7	16.5	34.2	70,900
	965	1,331	7-29-85	575	34.1	30.7	13.7	42.0	69,000
	965	1,384	7-29-85	588	32.9	29.4	11.8	49.8	80,400
	965	1,437	7-30-85	576	32.7	29.3	12.3	46.8	58,400
	965	1,489	7-31-85	590	32.3	29.1	12.1	48.8	92,700
	Open-Hole Test								
	965	1,489	8- 2-85	378	30.9	9.6	8.4	45.0	86,800
	Packer Tests								
	965	1,075	8- 8-85	127	28.7	16.6	7.7	16.5	-
	965	1,177	8- 7-85	238	29.3	17.9	14.7	16.2	-
	1,177	1,489	8- 7-85	44	29.2	5.5	4.1	10.7	16,000
	1,276	1,489	8- 6-85	33	27.8	7.8	6.9	4.8	30,000
	Final Well (Screen)								
	1,218	1,264	8-14-85	22	24	23.7	23.1	0.9	-
A-2	50-Foot Flow Tests								
	964	1,019	9-13-85	9.1	18.5	16.3	16.3	0.6	-
	964	1,075	9-13-85	128	25.8	23.7	14.8	8.6	-
	Final Well (Screen)								
	1,014	1,067	9-17-85	24	29.8	14.4	4.8	5.0	11,700
A-3	50-Foot Flow Tests								
	964	1,019	10-10-85	5.4	35.9	32.2	32.2	0.2	60
	964	1,071	10-11-85	34	34.9	31.0	31.0	1.1	700
	964	1,123	10-14-85	73	34.9	31.7	31.3	2.3	9,800
	964	1,174	10-15-85	87	33.4	29.4	28.9	3.0	17,900
	Final Well (Screen)								
	1,115	1,165	10-21-85	35 5/	40.3	154.6	133.0	0.3	8,600

Table 4. Productivity Tests (Continued)

Well	Interval Tested, Feet From	Interval Tested, Feet To	Date	Flow Rate, gpm	Static Head, Feet 1/	Measured Drawdown, Feet 2/	Adjusted Drawdown, Feet 3/	Specific Capacity gpm/ft 4/	Approximate Transmissivity gpd/ft 4/
C-1	50-Foot Flow Tests								
	832	885	11-18-85	985	43.2	36.2	5.7	173	317,000
	832	938	11-19-85	992	41.9	34.7	3.7	268	-
	832	991	11-19-85	977	43.2	36.2	6.1	160	248,000
	832	1,042	11-20-85	971	43.0	35.8	5.9	164	288,000
	832	1,095	11-20-85	775	43.1	37.5	18.0 6/	-	301,000
	832	1,147	11-21-85	1,024	42.9	35.5	2.8	366	291,000
	832	1,199	11-21-85	1,026	43.1	35.9	3.2	320	274,000
	832	1,251	11-22-85	1,015	42.9	35.9	4.0	254	244,000
	832	1,300	11-22-85	1,011	42.6	35.8	4.4	230	230,000
	832	1,360	11-23-85	1,013	43.0	35.6	3.9	260	267,000
	Open-Hole Test								
	832	1,396	11-27-85	1,413	45.8	16.8	7.5	188	296,000
	Packer Tests								
	832	859	12- 2-85	1,127	48.1	36.0	22.7	49.6	444,000
	832	1,056	12- 3-85	1,147	48.8	37.7	25.2	45.5	488,000
	832	1,240	12- 4-85	1,167	48.5	38.4	25.1	46.5	335,000
	859	1,396	12- 2-85	96	44.4	29.7	25.3	3.8	8,800
	1,056	1,396	12- 3-85	72	42.2	26.8	23.6	3.1	6,070
	1,240	1,396	12- 4-85	27	41.9	30.7	30.1	0.9	2,650
	Final Well (Open Hole)								
	840	891	1-31-86	42	46.7	32.1	10.8	3.9	24,800
C-2	50-Foot Flow Tests								
	832	882	1-14-86	24	46.2	43.0	43.0	0.6	390
	832	932	1-15-86	27	45.9	42.7	42.7	0.6	360
	832	986	1-15-86	28	46.4	43.2	43.2	0.6	-
	832	1,049	1-16-86	31	46.9	43.7	43.7	0.7	310
	832	1,101	1-17-86	37	47.1	43.8	43.8	0.8	-
	832	1,150	1-17-86	96	45.9	42.2	41.6	2.3	5,190
	Packer Test								
	1,049	1,150	1-20-86	40	46.0	23.1	22.1	1.8	4,160
	Final Well (Screen)								
	1,090	1,140	1-22-86	28	46.2	29.1	15.0	1.9	4,700

Table 4. Productivity Tests (Continued)

Page 3

Well	Interval Tested, Feet From	Interval Tested, Feet To	Date	Flow Rate, gpm	Static Head, Feet 1/	Measured Drawdown, Feet 2/	Adjusted Drawdown, Feet 3/	Specific Capacity gpm/ft 4/	Approximate Transmissivity gpd/ft 4/
D-1	50-Foot Flow Tests								
	854	894	3- 4-86	412	25.8	8.5	4.2	98	-
	854	947	3- 5-86	713	25.5	20.4	8.1	88	-
	854	999	3- 6-86	743	25.2	18.6	4.4	170	-
	854	1,052	3- 7-86	733	25.1	19.0	4.4	160	541,000
	854	1,105	3-12-86	768	24.5	18.4	1.8	426	-
	854	1,157	3-14-86	797	25.3	20.2	2.7	295	-
	854	1,209	3-17-86	797	24.3	19.1	1.6	498	-
	854	1,261	3-18-86	825	24.6	20.2	2.5	330	-
	854	1,312	3-19-86	838	24.5	20.3	1.2	698	-
	854	1,364	3-20-86	809	23.6	19.4	1.4	577	-
	Open-Hole Test								
	854	1,384	3-24-86	1,348	21.1	13.2	3.0	449	591,000
	Packer Tests								
	1,040	1,384	3-27-86	64	18.5	7.2	4.6	13.9	21,000
	1,158	1,384	3-25-86	34	22.3	10.0	9.1	3.7	40,000
	1,225	1,384	3-26-86	5.5	20.5	9.4	9.4	0.4	3,400
	Final Well (Screen)								
	1,156	1,209	4- 1-86	7.5	17.3	2.8	1.5	5.0	-
D-2	Final Well (Open Hole)								
	874	926	5- 6-86	351	13.2	4.8	1.8	195	-

Footnotes:

1/ - Static head is in feet of water above ground level.

2/ - Measured drawdown determined from field measurements.

3/ - Drawdown adjusted for estimated head losses in pipe and hole due to friction.

4/ - Values are from analysis of water-level data and are approximate due to areal fluctuations in water levels and the effect of changing water quality and temperature in water column.

5/ - Pumped by airlift method because of small natural flow rate (13.3 gallons per minute).

6/ - Mud ball formed during drilling restricted flow through annulus and caused additional unaccounted for head loss.

hole at Site D because the dangerously poor condition of the hole could have resulted in the loss of the nuclear logging source required for making these logs. Logs made by the Texas Water Development Board included electric logs and gamma ray logs. No logs were made in the primary test hole at Site D by Schlumberger or the Texas Water Development Board because of the danger of losing logging tools in the hole.

Information from the logs was used as an aid in determining contacts between geologic units, formation porosity, zones of possible productivity, and water quality. As noted earlier in this report, copies of the geophysical logs described above have been provided each of the cooperating agencies on this project. A tracing of the neutron, sonic, and caliper logs is included with the selected primary test hole information that is presented for the respective primary test holes on Figures 6, 7, and 8.

Bore Hole Surveys. A drift-indicator survey was made to determine the vertical alignment of each bore hole. Deviations from vertical were measured at intervals of approximately 30 feet of depth to the total depth of the hole by means of an Eastman mechanical drift indicator. A maximum deviation from vertical of 1 degree was allowed, and if this amount of deviation was exceeded as was the case at Site D, the drilling contractor straightened the hole until it was within this limit. Deviations from vertical are included in Layne Texas' monitor well completion report. Good alignment was required to be sure the spacing at depth between the holes drilled at each site was reasonably close to that at the surface, and to facilitate proper placement of materials in the holes for construction of monitor wells.

Other types of bore hole surveys also were made of the Edwards Group portions of the primary test holes. These included a temperature log, water resistivity log, and spinner (velocity) log which the U. S. Geological Survey made in all three primary test holes. A spinner and temperature survey also was made by Schlumberger in the primary test hole at Site A, but they were not as sensitive as the logs provided by the U. S. Geological Survey. Therefore, these Schlumberger bore hole surveys were not made in the primary test holes at the two other drilling sites.

Information from the U. S. Geological Survey bore hole surveys was used as an aid in identifying the better zones of production in the primary test holes and in selecting intervals for completion of monitor wells. Copies of the U. S. Geological Survey and Schlumberger logs have been provided to the cooperating agencies. Curves from the water resistivity surveys are included with the information presented for the respective primary test holes on Figures 6, 7, and 8.

Television Survey. A television survey was made in each of the three primary test holes after it had been drilled to its total depth, the hole had been flushed by production of water at high rates during the open-hole flow test, and the geophysical and other bore hole logs referred to above had been made. Video cassette recordings were made of the television survey and they are filed at the City Water Board of San Antonio. Copies of the video cassette recordings were purchased by the U. S. Geological Survey and William F. Guyton Associates, Inc. for internal use and are available for reference in the event they are needed.

The U. S. Geological Survey in the course of its logging operations made what is referred to as an acoustical televiewer survey. This survey presents by means of gradational black and white shading on a continuous log the porosity that is detected from a 360-degree scan of the bore hole. Copies of these logs, which were made in all three primary test holes, were retained by the U. S. Geological Survey and are available there for examination.

Information from the television and acoustical televiewer surveys was used to assess the general porosity of the exposed formation and the condition of the bore hole in terms of cracks, fractures, cavities, and caving. The condition of the hole was important in selecting depths at which expandable packers could be set to obtain an acceptable seal for making packer tests and in determining the depths at which monitor wells should be completed. They also were useful in deciding where cement and gravel should be placed in plugging the hole below the selected depth of well completion and in filling the annulus outside the production string.

Packer Tests. Packer tests were made in the primary test hole to provide information on productivity and water quality for selected intervals of the Edwards aquifer. The intervals tested were selected from an evaluation of the information collected during drilling, testing, and logging. A packer test involved expanding an inflatable packer attached to the end of drill pipe set at the depth below which productivity and water-quality information was desired. The packer isolated the section below the packer from which water was produced through the drill pipe by pumping or natural flow. A valve was installed on the drill pipe to control natural flow. Because of natural flow conditions, it also was possible to test the open-hole section of the Edwards aquifer above the packer at each setting, if desired, as well as the section below it. The flow from the annulus outside the drill pipe was controlled with the rotary drilling head, the blowout preventer, and the discharge piping equipment installed on the 9-inch surface casing. The packer was installed at three different settings in each of the three primary test holes. Four tests were conducted at Site A (three below the packer and one above), six at Site C (three below the packer and three above the packer), and three at Site D (below the packer).

The testing procedure was similar to the open-hole tests which are described above. Water was allowed to flow from the section to be tested at a rate that could be maintained with an above-ground head during the period of the test. After water samples were collected just prior to the end of the flow period, the valve was closed to stop the flow and water levels were allowed to recover. Flow periods ranged from about 4 hours for the test at Sites A and C, to as much as 9 hours at Site D where the effects of nearby pumping from the Artesia Well Field required a longer period to establish a water-level trend. Water levels recovered quickly to near the original static level in the primary test holes once pumping stopped. Therefore, the recovery periods ranged from 1 hour at Site D to 2 hours at Sites A and C. Constant flow rates were maintained during the tests by adjusting the valve installed on the discharge pipe. Water levels in the producing section were measured periodically, during both the pumping and recovery periods. Water levels also were measured in the section that had been isolated from the producing section by means of the packer to insure that an adequate seal had been obtained.

Data obtained from the packer tests were used to determine specific-capacity values and approximate transmissivities for the sections tested. The results of these tests are included in Table 4. As indicated in Table 4, the data for some of the packer tests were considered inadequate for arriving at approximate transmissivity values. The results of chemical analyses that were made of the water samples collected during the packer test are presented in Table 5.

Test Holes for Other Monitor Wells

The same information for the section above the Edwards that was obtained for the primary test holes was obtained for each of the holes drilled for construction of the other monitor wells at the drilling sites. Information obtained for the hole drilled through the Edwards Group at these other monitor wells includes drillers' logs, drill cutting samples, electric and/or gamma ray logs, 10-foot water conductivity measurements, and 50-foot flow test data. The only logs made in the hole drilled below the surface casing for constructing the other monitor wells were logs that were made by the Texas Water Development Board or the Edwards

TABLE 5. CHEMICAL ANALYSES OF WATER SAMPLES COLLECTED DURING PACKER TESTS

(Analyses by U.S. Geological Survey; results in milligrams per liter except pH and specific conductance)

Depth of Interval Tested, Ft. From To	Date Sampled	Production Rate, gpm	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved Solids	Specific Conductance, Micromhos/cm	Hardness as $CaCO_3$	pH	Temperature, °C
SITE "A" - PRIMARY TEST HOLE																
965-1,075	8-8-85	127	16	260	89	200	13	259	370	380	2	1,900	2,680	1,000	6.9	32
965-1,177	8-7-85	238	17	390	140	320	21	273	1,200	570	2.5	2,900	4,040	1,600	6.6	32.5
1,177-1,489	8-7-85	44	19	590	210	430	29	293	1,800	1,000	2.9	4,300	6,060	2,300	6.5	33
1,276-1,489	8-6-85	33	20	600	230	550	33	304	2,000	1,200	3	4,800	6,650	2,400	6.6	33
SITE "C" - PRIMARY TEST HOLE																
832-859	12-2-85	1,127	14	87	28	35	3.4	228	130	60	0.9	470	772	330	6.8	28.5
832-1,056	12-3-85	1,147	14	88	28	35	3.3	240	120	59	0.9	470	784	330	6.9	28.5
832-1,240	12-4-85	1,127	14	87	27	35	3.2	240	120	61	0.9	470	826	330	7	-
859-1,396	12-2-85	96	16	390	170	340	21	268	1,300	760	2.3	3,100	3,860	-	6.6	29
1,056-1,396	12-3-85	72	17	560	250	540	29	300	1,800	1,100	2.7	4,400	5,860	2,400	6.7	29
1,240-1,396	12-4-85	27	17	560	250	550	31	300	1,900	1,100	2.8	4,600	5,870	2,400	6.5	29
SITE "D" - PRIMARY TEST HOLE																
1,040-1,384	3-27-86	64	12	64	16	9.9	1.2	241	16	17	0.3	260	474	230	6.9	26.5
1,158-1,384	3-25-86	31	13	170	69	120	7.8	249	470	220	1.2	1,200	-	710	6.9	26.5
1,225-1,384	3-26-86	3	20	630	280	600	33	311	2,000	1,100	3.3	4,800	6,380	2,700	7.1	-

Underground Water District. Except for alignment surveys, no bore hole surveys were made of the holes drilled below the surface casing for constructing the other monitor wells. Only one packer test was made in the test holes drilled for the other monitor wells, and this was at the site of Monitor Well C-2. The packer test was made in that hole to be sure there was sufficient production in the lower part of the hole that had been drilled to insure satisfactory completion of the monitor well at that depth. Productivity information from this packer test is included in Table 4.

MONITOR WELL CONSTRUCTION

Sequence of Drilling and Construction

The sequence of drilling and constructing the monitor wells is shown numerically by stages on Figure 3. It involves the following sequential steps.

Stage 1.

1. A 7-7/8-inch hole is drilled into the Georgetown Formation using the mud-rotary method of drilling.

Stage 2.

1. The 7-7/8-inch hole is reamed to a diameter of 14 inches (12 inches at Monitor Well D-2) using the mud-rotary method of drilling.

2. A 9-5/8-inch O.D. casing is installed to near the total depth of the 14-inch hole (7-5/8-inch O.D. casing installed in 12-inch hole at Monitor Well D-2).

3. The 9-5/8-inch casing is cemented back to the surface by placing sulfate-resistant cement in the annulus between the casing and the wall of the hole.

Stage 3.

1. A 7-7/8-inch hole (6-1/2-inch hole at Monitor Well D-2) is drilled in the Edwards aquifer below the surface casing using the air-assist reverse circulation method of drilling. This hole penetrates the entire section of the Edwards Group in the primary test holes and only to the depth selected for well completion at the other well sites.

Stage 4.

1. A cement plug is placed in the hole below the depth selected for well completion in the primary test hole (gravel is used between cement plugs if zones of high porosity are encountered, or if the length of the hole to be plugged is large).

2. Materials are installed for well construction as follows:

   a. A length of 2-inch pipe is placed at the bottom of the production string to serve as a sump for materials drawn into the well during development.

   b. Manufactured stainless steel screen, approximately 50 feet in length, is placed above the 2-inch sump. Stainless steel was used to insure the long-life required for 50 years or more of monitoring.

   c. Blank 2-inch pipe is installed from the top of the screen upward to within 200 feet of the surface.

   d. Blank 4-inch pipe is installed from a depth of 200 feet to a level a few feet above land surface. This 4-inch pipe allows a pump to be installed in the monitor well to produce water for collection of water samples if and when water levels decline to levels that provide unacceptable rates of natural flow.

   e. The 4-inch pipe is capped at the top and equipped with a valve to control the flow of water from the well.

3. Gravel is placed around the screen and the 2-inch pipe to a level several feet above the top of the screen to provide support for cementing the annulus back to the surface.

4. A layer of sand is placed above the top of the gravel to minimize invasion of cement into the gravel envelope.

5. Cement is placed in stages to fill and seal the annulus between the production string and the wall of the hole and surface casing back to the surface. In very porous zones gravel was placed in the annulus to provide fill up between underlying and overlying cemented zones. Cement in the annulus was placed in stages in order to prevent high pressure due to the height of the column of cement which would cause excessive loss of cement into the sand

layer on top of the gravel envelope or into cracks and porous zones in the Edwards Group.

Information on hole depths, and material sizes and settings is given in Table 1. The deepest monitor wells at Sites A and D were constructed in the primary test holes. At Site C a large cavity was encountered at the top of the Edwards aquifer in the primary test hole, and the hole for the other monitor well planned for this site was drilled to find out if cementing through the cavity could be avoided. The cavity was not encountered at the site of Monitor Well C-2 so the deeper well was constructed there. The primary test hole was then plugged back, and Monitor Well C-1 was constructed in it to produce water from the cavity in the upper part of the Edwards aquifer. No screen was installed in Monitor Well C-1, but a 4-inch and 2-inch production string with cementing baskets attached at the lower end of the 2-inch pipe was set in the 7-7/8-inch hole to just above the large cavity and the annulus above the cementing brackets was cemented back to the surface.

A similar cavity was encountered in the primary test hole at Site D, but the deeper well was constructed in it because of general aquifer conditions in the area and financial constraints. Problems were encountered in filling the annulus in the upper part of the hole where the large cavity was encountered, and considerable time and material were expended in completing the monitor well through this section.

The dimensions of Monitor Well D-2 also were modified because of financial constraints. No 2-inch or 4-inch pipe was set in this well, and the 7-5/8-inch O.D. surface casing serves as a production string for the water produced from the 6-inch hole that was drilled into the Edwards aquifer. Smaller hole and casing diameters were feasible in this case because no logging operations, bore hole surveys, or packer tests were planned for the Edwards Group.

Selection of Hole and Pipe Diameters

Diameters of 9-5/8 inches O.D. for the surface casing and 7-7/8 inches for the hole through the Edwards Group were the minimum feasible sizes which allowed for drilling, testing, and construction operations. The diameter of the hole through the Edwards had to be large enough to accept the logging and bore hole surveying instruments and for installation and operation of expandable packers for testing. The surface casing in turn had to be large enough in diameter to permit drilling the 7-7/8-inch hole into the Edwards aquifer and also to allow room for insertion of a tremie pipe in the annulus between the 4-1/2-inch O.D. pipe of the production string and the surface casing for placement of cement, sand, and gravel in constructing the monitor wells. A 4-inch diameter pipe is the smallest practicable size for installation of a submersible pump that will produce water at an acceptable rate for collection of water samples during long-term monitoring. Two-inch pipe and screen are considered to be the smallest size which will keep head losses due to pipe friction reasonably low at the yields that are desirable for water-sampling operations. In addition, the small diameter is needed in order to allow a tremie pipe to be inserted between the production string and the 7-7/8-inch hole for placement of gravel, sand, and cement.

Placement of Cement, Sand, and Gravel

Sulfate-resistant cement was used for plugging the bottom of the hole and for filling the annulus between the production string and the hole and surface casing in order to provide an effective seal and protection that would last during the expected 50 years or more of monitoring water levels and water quality.

The surface casing was cemented by using the standard Halliburton pumped plug method which involves forcing a predetermined volume of cement down the casing and into the annulus between the casing and the hole from the bottom upwards. In those instances where cement pumped into the annulus was insufficient to fill the annulus all the way back to the surface, the depth of the hardened cement in the annulus was sounded, a cementing line was installed to just above the top of the hardened cement, and cement was then placed in the annulus through the cementing line until the level of the cement was at the surface.

Gravel, sand, and cement used for filling the holes drilled deeper than the planned depth of well completion and for filling the annulus between the production string and the wall of the hole and surface casing were placed through a tremie line. Cement in the annulus above the gravel and sand that formed the envelope around the screen was placed in stages to minimize the loss of cement into the Edwards aquifer and the upper part of the gravel envelope. Cement placed in each stage was allowed to harden sufficiently for it to support the weight of the next stage of cement to be placed above it before cementing operations continued. As noted earlier, gravel was placed opposite the very porous zones in the Edwards aquifer to prevent the loss of cement. Any vertical communication between the porous zones through the bore hole was prevented by the cement that was placed above and below each section of gravel.

Well Completion Checks

Production from each monitor well was checked immediately following the placement of the first stage of cement above the sand layer on top of the gravel envelope. This was done to be sure that the cement had not moved into the producing section through the gravel or through cracks or openings in the Edwards aquifer.

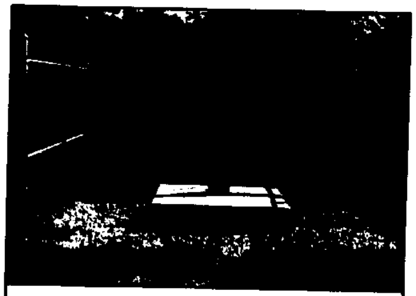
Surface Facilities

Concrete slabs, as required by the Texas Water Commission Rules and Regulations, were placed around the monitor wells at the surface after they had been constructed.

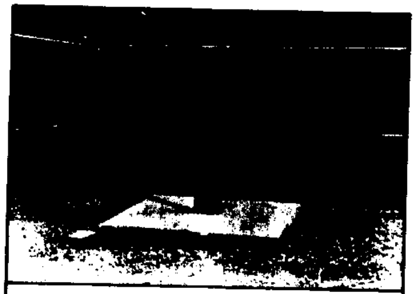
At Wells D-1 and D-2 the top of the surface casing is about 4 feet below ground level. A concrete slab was poured at this level and a 48-inch diameter reinforced concrete pipe was set from the land surface down to the top of this slab to provide a vault. The 4-inch pipe which extends upward through this vault is equipped with a 4-inch gate valve just above the bottom of the vault. The vault is filled with sand to just above the land surface where a second concrete slab was poured to provide the foundation around the well. Construction of this vault allows for continued monitoring of water levels and water quality in the event the Bexar County Coliseum Board requires use of the land surface for parking lots or other facilities. This can be accomplished by removing the concrete slab at the surface, the sand from inside the vault, and the piping above the 4-inch gate valve at the bottom of the vault, and then installing an access cover which will allow periodic entry for monitoring purposes. Special drainage facilities for water produced during sampling also were provided at the sites of Monitor Well D-1 and D-2 to avoid interference with use of the surrounding land by the Bexar County Coliseum Board.

Each monitor well is enclosed by a 6-foot chain-link fence equipped with a gate that provides access to the well. The fencing meets the requirements of the City of San Antonio Parks Department and the Bexar County Coliseum Board and provides protection for the well, any monitoring equipment that is installed, and the cathodic protection equipment which is an integral part of the monitoring well system. Photographs of the completed monitor well installations are shown on Figure 9.

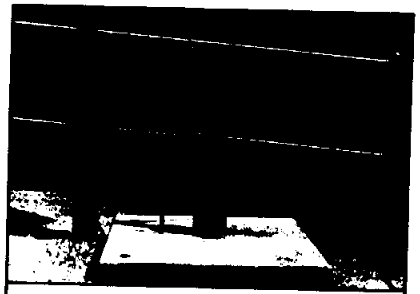
MONITOR WELL A-1



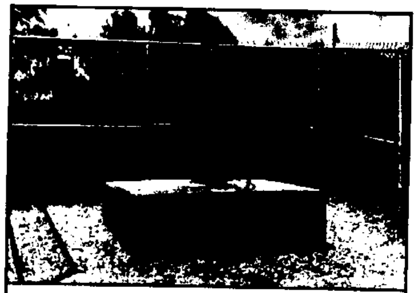
MONITOR WELL A-2



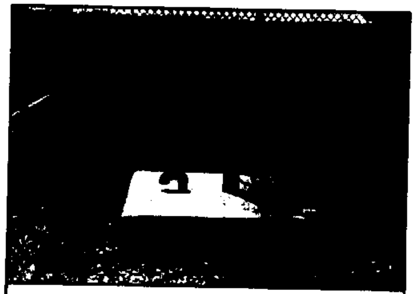
MONITOR WELL A-3



MONITOR WELL C-1

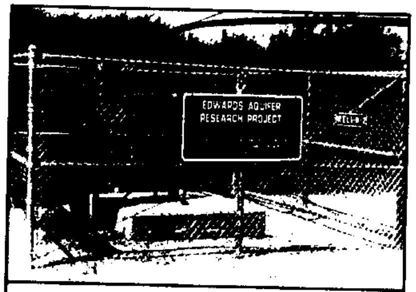


MONITOR WELL C-2



MONITOR WELL D-1

MONITOR WELL D-2



TYPICAL
SITE IDENTIFICATION

COMPLETED MONITOR WELLS ON THE BAD WATER LINE TRANSECT

Figure 9

Cathodic Protection

Cathodic protection is provided for all the monitor wells to prevent corrosion of the piping during the expected 50 or more years of monitoring. Natural electrical current that is present in the earth removes metallic ions from the production string and surface casing and deposits them elsewhere in the ground. In time this could cause holes to form in the production string and casing. Any leaks that might develop in the piping as a result of corrosion could jeopardize what was learned from long-term monitoring along the bad water line transect. The principle of the cathodic protection is to induce an electrical current into the system which reverses the flow of electrical current and prevents the removal of metallic ions from the production string and surface casing.

The cathodic protection installed in the monitor wells involved installation of a ground well in which fluidized carbon and anodes are installed. A 10-inch diameter hole was drilled to a depth of approximately 185 feet using the standard mud-rotary method of drilling. A 6-inch extra-strength plastic casing with perforations opposite predetermined levels at which the graphite anodes were to be positioned was then installed in the hole. Seven graphite anodes were then lowered inside the plastic casing on wire leads to predetermined depths and a slurry of fluidized carbon was introduced to fill the plastic casing and the annulus around it back to the land surface. The lead wires were then run to a junction box at a central location. The plastic casing was capped and a concrete foundation was poured around it. The positive lead from the rectifier which provides direct current from an alternating current source is connected to the anode junction box. The negative lead from the rectifier is connected directly to the casing and production string at each monitor well that is to be protected. The rectifier system is equipped with a DC output meter and controls for adjusting the amount of current introduced into the system to the level required for adequate cathodic protection. The carbon anodes installed in the ground beds are replaceable if this should be required in time.

Test of Completed Monitor Well

Completed monitor wells were tested to obtain information on productivity and water quality and to determine whether a hydraulic connection existed between the different zones screened by the monitor wells at each site. Productivity testing consisted of allowing a well to flow at a controlled constant rate for 1 or more hours and then stopping the flow and allowing the water level to recover. Measurements were made of the flow rate and the above-ground head periodically throughout the test and recorded. These data were subsequently analyzed to determine productivity and an index of aquifer transmissivity. Productivity and transmissivity information from the tests is included in Table 4.

Testing to determine vertical hydraulic communication between the zones in which monitor wells were constructed at a given site consisted of measuring the water levels in the non-flowing wells while a productivity test was made of one of the wells. A significant change in water level in the non-flowing wells as a result of starting and stopping the flow from the produced well was considered an indication of direct hydraulic communication between zones. The results of these tests show there was no direct hydraulic communication between the producing zones screened by the monitor wells at any of the three sites.

Water samples were collected from the monitor wells for chemical analysis. Samples were collected from Monitor Wells A-1, A-2, A-3, C-1, and C-2 on March 13, 1986 to provide a basis for identifying future changes in water quality that might be indicated by subsequent water sampling and analysis during long-term monitoring. Samples were collected from Monitor Wells D-1 and D-2 on July 18, 1986 for the same purpose. These two wells had not been constructed when the samples were collected from the other wells in March. The results of the chemical analyses for the water samples collected from the final monitor wells are given in Table 6.

In collecting the water samples, each of the monitor wells was allowed to flow for a sufficient period of time to have discharged several times the volume of water that was contained in the well bore in order to be sure that the water being produced was water that came directly from the Edwards aquifer. In addition, periodic measurements were made of the water's conductivity and pH to be sure that the quality of the water had stabilized prior to collecting water samples and that the water was representative of water in the aquifer.

GEOLOGIC AND HYDROLOGIC CONDITIONS

This section discusses the information obtained from drilling and testing the monitor wells that were constructed along the bad water line transect near the City Water Board's Artesia Well Field in San Antonio. The subjects discussed include general geology, hydrologic continuity, aquifer productivity, and chemical quality.

TABLE 6. CHEMICAL ANALYSES OF WATER FROM COMPLETED MONITOR WELLS
(Analyses by U.S. Geological Survey; Results in milligrams per liter except pH and specific conductance)

Monitor Well	Producing Interval, Feet From To	Date Sampled	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved Solids	Specific Conductance Micromhos/cm	Hardness as $CaCO_3$	pH	Temperature, °C
A-1	1,218-1,264	3-13-86	21	600	210	460	28	294	1,800	930	2.8	4,200	5,840	2,400	6.7	32.5
A-2	1,014-1,067	3-13-86	19	490	170	370	23	274	1,400	730	2.8	3,300	4,700	1,900	6.7	31.5
A-3	1,115-1,165	3-13-86	21	580	220	510	29	294	1,800	940	3.1	4,200	5,900	2,400	6.7	31
C-1	840-891	3-13-86	13	81	25	31	3.2	238	120	52	0.9	440	769	310	6.9	28.5
C-2	1,090-1,140	3-13-86	19	590	250	600	29	305	1,900	1,000	2.9	4,500	5,940	1,500	6.6	30
D-1	1,156-1,209	7-18-86	13	110	37	52	3.9	251	210*	110*	0.8	660	1,040	430	6.8	26.5
D-2	874-926	7-18-86	12	66	17	9.7	1.3	243	24	19	0.3	270	474	230	6.7	26.5

* Rerun of sulfate and chloride determinations requested, but not received as of the date of this report.

Geology

The geologic units penetrated in drilling the primary test holes are presented in Table 2. The stratigraphic units also are shown on Figure 10. Figures 6, 7, and 8 show the stratigraphic units of the Edwards Group encountered in the primary test holes along the bad water line transect.

The Person Formation of the Edwards Group is considered to include from bottom to top, the regional dense member, the collapsed member, the leached member, and the cyclic and marine member. Except for the regional dense member, these members could not be identified from field examination of drill cuttings and other data.

The Kainer Formation of the Edwards Group is considered to include from bottom to top, the basal nodular member, a dolomitic member, the Kirschberg evaporite member, and a grainstone member. The grainstone and basal nodular members have been identified from field examination of drill cuttings, but differentiation of the Kirschberg evaporite and the dolomitic members could not be done.

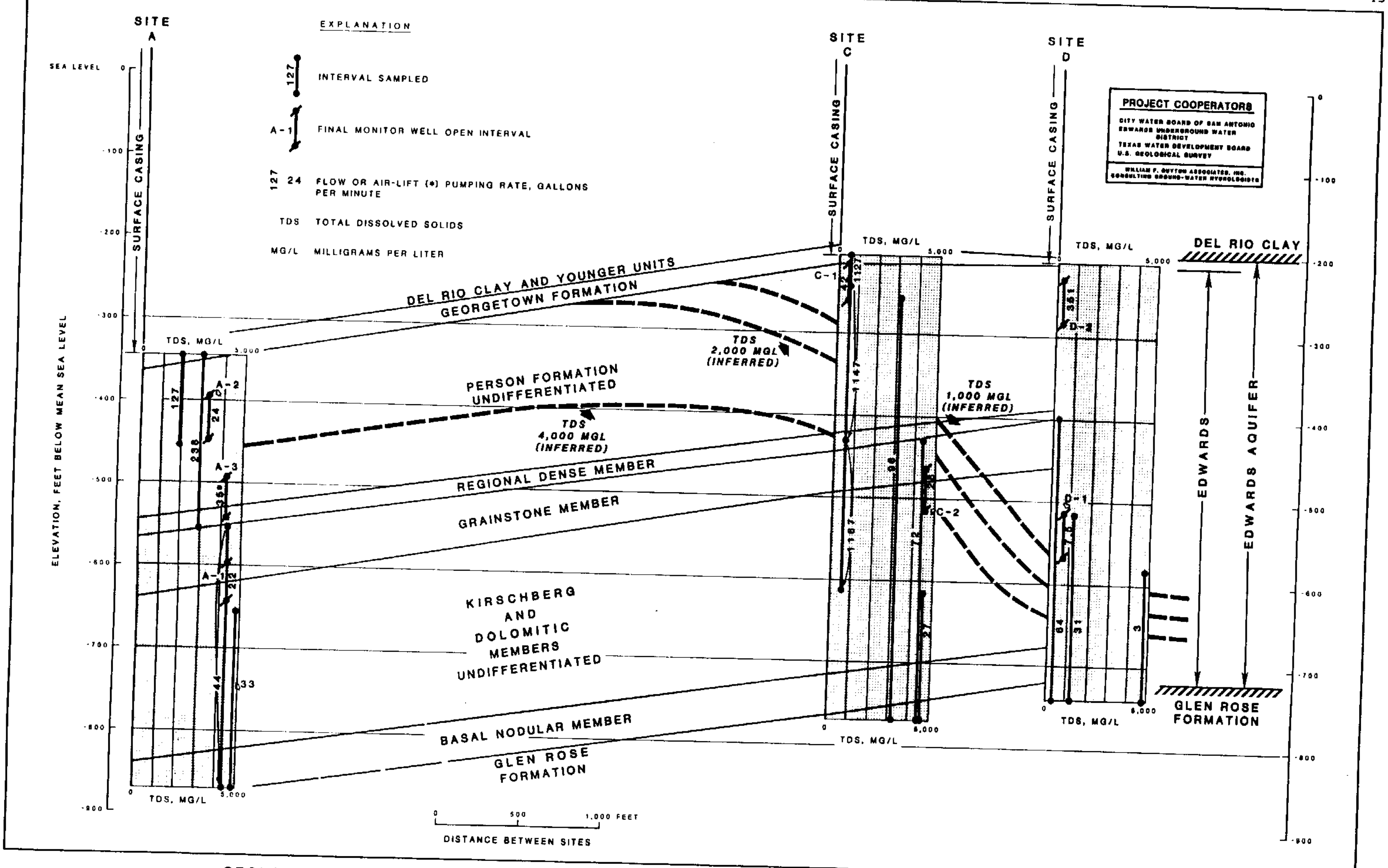
It may be possible to identify the members more definitively through microscopic examination of the drill cuttings and detailed analysis of the geophysical logs that were obtained. However, this was not done as a part of the present study which consisted primarily of a general evaluation of conditions based on field observations and data.

A study of available data indicates that the geologic units have not been significantly offset vertically by faulting along the bad water line transect between Site A and Site D. This is illustrated by the geologic section of Figure 11, which also shows the chemical quality of the water that is present in the Edwards aquifer along the transect. However, significant faulting is known to be present in the City Water Board's Artesia Well Field just north of Site D, and the broken character of the rocks encountered in drilling the primary test hole at Site D indicates that the faulting may have affected the subsurface strata at the site. It appears that the faulting itself, or the effects of faulting, has resulted in the thicknesses of the Georgetown Formation and Person Formation, including the regional dense member, being less at Site D than they are at the other sites. The formations generally dip in a southward direction along the transect with the dip being on the order of 150 feet per mile or more.

STRATIGRAPHIC UNITS			GENERAL DESCRIPTION OF MATERIALS
NAVARRO GROUP			Clay, marl, and limestone
TAYLOR GROUP			Marl and calcareous clay
ANACACHO GROUP			Marly chalk
AUSTIN GROUP			Chalk, marl, and hard limestone
EAGLE FORD GROUP			Shale, siltstone, and limestone
BUDA LIMESTONE			Limestone, hard, nodular
DEL RIO CLAY			Clay
GEORGETOWN FORMATION			Limestone, dense, argillaceous
EDWARDS GROUP	PERSON FORMATION	Cyclic and Marine Member	Limestone and dolomite
		Leached Member	
		Collapsed Member	
		Regional Dense Member	Limestone, dense, argillaceous
	KAINER FORMATION	Grainstone Member	Limestone, hard
		Kirschberg Evaporite Member	Limestone, calcified dolomite, and dolomite
		Dolomitic Member	
		Basal Nodular Member	Limestone, hard, dense, clayey
GLEN ROSE FORMATION			Limestone, dolomite, shale, and marl

STRATIGRAPHIC UNITS

Figure 10



GEOLOGIC SECTION SHOWING CHEMICAL QUALITY ALONG THE BAD WATER LINE TRANSECT

Figure 11

Hydraulic Continuity

Examination of water levels measured in the non-producing wells during flow tests and recovery tests shows that the different water-producing zones are not hydraulically connected locally. Where there is a small change in water levels in the non-flowing wells with time, which may reflect the effect of starting and stopping the flow from a well at the site, the change tends to reflect more of an areal or leaky-type condition than a direct hydraulic connection.

Measurements made during the packer tests indicate the rocks between producing zones are effective confining layers which hydraulically separate the producing zones in a vertical direction. The expandable packers provide a seal over a length of well bore that probably was not more than 3 or 4 feet in length, and the packers were set at those depths where available data indicated the rocks were essentially non-productive. Measurements made of water levels show that when flow from a section on one side of the packer starts or stops, water levels for the section on the other side of the packer did not respond instantaneously or in a degree of magnitude that would reflect significant local hydraulic communication through the rocks immediately adjacent to the well bore. However, the delayed and modulated change in water levels that occurs with time does indicate the presence of hydraulic communication in a vertical direction on an areal basis.

The data obtained from the monitor wells do not reflect the presence of vertical gradients between producing zones that would cause movement of water between them under static conditions. The measured above-ground head at Monitor Well A-3, the shallow monitor well at Site A, was greater than the above-ground head at Monitor Well A-1, the deepest monitor well. Under normal conditions this would tend to indicate water was moving into the deeper zone from the shallow zone. However, when the heads are adjusted for differences in the density of the water in the well bores, the differences in head can be accounted for. Thus, measured above-ground heads, while different, do not necessarily reflect the presence of vertical gradients.

Water levels in the monitor wells appear to change in accordance with areal changes in water levels in the fresh water part of the aquifer. This effect extends to all monitor wells along the transect, both deep and shallow, and to the wells that are located in the bad-water zone at Site A as well as to those that are located in the good-water zone at Site D. Thus, it appears that the entire Edwards aquifer system is hydraulically interconnected on an areal basis. This may reflect communication through primary porosity or it may reflect transmission of pressure effects through widely spaced avenues of secondary porosity such as that found along the faults and fractures. It is doubted, however, that this areal communication results from communication in a vertical direction through solution openings. The layered nature of the rocks with their differing transmission capacity for ground-water movement tends to support this.

Aquifer Productivity

Productivity data were obtained from the 50-foot flow tests, open-hole flow tests, packer tests, and tests of final monitor wells. These data were analyzed to determine the 1-hour drawdown for the discharge rate at which each test was made, the 1-hour specific capacity at that rate, and an estimate of the transmissivity for the parts of the Edwards aquifer being tested where the data were found to be adequate. The results of these analyses are given in Table 4.

The drawdown in a well for a particular pumping rate is a combination of the friction head loss resulting from flow in the formation from which the water is produced, movement of water through the gravel envelope and well screen, and flow inside the well bore. Estimates were made of the friction head losses that occurred in the 9-5/8-inch O.D. casing, in the annulus between the 9-5/8-inch O.D. casing and the 7-7/8-inch hole, in the annulus between the 4-1/2-inch drill pipe and 6-inch drill collars, in the 4-1/2-inch drill pipe, and in the 4-1/2-inch and 2-3/8-inch O.D. production string installed in the final monitor wells. Head losses due to movement of water through the gravel envelope and well screen were not estimated, but they are expected to be insignificant because of the small flow rates, the large open area of the screen, and the large porosity of the gravel.

The estimated friction losses were subtracted from the drawdown measured during the test to try to arrive at an adjusted drawdown that equates to a common basis, the drawdown in the formation at the face of the screen or open hole. Thus, the computed specific capacity based on adjusted drawdown reflects the productivity of the aquifer. The measured drawdowns, adjusted drawdowns,and specific capacities based on adjusted drawdowns are shown in Table 4. Specific-capacity values determined from the 50-foot flow tests for the primary test holes and the associated flow rates are plotted on one of the graphs that are included on Figures 6, 7, and 8. Under normal conditions the larger specific capacities reflect more productive conditions.

The transmissivity of the various parts of the Edwards aquifer was computed from the water-level recovery and/or drawdown data from the flow tests by using the modified Theis non-equilibrium formula. The non-equilibrium formula is based on the assumption that the aquifer is homogeneous, isotrophic, and of infinite areal extent, the well penetrates and receives water from the entire thickness of the aquifer, the well has a reasonably small diameter, and the water removed from storage in the aquifer is discharged instantaneously with the decline in head. Except for the reasonably small diameter of the well these assumptions are rarely met, particularly in limestone aquifers. Therefore, the transmissivities computed from the test data are not considered to be true values of the transmissivity of the Edwards aquifer at the monitor well sites. Additionally, in some instances pumping from existing Edwards aquifer production wells caused water levels at the monitor well sites to change during the flow tests, and this affected the determination of transmissivity from water-level drawdown and recovery data. In a number of instances it was not possible to calculate a value for transmissivity. This was especially true at Site D which was adjacent to the City Water Board's Artesia Well Field. However, even with these shortcomings, the computed transmissivities combined with the adjusted specific capacities are useful for relative comparisons of the hydraulic properties in the various producing zones of the Edwards aquifer in the same test hole and for relative comparisons of the hydraulic properties of the Edwards aquifer from test hole to test hole and drilling site to drilling site.

Site A. The 50-foot flow tests and the packer tests of the Edwards aquifer in the primary test hole at Site A indicate the most permeable and productive part of the aquifer in this hole is above a depth of about 1,331 feet and that the aquifer below this depth is not very permeable or productive. The 50-foot flow tests show that the specific capacity and computed transmissivity increase progressively from the top of the aquifer at a depth of about 982 feet to a depth of about 1,331 feet. Specific capacities remain fairly constant from 1,331 feet to the bottom of the hole at a depth of 1,489 feet.

The packer test of the zone between 1,276 and 1,489 feet indicates that the base of the most productive part of the Edwards aquifer in this hole probably is above a depth of 1,276 feet instead of 1,331 feet as indicated by the 50-foot flow tests because the specific capacity of the zone below a packer setting of 1,276 feet was only 4.8 gallons per minute per foot of drawdown (gpm/ft). From the packer test data, it also can be deduced that a significant improvement in productivity occurred between the packer setting of 1,177 feet, which is in the lower part of the dense bed, and the packer setting at a depth of 1,276 feet. This portion of the Edwards aquifer would reflect production from the grainstone member, and according to discussions with personnel of the U. S. Geological Survey, this is somewhat unusual. In the fresh-water part of the Edwards aquifer the Kirschberg evaporite member, which is below the grainstone member, is reported to normally be more productive than the grainstone member. This may reflect the geochemistry associated with the rocks, and the related solution and deposition of minerals in the bad-water zone as opposed to the fresh-water zone.

The specific capacities determined from the 50-foot flow tests made of the test hole drilled for Monitor Well A-2 to a depth of 1,075 feet and the flow test of the final well indicate the productivity and permeability of the Edwards aquifer between the depths of 964 feet and 1,075 feet at this site are not greatly different than those for the same interval in the primary test hole at Monitor Well A-1. Monitor Well A-2 is located 100 feet from Monitor Well A-1. However, the specific capacities and transmissivities determined from the 50-foot flow tests of the test hole drilled for Monitor Well A-3 to a depth of 1,174 feet indicate the productivity and permeability of the Edwards aquifer between the depths of 964 feet and 1,175 feet at this location midway between Monitor Wells A-1 and A-2 are not as good as they are for the same interval at the other two monitor wells.

Site C. The 50-foot flow tests of the primary test hole in which Monitor Well C-1 was constructed indicate the principal productivity of the Edwards aquifer in this hole is between the bottom of the casing at a depth of 832 feet and a depth of 885 feet. The tests with a packer indicate that the principal productivity and permeability at this test hole occurs in the zone above 859 feet. That this part of the Edwards aquifer appears most productive and permeable is reasonable because of the large cavity that was encountered between the depths of about 841 feet and 849 feet.

The cavity that is present in the uppermost part of the Edwards aquifer at the site of Monitor Well C-1 was not encountered at Monitor Well C-2 located 100 feet north of Monitor Well C-1. The 50-foot flow tests conducted at Monitor Well C-2 indicate that there is very little productivity in the zone just below the surface casing, and that principal productivity in the Edwards aquifer occurs between the general depths of 1,101 feet and 1,150 feet. The results from the packer test that was made in the hole drilled for the construction of Monitor Well C-2 and the test of the final well, which has screen set in the interval between the depths of 1,090 feet and 1,140 feet, show the same degree of productivity for this portion of the Edwards aquifer in this hole as do the 50-foot flow tests. Thus, in terms of productivity, conditions at Monitor Well C-2 are significantly different from what they are at Monitor Well C-1 only 100 feet away.

The more productive interval at Monitor Well C-2 encompasses the lower part of the grainstone member just below the regional dense member and the upper part of the Kirschberg evaporite member. This zone is shown to be productive at Monitor Well C-1 also, but not as productive as the zone with the cavity near the top of the Edwards aquifer.

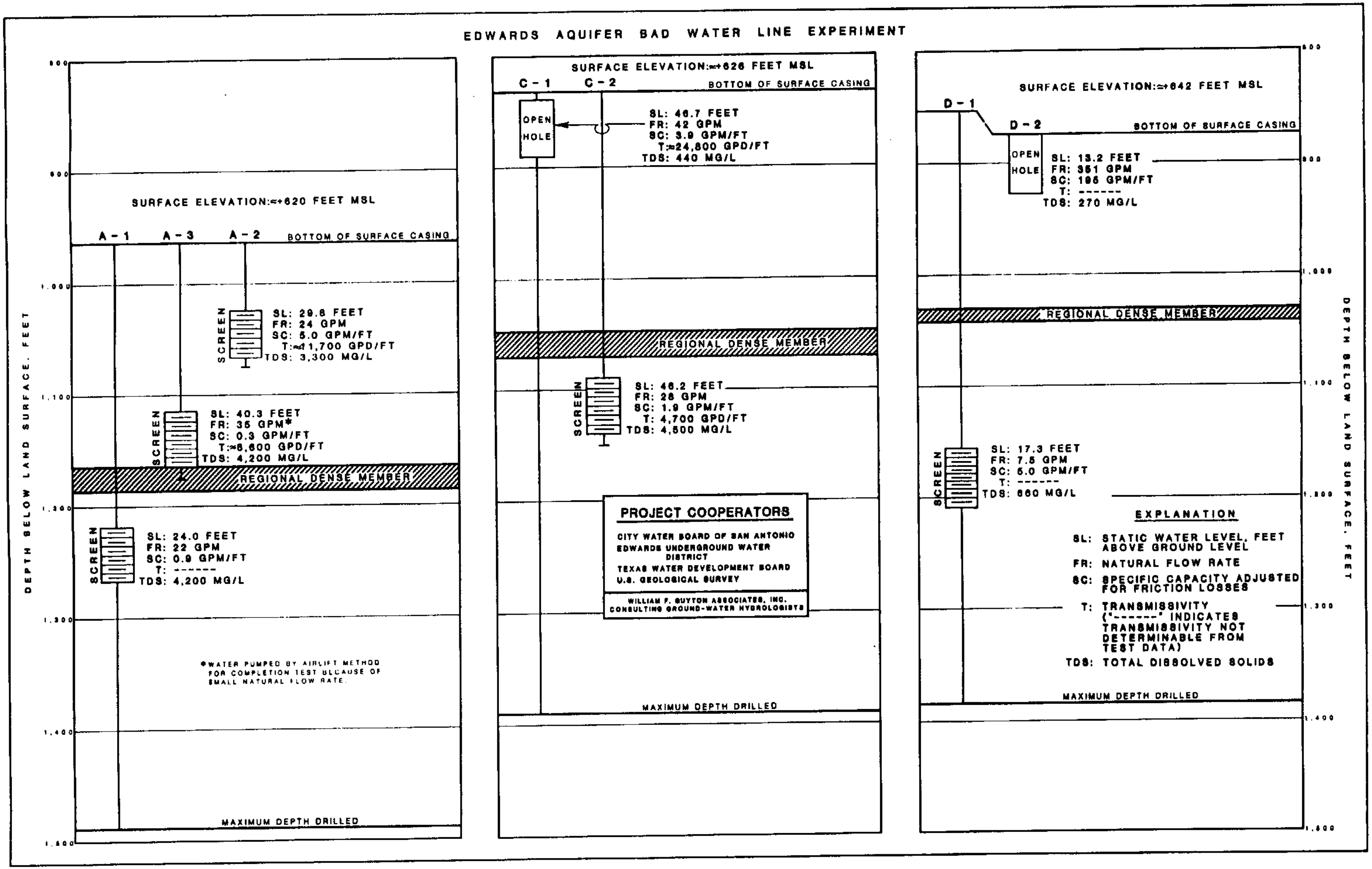
Site D. Flow tests and packer tests conducted in the primary test hole drilled for construction of Monitor Well D-1 indicate the principal productivity and permeability in the Edwards aquifer at this site occurs in the interval from the bottom of the surface casing at a depth of 854 feet to a depth of 1,105 feet. Large cavities and a significant number of cracks and fractures are present in the section of the hole above a depth of about 1,105 feet. This indicates the possiblilty of fracturing of rock related to faulting which would normally enhance the productivity of that part of the hole. The flow test at Monitor Well D-2 shows that the upper part of the Edwards aquifer between the depth of 874 feet and 926 feet is as permeable or more permeable than this same zone at Monitor Well D-1.

As stated earlier, the measurements obtained during the testing conducted at Site D was severely influenced by the effects of changes in pumping from the nearby Artesia Well Field, and thus the results of analysis are less specific than those obtained from most of the tests at the other sites. In fact, most of the data available for determining aquifer transmissivity were so affected by changes in water levels caused by pumping at the Artesia Well Field that reliable values could not be determined. Specific capacities are less seriously affected by changes in water levels caused by changes in nearby pumping.

Productivity and transmissivity information for the completed monitor wells at Sites A, C, and D are presented in perspective on Figure 12. Static above-ground heads and the total dissolved solids contents of the produced water also are shown on Figure 12.

Summary of Productivity

Data from the flow tests show that the principal productivity of the Edwards aquifer is in the upper one-half of the aquifer, and generally above the regional dense member, at all the monitor well sites. However, the data also show that the productivity for



PRODUCTIVITY INFORMATION FOR COMPLETED MONITOR WELLS

Figure 12

the same zone in the aquifer can be significantly different in holes that are not very far apart as is the case at Sites A and C. Thus, ground-water flow in the Edwards aquifer is shown to be extremely anisotropic.

The results of the tests made in the primary test holes at the three sites show that the productivity of the upper part of the Edwards aquifer is greatest at Site D, the good-water site, somewhat less productive at Site C, the transition-zone site, and significantly poorer at Site A, the bad-water site.

Water Quality

Complete chemical analyses were made of samples collected during the 50-foot flow tests and the packer tests of the primary test holes at Sites A, C, and D. Chemical analyses also are available for water samples collected from the completed monitor wells. The results of these analyses are presented in Tables 3, 5, and 6, respectively. The total dissolved solids content of water samples collected from specific intervals in the primary test holes, and from the final monitor wells is shown on the cross section of Figure 11, which also shows the position of the geologic units along the transect. Dissolved solids contents of water from the final monitor wells also are included with the information presented on Figure 12.

The results of chemical analyses show that the chemical quality of the water in the Edwards aquifer increases with depth. This is illustrated by the information presented on Figure 11. It should be noted that the 1,000, 2,000, and 4,000 milligram per liter total dissolved solids lines shown on Figure 11 are inferred, and the actual positions of these lines could be significantly different from what is shown. In actuality, the lines are probably "stair-stepped" across the zones of production rather than being smooth curves drawn through productive and non-productive zones.

The total dissolved solids content of the water in the upper part of the Edwards aquifer at Sites A, C, and D is about 1,900, 440, and 270 mg/l, respectively, and in the bottom part of the aquifer it is about 4,800, 4,600, and 4,800 mg/l, respectively. This increase in mineralization with depth also is generally reflected by the resistivity surveys that were made of the water in the primary test holes and the conductance measurements that were made of water samples collected at 10-foot intervals during drilling of the Edwards Group at Site A. High productivity in the uppermost part of the aquifer at Sites C and D overwhelmed the productivity from the rest of the hole and essentially negated the value of the 10-foot and 50-foot water-quality checks. Plots of this information are included with the selected information that is presented on Figures 6, 7, and 8.

The sulfate/chloride ratio of the water from the Edwards aquifer generally ranged from about 1.7 to 2.1 and the calcium/magnesium ratio generally ranged from about 2.2 to 4.0. The sulfate/chloride ratio does not appear to change significantly when the water quality changes. In the case of the calcium/magnesium ratio, however, it appears that the smaller ratios generally are associated with poor quality water and the higher ratios are more typical of good quality water. Inasmuch as calcium and magnesium are primary constituents of limestones and dolomites, variations in these ratios in water quality need to be evaluated in terms of the character of the rocks from which the water was produced. This subject needs additional study insofar as it relates to conditions along the bad water line transect between Sites A and D.

Conductivity measurements made of water collected from the primary test hole at Site A in July and August 1985 and conductivity measurements made of water samples collected from Monitor Wells A-1, A-2, and A-3 in March 1986 are different. The conductivity measurements indicate the water became poorer in quality during this 7- to 8-month period. The degradation in quality was least for the deepest monitor well and greatest for the shallow monitor well. Additional water-quality monitoring is needed to provide information for determining whether this change in quality results from seasonal stresses on the aquifer system due to changes in ground-water withdrawal or whether it might be due to other causes.

The presence of poor quality water in the lowermost part of the Edwards aquifer at Monitor Well D-1, located only a few hundred feet from production wells in the City Water Board's Artesia Well Field, was unexpected. Analysis of the water sample from the packer test of the lower part of the aquifer in the primary test hole at Site D shows a total dissolved solids content of 4,800 mg/l. This is 200 mg/l greater than the total dissolved solids content of water in the lower part of the aquifer at Site C, the transition-zone site, and the same as the dissolved solids content of the water encountered in the bottom of the aquifer at Site A, the bad-water zone site. The productivity tests show that the lower part of the aquifer is less permeable and productive than the upper part. Thus, movement of poor quality water through the lower aquifer would be expected to be slow. However, with the extensive faulting that is known to be present within a few hundred feet north of Site D and the production of large quantities of water from the Artesia Well Field which reflects a large amount of circulating fresh ground water in this vicinity, it is somewhat surprising to find that flushing has not caused the water to be fresher in the bottom part of the aquifer at this site even though it may be less permeable.

It appears that some general conclusions can be reached with regard to chemical quality such as that the chemical quality becomes poorer with depth, that the water quality in the shallow part of the Edwards aquifer generally becomes poorer in a downdip direction, and that Monitor Wells C-1 and C-2 are located in the transition zone between good and bad quality water in the aquifer. Also, the position of the bad water line appears to be different for different depths of production zones, with the bad water line for the shallowest production zone being south, or downdip of the bad water line for the deepest production zone. However, it appears that a considerable amount of water-quality monitoring and detailed study probably will be required to identify and explain the differences in present water quality and those that are likely to occur in the future.

CONTINUING STUDIES

The work done on the Edwards aquifer bad water line experiment to date has answered some questions and left some unanswered. It also has resulted in new questions which remain to be answered.

The Edwards aquifer bad water line experiment transect is comprised of two basic phases. The first phase involves the drilling, testing, and construction of monitor wells to obtain site-specific ground-water information and provide a means for long-term monitoring. The second phase involves the long-term monitoring of water levels and water quality and ongoing evaluation of the data.

The work done thus far involves only the drilling, testing, and construction of monitor wells and the associated collection of site-specific information on ground-water conditions along the transect. An in-depth analysis of all the geologic and hydrologic data that have been obtained has not been made, but the U. S. Geological Survey is pursuing this aspect of the work. This work needs to be followed through to its completion including the publication of the results of the final analysis of the data presently available and that which is obtained from long-term monitoring.

Long-term monitoring (up to 50 years or more) of the present bad water line transect is just beginning. Water-level measurements are currently being made in the monitor wells at intervals of about 15 minutes using automated pressure recording equipment and computerized processing in an effort to develop a knowledge about the amount water levels fluctuate in the different wells and the differences in time it takes for the full amplitude of a change in water level to reach the different monitor wells along the transect. The frequency of obtaining measurements will be modified once an understanding of how and when the changes that do take place is developed.

Water samples also are being collected monthly for chemical analysis as part of the long-term monitoring. A complete mineral analysis is being made of the samples collected every third month. Samples collected during the intervening 2 months are being analyzed for alkalinity, calcium, magnesium, chloride, sulfate, conductance, and pH. Once a history of the changes in the water quality is established (possibly over a 1- or 2-year period) the frequency of sampling for chemical analysis and the type of analysis that is made may be modified.

In view of the poor quality water that has been found in the lower part of the Edwards aquifer at Site D, only a few hundred feet from production wells in the Artesia Well Field that draw part of their water from this part of the aquifer, it is desirable that the transect of the bad water line be extended northward by drilling one or more additional monitor wells to find out if poor quality water is present in the lower aquifer in a much larger part of what is considered the fresh-water zone.

It appears that the amount of poor quality water actually produced with good quality water by the production wells that are open to the full thickness of the Edwards aquifer may be small under present conditions. This could conceivably change, however, if for some reason the availability of good quality water from the upper part of the aquifer should become less. Water samples are currently being collected from selected production wells in the Artesia Well Field as part of the monitoring program to find out if minor but previously unrecognized changes in water quality actually do occur during the year as a result of stressing the aquifer by pumping. If they do occur, this may provide an indication of the effect poor quality water in the bottom of the aquifer is likely to have on the quality of water produced from the wells under more stressful conditions.

Consideration needs to be given to constructing similar transects of the bad water line at other locations in the Edwards aquifer once data from monitoring conditions along the present transect of the bad water line become available and have been analyzed to develop a better understanding of the changes that occur. One of these transects might be located in the area north of San Antonio in the New Braunfels or San Marcos areas and one might be located west of San Antonio in the D'Hanis or Uvalde areas. These additional transects would provide a more regional perspective of the changes that are occurring along the bad water line or that might occur along it in the future. The information also would help in determining how changes are likely to affect the long-term availability of fresh water from the aquifer under more stressful conditions in the future, such as those imposed by continuing increases in withdrawals from the aquifer and/or severe drought conditions.

SUMMARY OF PRINCIPAL OBSERVATIONS AND FINDINGS

1. The seven monitor wells that have been constructed on the transect of the bad water line just south of the City Water Board's Artesia Well Field establishes a monitoring system that will supply information useful in determining whether encroachment of poor quality water will or will not present a problem to maximum use of the Edwards aquifer.

2. The monitor wells are designed to provide reliable water-level and water-quality data for discrete hydraulically separated zones of the aquifer at each of the three sites, and they are constructed to last many decades. Three of the wells are located in the bad-water zone, two are located in the transition zone between bad water and fresh water, and two are located in the fresh-water zone.

3. An agreement between the City Water Board and the Edwards Underground Water District is in effect which assures that monitoring of the bad water line transect will continue for 50 years or more. Data and related interpretations from the monitoring wells established by this project are to be made available at periodic intervals to the Texas Water Development Board and other cooperators.

4. The air-assist reverse circulation method of drilling proved to be an effective and efficient way to drill the Edwards Group encountered in constructing the monitor wells. Among its advantages were the continuous production of formation samples, even under cavernous conditions, and the ability to readily obtain productivity and water-quality information as the hole was progressively deepened. In addition, no foreign fluids were introduced into the Edwards aquifer and a clean hole was maintained at all times.

5. The use of a single expandable packer installed on drill pipe proved to be an effective and economical way to test specific intervals of the Edwards aquifer for productivity and water quality.

6. Television surveys made in the primary test hole at each drilling site provided information for making a better assessment of the physical nature of the rocks that make up the Edwards aquifer and proved to be invaluable in selecting zones in the hole where good seals could be obtained with the expandable packer used for testing specific intervals of the aquifer.

7. The upper part of the Edwards aquifer, generally the part above the regional dense member, is more productive than the lower part. It also is more productive in the updip (northwest) part of the transect. Productivity of the aquifer in the fresh-water zone also is better than it is in the bad-water zone.

8. The grainstone member of the Kainer Formation of the Edwards Group is more productive at Site A, which is in the bad-water zone, than it is at the other two sites. This may be related to the geochemistry of the rocks and the related solution and deposition of associated minerals.

9. Productivity of the Edwards aquifer can vary appreciably within a small distance. At Monitor Well C-1 a cavity was encountered in a producing zone at the top of the aquifer which produced 985 gallons per minute, whereas for the same zone 100 feet away at Monitor Well C-2, no cavity was encountered and only 24 gallons per minute were produced with the same amount of water-level drawdown. This illustrates that ground-water flow in the aquifer is extremely anisotropic.

10. Locally, the producing zones of the Edwards aquifer along the bad water line transect appear to be hydraulically separated in a vertical direction, but areally this does not appear to be the case. Vertical hydraulic communication between producing zones on an areal basis may be due to a leaky-artesian type condition or to widely spaced faulting which would provide avenues for hydraulic communication between producing zones.

11. It appears there is little if any vertical hydraulic gradient between producing zones that would cause water to move from one producing zone into another. This apparently reflects the areal vertical communication mentioned above which would

allow the hydraulic heads in the various producing zones to equalize.

12. As shown by analyses of water from completed monitor wells, water quality in the Edwards aquifer along the bad water line transect becomes poorer with depth and generally in a downdip (southeastward) direction. Good quality water at Sites D and C contains total dissolved solids ranging from 270 to 440 milligrams per liter, and bad quality water at Sites C and A contains total dissolved solids ranging from 3,300 to 4,500 milligrams per liter.

13. Poor quality water is present at the bottom of the Edwards aquifer at Site D, which is within a few hundred feet of the City Water Board's producing water wells in the Artesia Well Field. This was unexpected because chemical analyses of water from the City Water Board's wells, which are open to the full thickness of the aquifer, provide no indication that poor quality water containing 4,800 milligrams per liter of total dissolved solids is present nearby.

14. In view of the poor quality water that is present in the lower part of the Edwards aquifer at Site D near the Artesia Well Field, it is desirable that the transect of the bad water line be extended northward by drilling one or more additional monitor wells to find out if poor quality water is present in the lower aquifer in a much larger part of what is considered the fresh-water zone.

15. Consideration needs to be given to constructing similar transects of the bad water line at other locations in the Edwards aquifer so a better understanding of conditions along the line can be obtained for determining whether encroachment of poor quality water presents a problem to maximum use of the aquifer on a regional scale. One of these transects might be located in the New Braunfels or San Marcos areas to the north and one might be located in the D'Hanis or Uvalde areas to the west. In the areas to the north, the bad water line may be related to faulting, and in the areas to the west, it may be related to rock permeabilities. In addition, these areas are in or near major ground-water flow paths. Thus, information from the transects also would aid in developing a better understanding of the hydrology of the Edwards aquifer.