AQUIFER STORAGE RECOVERY FEASIBILITY INVESTIGATION

PHASE IIA MONITORING WELL PZ-1

VOLUME I -- REPORT

PREPARED FOR

Upper Guadalupe River Authority
Kerrville, Texas

December 1989

CH2M HILL

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FEASIBILITY INVESTIGATION

PHASE IIA: MONITORING WELL PZ-1

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Kerrville, Texas

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PREFACE

This report presents the results of the construction of production zone monitoring well PZ-1. This work was conducted as part of the Upper Guadalupe River Authority's Aquifer Storage and Recovery Investigation. It was prepared by CH2M HILL under the requirements of the contract amendments of April 6, 1989.

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The contribution to the successful completion of this report by the following is greatfully acknowledged:

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Texas Water Development Board
Bill Neill/Page Drilling Company

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EXECUTIVE SUMMARY

PROJECT OVERVIEW

Water demands by the City of Kerrville are projected to exceed the Upper Guadalupe River Authority's (UGRA's) supply by the year 1992. To meet these demands, the UGRA is conducting a feasibility study to evaluate the use of underground aquifers to store treated drinking water. Excess water from "wet" periods will be stored underground, beneath the City of Kerrville, for recovery during "dry" periods. This concept, known as Aquifer Storage Recovery (ASR), has the potential to postpone the expansion to the existing treatment plant and significantly reduce the size and cost of the planned off-channel storage reservoir.

A Phase I Feasibility Study, completed by CH2M HILL in April 1988, identified the Hosston-Sligo Sand as the aquifer showing the highest potential for storing water, but additional geological data is needed to confirm the preliminary conclusions presented in the study report.

This current study (Phase IIA) was conducted to construct and test a 7-inch-diameter production zone monitor well (PZ-1) in the Hosston-Sligo Sand. The well was constructed at the UGRA plant site (see Figure 1-1) and completed in September 1989. A well completion diagram is presented in Figure 3-1. Construction methods, testing, and recommendations for future work are presented in the Phase IIA report.

A summary of the conclusions and recommendations described in this report is presented below.

CONCLUSIONS FROM CONSTRUCTION AND TESTING OF PZ-1

1. The Hosston-Sligo Aquifer has high potential to be a suitable ASR storage zone. Transmissivity and geochemical properties suggest that adequate storage and recovery efficiencies are possible.

2. At this site, the Hosston-Sligo Aquifer is almost twice as thick as originally estimated (135 feet versus 75 feet), which increases the storage potential of the formation.

3. The storage capacity of the aquifer is estimated to range from 3,600 to 36,000 acre-feet, but additional tests will be required to refine this estimate.

4. Production within the Hosston-Sligo Aquifer is predominantly from the middle portion of the aquifer and is greatly enhanced by acidification.

5. Open boreholes completed in the aquifer may be unstable; therefore, screening of the production zone may be required. This will increase well costs but should increase the long-term productivity of the well.

6. The treated UGRA water is compatible with aquifer water and minerals; therefore, geochemical and biological plugging of the aquifer is not expected. However, physical plugging by air binding is possible and special consideration in the design of the recovery well will be required.

RECOMMENDATIONS FOR PHASE IIB WORK

1. Proceed with Phase IIB and the installation of the ASR prototype well (R-1) and two additional monitoring wells, one in the Cow Creek and Hensell Sand and the second in the Lower Glen Rose Formation. These should complete the wells required to test and evaluate the ASR concept.

2. Conduct two long-term pump tests to further refine aquifer properties and leakage. These tests are required to improve storage capacity estimates. One test will be conducted at well R-1 and the second at existing Kerrville Well No. 9.

3. Conduct two ASR test cycles in well R-1. If initial results are encouraging, initiate efforts to modify existing Kerrville Well No. 7 for ASR test operations and conduct cycle testing.

4. Develop a computer model of the aquifer under Kerrville to simulate ASR operation and estimate long-term yields of groundwater.

5. Perform an off-channel reservoir evaluation.

6. Evaluate the feasibility and cost-effectiveness of an expanded ASR (Phase III) program to meet long-term water demands.

Cost and schedule requirements to complete the recommended work for Phase IIB have been developed. Costs are projected to range between $550,000 and $765,000. The time required to complete the recommended work is projected to range from 22 to 28 months. Final cost and schedule projections will be developed during negotiations with UGRA.

Section 1
INTRODUCTION

1.1 PROJECT OVERVIEW

The Upper Guadalupe River Authority (UGRA) supplies potable water to the City of Kerrville by withdrawing and treating surface water from the Guadalupe River. A recent study[1] has shown that by 1992 water demands will exceed existing plant capacity and additional supplies will be needed.

The UGRA is planning for the future by conducting a series of engineering studies to provide additional water supply and storage capacity. This study, the Aquifer Storage Recovery (ASR) Feasibility Study is being conducted to investigate the concept of storing treated surface water underground during "wet" periods for recovery and use during "dry" periods. If feasible, the ASR concept offers significant cost savings by postponing expansion of the water treatment plant and significantly reducing the size and cost of an off-channel storage reservoir. This concept also offers a cost-effective method for storage of large volumes of water and significantly reduces evaporative water losses from a surface storage reservoir.

The ASR Feasibility Study is being conducted in three phases which will be discussed below. The goal of the study is focused on the long-term storage and recovery capacity of the Hosston-Sligo formation and its ability to provide firm water yield for UGRA and the City of Kerrville. A discussion of the ASR study project phases is presented below.

- Phase I - Feasibility Study, completed in April 1988
- Phase II - Well Construction and ASR Testing
    - IIA, Construction of Monitoring Well PZ-1 (current work)
    - IIB, Construction of Remaining Wells and ASR Testing (future work)
- Phase III - ASR Facilities Expansion Program (Future Work)

The Phase I Feasibility Study was conducted to determine if water use and hydrogeologic conditions in the Kerrville area displayed positive potential for an

[1] Aquifer Storage Recovery Feasibility Investigation Phase I - Preliminary Assessment. CH2M HILL. April 1988.

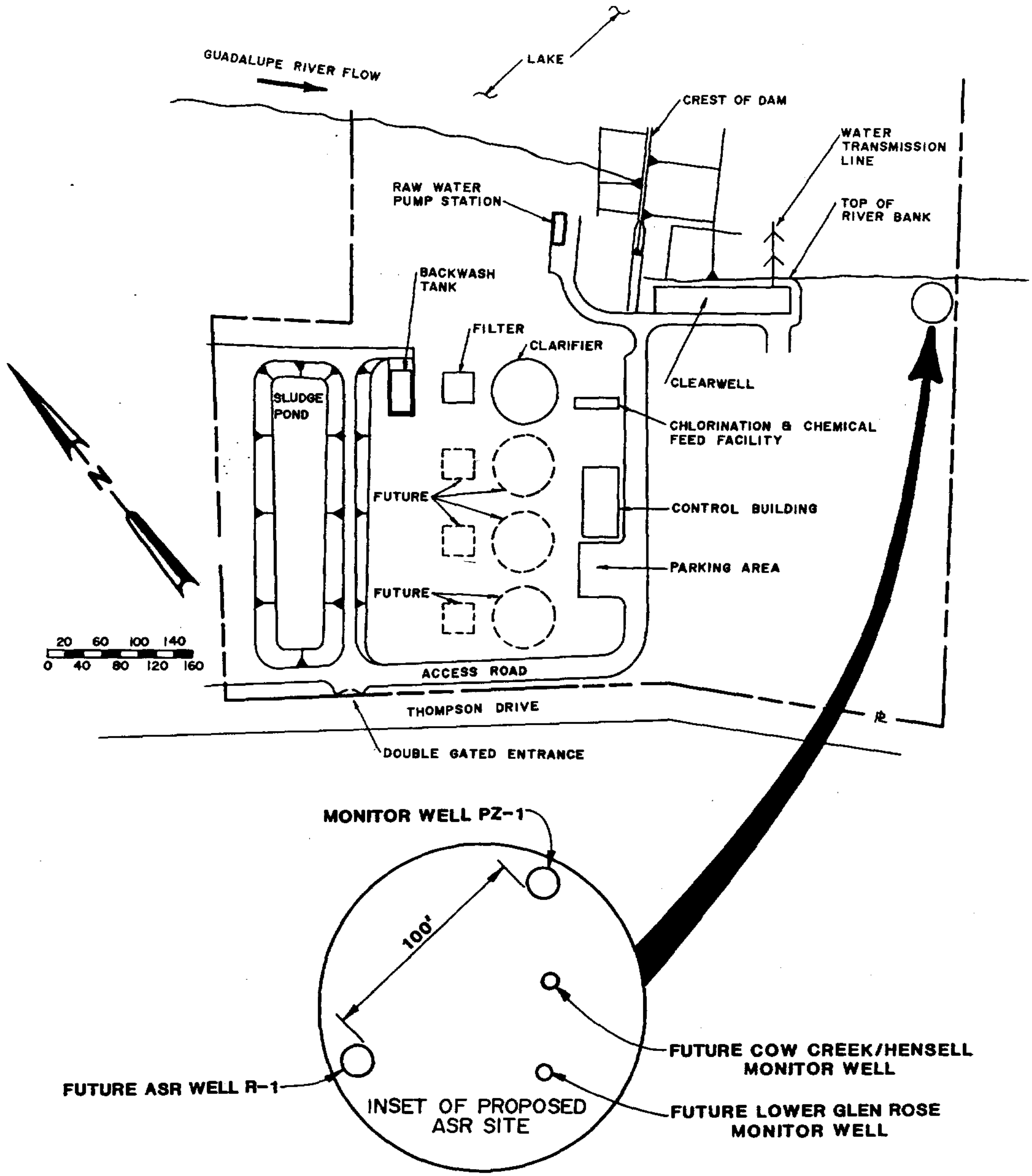

Figure 1-1
Proposed ASR Site Plan

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Section 2
FIELD INVESTIGATION PROGRAM

2.1 FIELD PROGRAM

The field program which was conducted from July 17 to September 28, 1989 was described in the Scope of Work dated October 27, 1988. Details, rationale, and changes of the Scope of Work for the field program are contained in this section.

2.1.1 Goals of the Field Program

Several goals for the field program were established in the Scope of Work for this Phase II study. Following are some of the major goals:

- Confirm that a suitable ASR storage zone exists at the UGRA water treatment plant site
- Verify subsurface geologic units and contacts
- Install a monitoring well (PZ-1) in the Hosston-Sligo Sand
- Determine aquifer properties of the Hosston-Sligo Formation
- Obtain water samples of the Cow Creek, Hosston-Sligo, and UGRA treated water

Core samples and geophysical logs were obtained to identify and characterize the subsurface stratigraphy. Pump tests were conducted to determine aquifer characteristics and obtain water quality samples. Samples of selected geologic units were submitted to a mineralogical testing laboratory for detailed mineralogical and microscopic analyses. Downhole color video cameras were used to videotape and document borehole conditions.

2.2 FIELD PROGRAM IMPLEMENTATION AND SUMMARY

This section includes the methodology used during the field investigation at PZ-1. This field investigation included 635 feet of coring and rollerbit drilling to advance the hole for well installation and to collect lithological samples for study; the collection of water samples from the Hosston-Sligo and treated surface water, the installation of 495 feet of well casing, the acidification of the well to improve yield, videotape documentation of borehole conditions pre- and post-acidification, and geophysically logging the borehole at four different times during the field program.

2.2.1 Work Sequence

Table 2-1 provides the sequencing of the field tasks for the construction of PZ-1. The field investigation commenced following the preparation of bid documents for the Texas Water Development Board (TWDB) and drilling contractor (Page Drilling).

On July 17, the TWDB mobilized a Failing 1500 drill rig and support equipment to the site. The TWDB rig and crew remained onsite through August 30. During this period the hole was drilled, well casing was installed, and several geophysical logs were run in the uncased sections of the borehole.

On September 5, Page Drilling mobilized a Gardner-Denver 1500 drill rig to the site. During their work onsite, which concluded on September 28, Page Drilling developed the well (pre- and post-acidification), acidified the well, supported geophysical and downhole video camera crews, conducted several pump tests, and completed the site wellhead.

2.3 BOREHOLE DRILLING AND WELL INSTALLATION

All borehole drilling was conducted by the TWDB drilling crew. Surface casing (10-3/4-inch OD) was set and grouted to a depth of 39 feet in a borehole drilled with a 14-3/4-inch rollerbit using mud rotary techniques. From 39 feet to 400 feet, a 9-7/8-inch rollerbit was used to advance the hole utilizing mud rotary techniques. From 400 to 496 feet, 4-inch-diameter core samples were obtained using a 6-1/8-inch OD 10 foot long core barrel. The borehole was then reamed from 400 to 495 feet with the 9-7/8-inch rollerbit. Following reaming, the well casing was installed.

Well casing consisted of nominal 21-foot-long threaded 7 inch OD pipe (Grade J-55 20 lb/ft). The pipe was tested to 3,000 psi at the factory and had an ID drift of 6.456 inches. Nominal pipe inner diameter is 6.625 inches. The pipe lengths were threaded and coupled and the lower eight sections were tack welded. A concrete float shoe was installed at the base of the pipe to facilitate grouting.

Grouting was accomplished by pressure methods by B.J. Titan of Seguin, Texas under subcontract to Page Drilling. Once the casing was placed in the well, several volumes of water were pumped into the well to displace drilling muds. Grout (150 bags of portland cement) was mixed with approximately 780 gallons of water. The slurry was pumped under pressure into the inside of the 7-inch

Table 2-1
SEQUENCE OF FIELD ACTIVITIES

Activity	Duration
Mobilization to site	7/17/89
Drill to 39 feet and set surface casing	7/18/89
Rollerbit drill to 400 feet	7/20/89 - 7/25/89
Core into top of Hosston-Sligo Sand (495 feet)	7/25/89 - 8/09/89
Install 7-inch O.D. casing to 495 feet	8/10/89 - 8/11/89
Obtain core samples to top of pre-cretaceous rocks	8/16/89 - 8/28/89
Run geophysical logs	8/29/89
Develop well and conduct a pump test	9/05/89 - 9/10/89
Conduct a downhole camera survey	9/11/89
Acidize and redevelop well	9/12/89 - 9/19/89
Conduct flow logging and rerun color camera survey	9/20/89
Conduct 2 pump tests	9/21/89 - 9/22/89
Run geophysical logs	9/25/89
Complete well head and demobilization from site	9/26/89 - 9/28/89

casing. A plug was then forced to the base of the well with a casing volume of water. The plug forced grout out of the casing and up through the annulus of the hole. Thick grout return was observed to return to the surface through the pipe and borehole annulus during the grouting process. The grout was allowed to cure for 2 days before drilling recommenced.

Core drilling with the 4-inch ID core barrel continued to a depth of 635 feet. Geophysical logs were run in the hole and the base of the Hosston-Sligo aquifer was identified at 620 feet. Grout was tremmied through the drill pipe to seal the 620 to 635 foot interval.

2.4 ROCK SAMPLING AND ANALYSES

Lithologic samples were collected through the entire length of the borehole. The samples were used to identify the subsurface stratigraphy. Borehole logs are contained in Appendix A. From ground surface to 400 feet, rock chip samples were collected at 5 to 10 foot intervals during rollerbit drilling.

From 400 to 635 feet, the rock was drilled and sampled using the 4-inch diameter core barrel for the majority of the section. In a few places a 6-inch nominal diameter rollerbit was used to advance the hole.

A total of 24 core runs were conducted at the site. Typical run lengths were 10 feet. From 400 to 635 feet, 207 feet of rock were cored with 147 feet of recovery. From 400 to 557 feet, core recovery averaged 92 percent. The remaining portion of the hole had average core recovery of less than 7 percent.

Core collected from the barrel was placed on holding trays, washed, labeled, and photographed. The core was logged by the site geologist prior to packaging in 3-foot-long waxed cardboard boxes.

From the ASR zone (Hosston-Sligo), and the confining bed (Pine Island Shale) four rock cores were selected for detailed microscopic chemical and physical testing. The rock core samples were sealed in plastic wrap and aluminum foil and covered with wax to seal in moisture. The samples were frozen and shipped with dry ice to Mineralogy, Inc. in Tulsa, Oklahoma. At the laboratory, one of the rock cores was split into two samples because it represented two distinct geologic units. The five zones that were analyzed included:

- 481.1' - 481.8' Pine Island Shale
- 511.5' - 512.0' Hosston-Sligo Sand
- 539.6' - 539.9' Hosston-Sligo Sand
- 539.9' - 540.3' Hosston-Sligo Sand
- 552.5' - 553.4' Hosston-Sligo Sand

In the original scope of work, a sample of the pre-Cretaceous rocks was to be collected and analyzed. No core recovery was obtained from the pre-Cretaceous rocks due to drilling difficulties. Therefore, no sample from this formation was analyzed.

The five zones were tested by the following methods:

- Vertical permeability to air
- Horizontal permeability to air
- Porosity
- Grain size distribution
- X-ray diffraction
- Scanning Electron Microscope (SEM) analysis
- Cation exchange capacity
- Energy dispersive chemical analysis
- Thin slab description
- Thin section analysis
- Acid residue analysis

2.5 BOREHOLE GEOPHYSICS AND VIDEO SURVEY

Texas Water Development Board (TWDB) supplied geophysical logging services on four separate occasions at the site. Geophysical logs are in Appendix B. The TWDB geophysical logging dates and activities were:

July 28 — Spontaneous potential, resistivity, and natural gamma logs were run from 0 to 455 feet to locate the Hensell/Cow Creek contact

August 1 — Spontaneous potential, resistivity, natural gamma, neutron, and caliper logs were run to confirm the Pine Island/Hosston-Sligo contact

August 28 — Spontaneous potential, resistivity, neutron, natural gamma, caliper and sonic logs were run from 495 to 627 feet to log the Hosston-Sligo Sand and locate the base of the formation

Sept. 25 — Spontaneous potential, resistivity and natural gamma logs were run from 495 to 600 feet to determine the effects of acidification on the Hosston-Sligo Sand

Additional geophysical logging was performed by Tejas Well Services on September 20. Tejas ran flow meter and caliper logs from 495 to 600 feet to locate production zones in the Hosston-Sligo Sand.

Color camera video logging was also performed by Tejas. On September 11, video logs were run from 0 to 610 feet to inspect the well casing and borehole following initial development and the pre-acid pump test. On September 20, following acidification and development, video logs were run from 0 to 603 feet to determine the effect of acidification. Video logging was conducted by a fixed positioned camera with a 4.8 mm F 1.8 lens that had a maximum viewing angle of 110 degrees. Results of the two video logging runs were recorded on a video tape using an onsite video cassette recorder.

2.6 WELL ACIDIFICATION

In order to improve well yield, PZ-1 was acidified with hydrochloric acid (HCl) on September 12, by B.J. Titan under subcontract to Page Drilling.

Prior to acidification, the wellhead was prepared by installing a header equipped with a ball and check valve for water flushing and an emergency bypass valve in case of back pressure buildup. Acid flow rate was controlled by a pump on the acid rig. Flow measurement and back pressure buildup were recorded on a strip chart.

Four thousand gallons of 15 percent HCl were pumped into the well. No back pressure buildup was noted on the chart recorder. Initial pumping was at a rate of 2 barrels per minute (bbl/min) which declined to 0.5 bbl/min after 5 minutes. Flow rate then gradually increased to 1 bbl/min and remained at this rate for the duration of the test. Approximately 1.25 hours were required to pump the acid in the well. Following the acid pumping, 300 gallons of fresh water were pumped into the well to force acid out of the well casing and into the formation. An additional five 300-gallon slugs of water were pumped into the well at 1/2-hour intervals. This water forced the acid further into the formation and away from the borehole.

The acid was allowed to react with the formation for approximately 24 hours. The reacted acid was then airlifted to the surface, neutralized with a caustic soda solution and allowed to infiltrate and/or flow overland into the alluvial gravels.

2.7 WELL DEVELOPMENT

Well development services were performed by Page Drilling at two separate phases during the project. The first phase of well development occurred on September 5 and 6. At this time, the well was developed by airlift methods to remove drilling mud from the producing formation. Drill pipe was lowered into the well and compressed air was forced into the borehole at various levels. Water and sediment were then lifted to the surface. This phase of development lasted for 15 hours over the 2-day period. Production rates during development were estimated to range from 50 to 100 gpm. At the end of development the water was visibly clear and exhibited a turbidity of only 2 to 4 NTU.

The second phase of development occurred after acidification. The well was then developed to remove residual acid products including chloride water and released sediment. Development was again accomplished by airlift methods. The residual chloride necessitated a longer than expected development period (48 hours over a 7-day period). Well yield during the second phase of development was noticeably improved over the first phase. Production rates were estimated between 100 and 150 gpm.

2.8 PUMP TESTS

Pump tests were conducted at various times to determine aquifer properties before and after acidification. The pump tests were conducted by Texas Water Supply under subcontract to Page Drilling. Two tests were conducted prior to acidification. These tests, pump tests 1 and 2, were run for 3 and 4 hours, respectively, at pumping rates of 150 gallons per minute.

Following acidification, two tests were performed. Initially, a 4-hour variable rate test (pump test 3) was performed. Pumping rates varied from 125 to 210 gpm. This test was followed by a constant rate test (pump test 4) at 200 gpm for a period of 8 hours.

Drawdown during and recovery after the pump tests were monitored by back pressure buildup on the discharge or water level indicators. Pumping rates were monitored with a circular orifice weir and a flow meter.

The pump used for the purge test was a Flint and Walling 6200, 9-stage vertical turbine submersible pump. The pump was set at 360 feet below ground surface during the pre-acidification tests and 340 feet below ground surface during the post-acidification tests.

Results (time and drawdown data) of the pump tests were recorded by the onsite geologist for later analysis of aquifer properties.

2.9 WATER SAMPLING AND ANALYSIS

Two water samples were collected for analysis during the field program. One sample was collected from the well at the end of the post-acidification pump test. In addition, a sample of the treated water was also collected. The purpose of water sampling was to obtain aquifer and finished water quality to perform geochemical plugging analysis.

Table 2-2 contains the analytical parameters for the two water samples. Water quality testing was performed at the UGRA laboratory and San Antonio Testing Laboratories in San Antonio. Additional analytical testing of the aquifer water was performed by the Texas Water Department Board.

Table 2-2
WATER QUALITY PARAMETERS AND DETECTION LIMITS

Parameter	Detection Limit mg/L	Parameter	Detection Limit mg/L
Total Alkalinity	1	Copper	0.01
Total Dissolved Solids	1	Manganese	0.01
Total Suspended Solids	1	Zinc	0.01
Turbidity	1 NTU	Cadmium	0.01
Color	1 CU	Selenium	0.01
Specific Conductance	1	Noncarbonate Hardness	1
pH (field)	--	Calcium Hardness	1
Temperature (field)	--	Nitrate	0.1
Dissolved Oxygen (field)	1	Phosphate (ortho)	0.01
Chloride	1	Ammonia	0.01
Fluoride	0.1	Hydrogen Sulfide	0.01
Sulfate	1	Total Organic Carbon	--
Carbonate Alkalinity	1	Total Coliform	--
Bicarbonate Alkalinity	1	Chloroform	0.01
Total Silica	1	Bromodichloromethane	0.01
Calcium	1	Dibromochloromethane	0.01
Magnesium	1	Bromoform	0.01
Sodium	1	Total Trihalomethane	0.01
Potassium	0.1	Total Hardness	1
Iron	0.01		
Aluminum	0.01		

3.0 DISCUSSION OF RESULTS

3.1 BOREHOLE STRATIGRAPHY

Drill cuttings, rock core, and geophysical logs were used to characterize the subsurface stratigraphy at PZ-1. Figure 3-1 summarizes the findings of the subsurface investigation. Six major geologic formations were penetrated in the PZ-1 borehole. These included, from youngest to oldest (top to bottom), the Glen Rose Limestone, the Hensell Sand, the Cow Creek Limestone, the Pine Island Shale, the Hosston-Sligo Sand, and the pre-Cretaceous Formations. The following subsections discuss the individual units in more detail. Geologic logs are included in Appendix A.

3.1.1 Glen Rose Limestone

The Glen Rose Limestone is subdivided into two units at the site. The Upper Glen Rose is found directly below the alluvium to a depth of approximately 120 feet. The lower contact is marked by a 5 to 10-foot thick anhydrite zone identified from geophysical logs and anhydrite crystals in drill cuttings. The Upper Glen Rose can be described as predominantly an interbedded sequence of light gray to olive gray clayey shale and mudstone with interbedded light gray limestone. The thinly laminated shales and mudstones are calcareous, soft to medium hard, slightly sandy, and contained some fossils. The limestone units of the Upper Glen Rose are finely crystalline and clayey. The limestones are slightly weathered to fresh and have trace amounts of pelecypod fossils. No major water bearing zones were found during the drilling of the Upper Glen Rose Limestone.

Beneath the anhydrite zone to a depth of 378 feet is the Lower Glen Rose Limestone. This 258-foot-thick unit is predominantly a mudstone/siltstone and limestone. The mudstone and siltstone units are light to medium gray, slightly calcareous to calcareous and soft to medium hard. Dolomite was found in a few locations. Lenses of a very fine to fine grained quartzic sandstone were found at several depths. At 240 feet, a thin conglomeritic zone was penetrated. At this depth, chert was also found. A thicker granule conglomerate was found at 310 feet.

The limestones of the Lower Glen Rose are similar to those found in the Upper Glen Rose. Typically light gray to medium gray, the limestones are finely crystalline, medium hard, contained some fossils, and in places were very clayey. No major water bearing units were penetrated in the Lower Glen Rose.

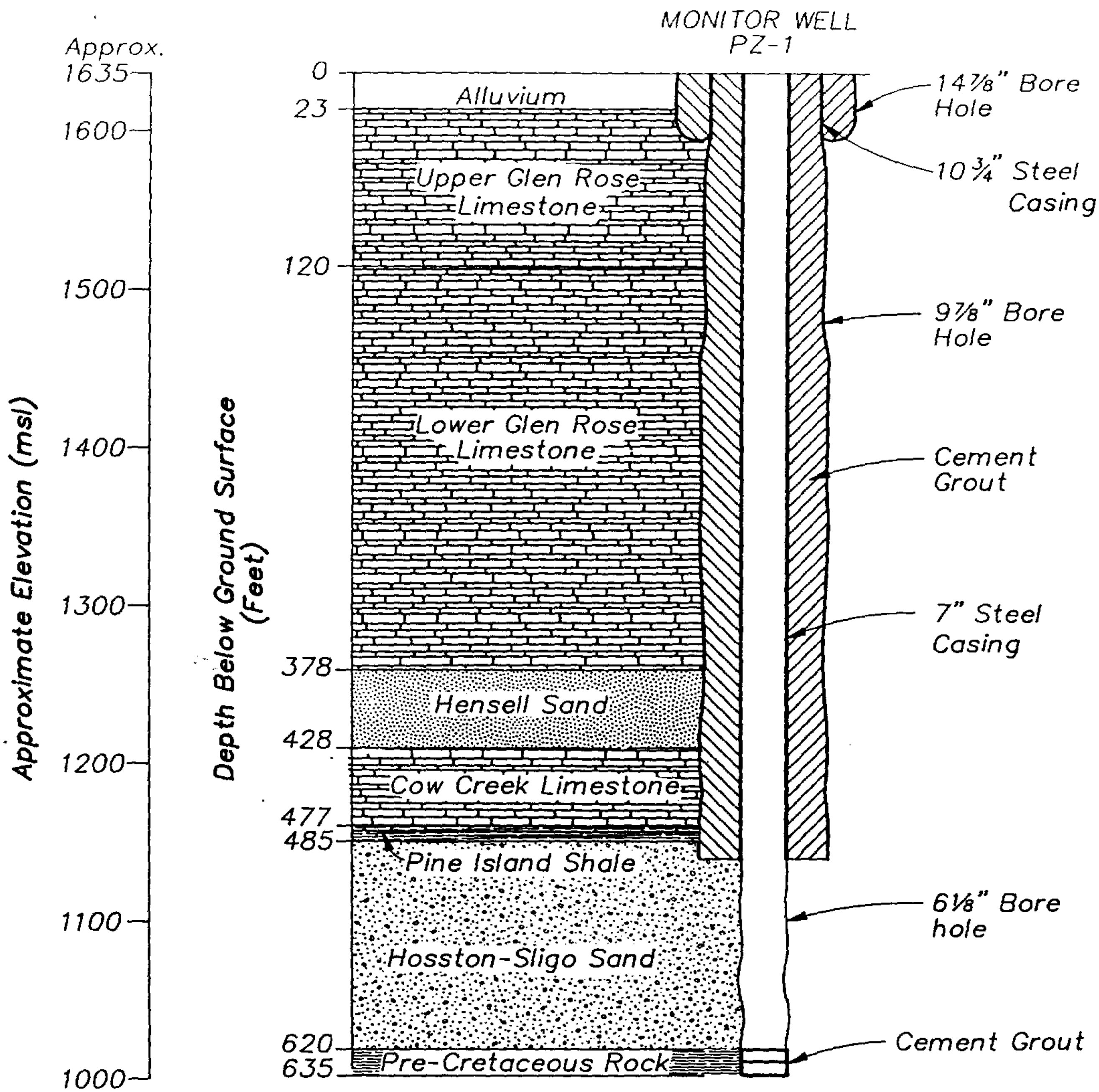

FIGURE 3-1
PZ-1 WELL COMPLETION AND
SUBSURFACE STRATIGRAPHY

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FIG3-1.DWG

3.1.2 Hensell Sand

The Hensell Sand was found to be present at depths of 378 to 428 feet below ground surface. The upper contact was chosen by reviewing drill cuttings and comparing geophysical logs (primarily resistivity) with adjacent wells (City Wells 8 and 13). Core sections of the Hensell were described from 400 to 428 feet. Rock chip descriptions comprise the remaining lithological analysis.

The upper 10 feet of the Hensell is a pale red clayey shale. The unit is soft, thinly laminated and non to slightly calcareous. The color change and the resistivity difference from the overlying units were the basis of the selection of the upper contact at 378 feet.

From 400 to 423 feet, the Hensell is represented by pale reddish-brown and light gray very fine- to medium-grained sandstone. Occasional conglomeritic or siltstone units are present. The sands of the Hensell are subround to subangular quartz with some clayey material. In general, the rocks are hard with siliceous cement. Calcite and dolomite cement are present in lesser quantities than silica. Primary porosity is moderate. High secondary porosity in the form of fractures occurs primarily from 413 to 418 and 400 to 403.

The base of the Hensell is marked by more than 5 feet of low permeability moderate reddish-brown mudstone. The contact with the underlying Cow Creek Limestone was chosen through review of geophysical logs and by color change with the underlying units.

3.1.3 Cow Creek Limestone

The Cow Creek Limestone is a highly variable lithologic unit. It is 48-feet-thick and was encountered at depths of 428 to 476 feet below ground surface (BGS). The upper 25 to 30 feet represents a rock sequence that includes light gray to brown siltstone and very fine to medium-grained sandstone. The rock is cemented with calcite, silica, and quartz. From 430 to 435 feet the unit contained vugs (small cavities) and was porous. In places, secondary calcite fills some of the voids. Coal and carbonaceous lenses were present at several depths (451.5 and 453 feet).

From 456 to 465 feet, the Cow Creek was found to be an extremely fossiliferous limestone. Fossils and fossil fragments comprised more than 70 percent of the rock. In places, the limestone was sandy and clayey.

The base of the Cow Creek from 465 to 476 feet is best described as a transitional sequence of interbedded sandstone, claystone, and limestone. A distinct boundary with the underlying Pine Island Shale was noted.

The Cow Creek at PZ-1 was not a major water bearing unit. Sampling of this unit through packers on the drill pipe was unsuccessful due to low production of the unit and difficulties in sealing the packers in the borehole.

3.1.4 Pine Island Shale

The Pine Island Shale was found between 476.6 and 485 feet BGS. The unit is represented by dark-greenish gray to olive gray siltstone and mudstone with some interbedded very fine- to medium-grained sandstone. Slightly carbonaceous zones are present and in some places thin coal zones were found. The rock is slightly pyritic and glauconitic. Dolomite was also found throughout the unit.

At PZ-1, the mudstones and siltstones may provide a good confining bed that separates the Cow Creek and Hosston-Sligo. However, the interbedded sandstones may provide a connection between these units at locales away from PZ-1.

3.1.5 Hosston-Sligo Sand

The Hosston-Sligo was present from 485 to 620 feet BGS. The 135-foot section was much thicker than the original estimate of 75 feet. From 485 to 557 feet, core recovery was good and averaged 86 percent. Lithologic descriptions were determined from these rock cores and geophysical logs. The lower half of the Hosston-Sligo was very difficult to core. From 557 to 620 feet, recovery averaged only 7 percent. Description of the lower zone was made from the limited core samples, geophysical logs and downhole color video tapes.

The upper 20 feet of the Hosston-Sligo Sand is characterized by brackish marine deposits and consists of irregularly interbedded siltstone and argillaceous fine- to medium-grained sandstone. The rocks are greenish-gray to olive-black and in places have abundant carbonaceous material. Trace amounts of pyrite and glauconite are present. The zone is slightly weathered and has a moderate to high porosity with abundant vugs (up to 5 cm in diameter).

From about 505 to 557 feet BGS, the Hosston-Sligo is predominantly represented by light-gray to reddish-brown dolomitic sandstones and sandy dolomites. The rock contains some silty and conglomeritic zones. Conglomeritic zones were found at 531.7 to 531.9, 539 to 539.9, 542 to 542.2, 544.8 to 546.8, and 556 to 556.3 feet.

The units are very variable in secondary porosity. Fracturing ranges from unbroken to very broken. The more porous zones (from visual observation) were between 509 to 512, which contained very large vugs; 520 to 525, characterized by vugs and fractures; 528 to 532, which was a massive-bedded but fractured zone; and 540 to 547, a very broken, slightly weathered zone.

Figure 3-2 contains pre-acid and post-acid caliper and post-acid sonic logs (porosity) for the Hosston-Sligo Sand. Review of the pre-acid caliper logs for this zone revealed only minor washouts or voids. Borehole diameter was up to 10 inches at approximately 505 feet and up to 9 inches at 512 to 513 feet. The remainder of the zone from 505 to 557 feet had borehole diameters of less than 8 inches.

Review of post-acidification caliper logs indicates that borehole diameters increased a minimum of 1 inch through the entire zone. Borehole diameter increases were observed at 505 feet (from 9 to 13 inches), 514 to 516 feet (from 9 to 12 inches) and 555 to 560 (from 8 inches to more than 2 feet).

Porosity corresponds well with the caliper logs. Highest porosity occurred from 555 to 565 feet BGS.

The lowest section of the Hosston-Sligo exhibited poor core recovery. Therefore, the stratigraphy is inferred from geophysical logs and downhole video surveys. From 557 to 565, the lithology is represented by an interbedded pebble-cobble conglomerate and sandy dolomite. The conglomerate is probably cemented by dolomite and dolomitic sands as evidenced by the effects of the acid. The cobbles are up to 4 inches in diameter. Large voids up to 1-foot-thick and more than 2 feet in diameter were noted following acidification.

From 565 to 570 feet, the rock appears to be a sandy dolomite with occasional conglomeritic pebbles. The diameter of the pebbles increases from 1 to 2 inches at the top to about 3 to 4 inches at the base. The conglomeritic pebbles/cobbles are well rounded.

The zone from 570 to 582 feet is represented by a fairly smooth borehole. The rock appears to be a dolomitic sandstone or sandy dolomite. Occasional pebbles are present.

A very porous zone is present from 582 to 586 feet. The upper half is a weakly cemented (dolomite), well rounded, pebble conglomerate. A void that developed by washout during acidification and development was noted at 584.5 to 586 feet.
The Hosston-Sligo from 586 to 598 feet exhibits a coarsening downward sequence. At 586 feet the rock is probably a dolomitic sandstone. Towards the base, grain size appears to increase in addition to the increased frequency of boulders. At 594 feet, 6-inch-diameter well-rounded cobbles were noted. Between 595 and

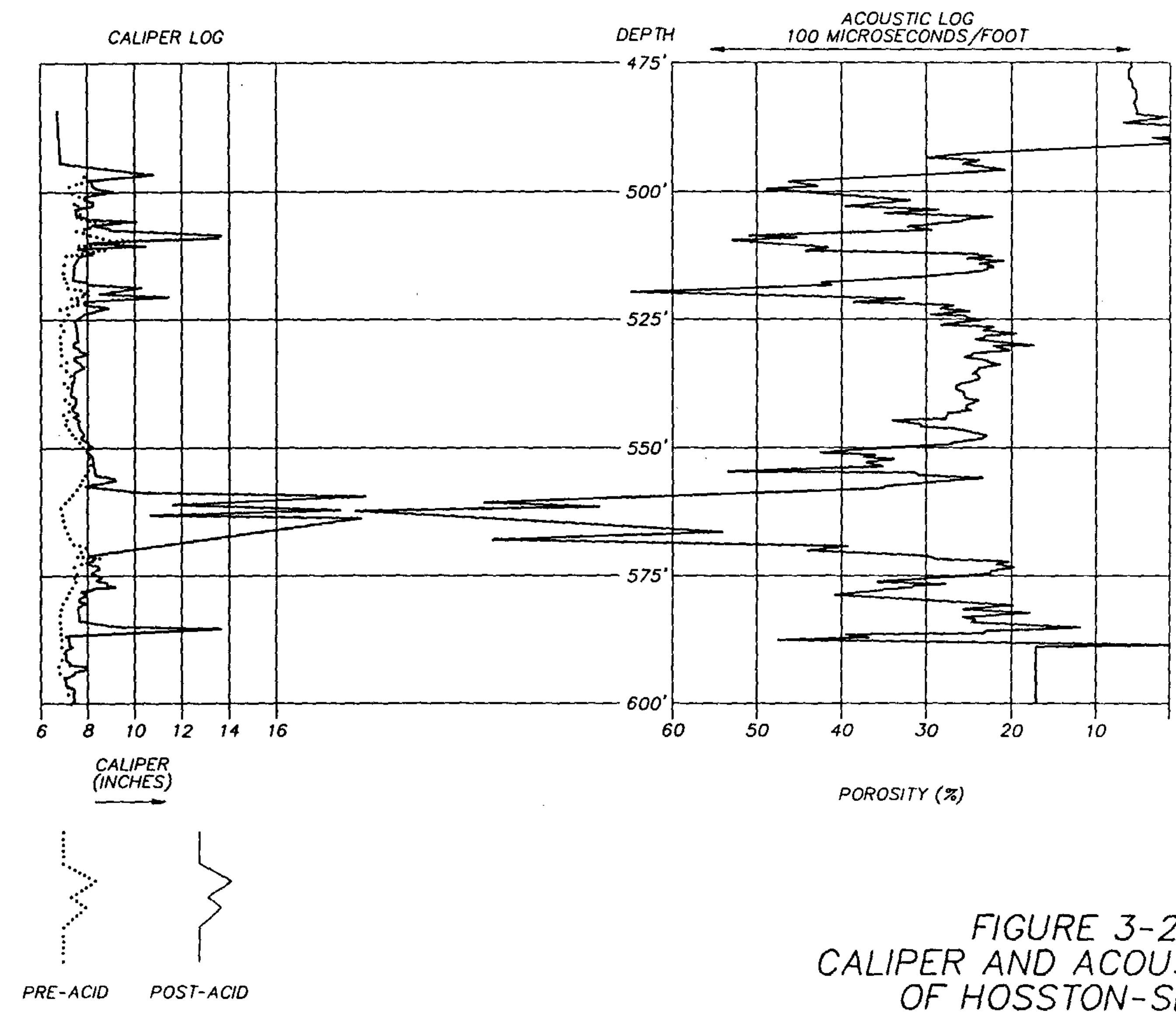

FIGURE 3-2
CALIPER AND ACOUSTIC LOG
OF HOSSTON-SLIGO

598 feet, the boulders increased to 12 inches in diameter and were cemented in a hard sandy dolomitic(?) matrix.

The remainder of the Hosston-Sligo was characterized as dolomitic sandstone with occasional pebbles. A void was found at approximately 601 feet. Below 601 feet the borehole caved after acidification and development. This caving continued during the post-acidification. It is suspected that the loosely cemented sand and gravel zones are caving into the borehole.

However, while the hole remained open immediately after drilling, geophysical logs were utilized to determine that the Hosston-Sligo has a sharp contact with the underlying precretaceous rocks.

3.1.6 Pre-Cretaceous Rock

Approximately 15 feet of the pre-Cretaceous rocks were penetrated in PZ-1. Five feet (620 to 625 feet) were penetrated by rollerbit drilling. From 625 to 635 feet, the rock was cored. No rock was recovered, however, on the core bit some light-gray clayey shale was found. The shale was presumed to have washed out during the drilling process. This material was very sticky, soft and slightly calcareous. Geophysical logs confirmed the presence of shale in this zone.

3.2 ROCK CORE ANALYSES

Mineralogy Incorporated prepared and conducted the detailed physical, chemical, and microscopic analyses of five samples. Four were from the production zone while the other was from the upper confining bed. The complete report is contained in Volume II, Appendix C. The following subsections summarize Mineralogy Inc.'s report.

3.2.1 Descriptions of Samples

The sample of the Pine Island Shale (481.1 to 481.8 feet) was a dolomitic shale characterized by low permeability and high porosity (24.3 percent). The shale was slightly glauconitic and burrowed. Micro shell fragments were also present. The shale also contained silty, sandy dolomite streaks and burrows.

The uppermost Hosston-Sligo Sand sample (511.5 to 512.0 feet) was represented by a mottled fractural silty sandy dolomite. The fractures were annealed by finely crystalline dolomite. The permeability was relatively low, but the porosity was moderate (19.2 percent).

The Hosston-Sligo Sand at 539.6 to 540.3 feet was represented by a fine-sandy dolomite that graded abruptly downward into a horizontally bedded dolomite-cemented conglomerate. The conglomeritic zone exhibited good porosity and permeability.

The sample from 552.5 to 553.4 feet was represented by a silty very finely crystalline dolomite with moderate porosity and very low permeability.

All of the dolomites have been interpreted as being deposited as silty or sandy limestone. Subsequent recrystallization occurred in the limestone, transforming the calcite to dolomite with intercrystalline micro porosity. The clays in the samples are primarily allogenic, formed elsewhere, and transported and deposited with the limestone when it precipitated.

3.2.2 X-Ray Mineralogy

Table 3-1 contains the results of the X-ray analysis of the five samples. The Pine Island Shale sample contained mostly quartz (57 percent) and dolomite (12 percent). Clays identified through X-ray analysis include illite/mica (10 percent), kaolinite (6 percent), and mixed layer illite/smectite (2 percent). This sample had the only occurrence of pyrite (4 percent). The remainder of the rock matrix included feldspars and calcite.

X-ray diffraction analysis from the sample at 512 feet indicated that dolomite (65 percent) and quartz (28 percent) were the major constituents. Less than 4 percent of the sample comprised clays (predominately illite) and the remaining materials were feldspars.

The samples at 539 feet 11 inches and 540 to 540 feet, 1-1/2-inches had near identical mineralogical constituents and percentages as the above sample.

The last sample analyzed from 552 feet, 3 inches to 552 feet 8 inches was more siliceous (quartz = 49 percent) than dolomitic (40 percent). Clays (kaolinite, illite, and smectite) comprised only 7 percent of the rock. Feldspar was the remaining constituent.

3.2.3 Acid Residue Analysis

The acid residue analysis is a measure of the reactivity of the rock to hydrochloric analysis. As expected the zones with the most dolomite were also the highest soluble zones. Therefore, more dolomitic zones will most likely result in higher porosity and potentially greater storage zones for the ASR program. Following are the analyzed depths and the acid soluble and dolomite percentages.

Table 3-1
X-RAY DIFFRACTION MINERAL PERCENTAGES

Depth	Quartz	Calcite	Dolomite	Pyrite	Koalinite	Chlorite	Illite/ Mica	Mixed-Layer Illite/ Smectite	Plagioclase Feldspar	Feldspar K
481'6" - 481'7"	57	4	12	4	6		10	2	tr	5
511'11" - 512'0"	28		65		1	tr	2	tr		4
539'11"	35		56		1		3	1		4
540'1/2" - 540'1-1/2"	38	1	52		1		3	1		4
552'7" - 552'8"	49	tr	40		2		3	2		4

NOTE: tr = trace amount

Depth	Acid Soluble (%)	Dolomite (%)
481' 6" - 481' 7"	14.0	12
511' 11" - 512' 0"	71.4	65
539' 11"	63.7	56
540' 1/2" - 540' 1-1/2"	54.7	52
552' 7" - 552' 8"	34.5	40

3.2.4 Permeability, Porosity, Density

Permeability (horizontal and vertical), porosity, grain density and specific gravity analyses were conducted on all samples. Results are summarized in Table 3-2. Horizontal permeabilities were always greater than vertical permeabilities. This is mostly the result of the horizontal alignment of the plate-like clay minerals and silt-sized particles. In the shale, the vertical permeability was 1,000 times less than the horizontal permeability. The highest horizontal permeability was observed in the dolomite-cemented conglomerate and was 1,505 millidarcies (md) or 4/ft/day. The lowest horizontal permeabilities were in the silty dolomite (1.17 md or 0.003 ft/day) and Pine Island Shale (1.91 md or 0.01 ft/day).

Vertical permeabilities ranged from a low of 0.002 md ($5x10^{-6}$ ft/day) in the Pine Island Shale sample to a high of 91.6 md (0.25 ft/day) in the coarse sandy dolomite. The low vertical permeability suggests that the Pine Island Formation has potential as a confining bed if it is uniform throughout the Kerrville area.

Porosities were fairly uniform and ranged from 18.7 to 29.8 percent. Rock density ranged from 2.75 to 2.80. Highest density was observed in the shale and largely reflects the lower percentages of dolomite in the shale.

Specific gravity values for the rock were very similar and ranged from 2.42 to 2.63.

3.2.5 Cation-Exchange Capacity

Cation exchange capacity (CEC) is a measure of the capacity a rock has to precipitate cations from solution. This precipitation could adversely affect ASR wells by plugging the pore spaces. CEC is dependent upon the amount and type of clay. The more clay minerals in a unit the higher the CEC will be.

In general the lowest CEC values are observed in the kaolinite clays while the highest CEC values would be found in the illite/smectite. Illite/micas would have intermediate CEC's. Table 3-3 contains the CEC of the five samples and the corresponding clay mineralogy.

Table 3-2
PERMEABILITY, POROSITY, SPECIFIC GRAVITY, AND GRAIN DENSITY RESULTS

Depth	Permeability-md Horiz.	Vert.	Porosity %	Specific Gravity	Grain Density gm/cc
481'6" - 7"	1.91	.002	24.3	2.42	2.80
511'11" - 512'	38.2	4.48	19.2	2.46	2.77
539'11"	1505	24.7	29.8	2.58	2.79
540'1/2" - 540'1-1/2"	95.3	91.6	24.7	2.63	2.75
552'7" - 552'8"	1.71	.32	18.3	2.54	2.75

Table 3-3
CATION EXCHANGE CAPACITY RESULTS

Depth	CEC (meq/100 gr)	Kaolinite (%)	Chlorite (%)	Illite/ Mica (%)	Mixed Layer Illite/ Smectite (%)	Total Clay
481'2"	11.1	6	--	10	2	18
512'0"	1.2	1	trace	2	trace	3
539'6"	0.7	1	--	3	1	5
540'1/2"	2.6	1	--	3	1	5
552'7"	4.5	2	--	3	2	7

3.2.6 Summary and Discussion

The reddish to brown color of the Hosston-Sligo rocks is supportive of a groundwater under oxidizing conditions. The thin dolomitic shale is gray and contains some pyrite (estimated to be 4 percent) indicating that at least at one time the Pine Island shale was under reducing conditions. No pyrite is reported for any of the Hosston-Sligo rocks. Either the pyrite was restricted to the shale or the dolomitization and subsequent groundwater flow destroyed the pyrite in the more permeable intervals. Iron staining around small fractures in the sands and color changes along fractures in the dolomite suggest that the aquifer is under oxidizing conditions and that the fractures may be controlling the permeability in the dolomite and fine-grained sands.

Dolomite and quartz are the dominant minerals that form the aquifer skeleton. Quartz ranges from 28 to 50 percent and dolomite from 40 to 65 percent. The dolomitic sands are dominantly quartz and the sandy to silty dolomites are mostly dolomite. Potassium feldspar is the next most abundant mineral at approximately 4 percent. It is most likely present in the fine sands. The clays make up to 18 percent of the dolomitic shale but in the other four samples they make up only 4 to 7 percent. The micaceous clay is dominant over the swelling clay, smectite or montmorillonite, kaolinite and chlorite. The pelletal grains called glauconite are a mixture of these clay minerals. There is a possibility that there may be some organic matter in the fine sands but, if true, it is not abundant.

Scanning electron microscopy confirms the mineralogical assemblage defined by x-ray diffraction but also indicates the structural form of the aquifer matrix. The dolomite is present throughout all core samples. It is present even in the coarse sands as small crystals attached to the sand particles. Pore throats (channels between sand particles) appear to be equal or larger than approximately 10 microns in diameter. A chlorite or kaolinite packet is pictured at the entrance to one of the pore throats. These appear to be very stably attached to the dolomite and therefore would not tend to be torn off and close the pore to groundwater flow. However, there appear to be few pores in the parts of the cores that were examined. If these samples are representative of the aquifer (and there is no reason to believe otherwise) the fractures and coarser grained sands and conglomerates are probably the dominant control on groundwater flow, rather than interpore space flow through the finer grained sands and dolomites.

3.3 HYDROGEOLOGIC PROPERTIES

The Hosston-Sligo formation is a confined aquifer at the site. The upper confining unit is the Pine Island Shale. Vertical permeability of this unit, as measured by a single rock core analysis, is 1.9×10^{-9} cm/sec or (5.5×10^{-6} ft/day). The

Hosston-Sligo also has a lower confining bed (pre-Cretaceous rocks) that includes gray shales. No permeability tests were conducted on the lower unit.

The hydrostatic head on the Hosston-Sligo sand is approximately 290 feet. The top of the formation was encountered at 485 feet and the final water level after all field testing was completed was measured at 195 feet BGS.

Two types of pumping tests were conducted on well PZ-1. A post-acidification variable rate pump test and a constant rate pump test was conducted to determine specific capacity and estimate the hydraulic parameters of the aquifer. Appendix D contains the results of all of the well tests in addition to the analysis of data.

The best data were obtained from the 8-hour constant rate (200 gpm) drawdown and recovery test. The data were analyzed by Theis drawdown and recovery methods and Jacob Straight Line Approximation to estimate transmissivity. Following are the results of the analyses.

Method	Transmissivity (gdf)
Jacob	9,600
Theis (drawdown)	11,128
Theis (recovery)	11,115

These values are less than the reported values for the Hosston-Sligo wells in the City of Kerrville. City wells have reported transmissivities ranging from 16,000 to 25,000 gallons/day/foot (gdf).

The effects of acidification of the well were evaluated by analyzing the specific capacity (pumping rate/drawdown) at a common period (4 hours) between two pump tests. The pre-acidification test (Pump Test 2) after 4 hours of pumping at 150 gpm resulted in a drawdown of 81 feet. Specific capacity for this time period was 1.85 gpm/ft. In contrast, the drawdown following 4 hours of pumping at 200 gpm in Pump Test 4 was 29.55 feet. Post-acidification specific capacity was 6.87 gpm/ft resulting in an increase of 3.6 times. Similar percent increases have also been noted in the City wells following acidification.

Specific capacity of a water supply (long-term pumping) well is best determined following a period of time after pumping initiates. The early drawdown in a well is the result of well casing storage and not aquifer response. For the post-acidification pump test, it was estimated that the effects of well casing storage were greatly reduced after the first 10 minutes of pumping. During this period, the water level dropped 18 feet. Subtracting the initial effect, the specific capacity for PZ-1 was re-estimated at 15 for the 8 hours of pumping. This value is consistent with the range of 10-22 gpm/ft for existing City wells.

Review of flow logs, lithology and geophysical logging results indicates that the majority of the water is produced in the middle to lower half of the aquifer. This is based upon review of lithology, borehole video and flow logs. Flow logging shows a steady increase in velocity from the top of the borehole to the voids encountered at around 560 feet BGS. At this location, a sharp velocity decrease occurs due to the large voids at this zone. When the flow log was conducted from the base to the top of the formation, similar velocities were found throughout the unit. This information indicates that the biggest production area is in the 550 to 580 feet BGS zone. Flow contribution below and above this zone are probably very similar.

Aquifer porosity was measured by two methods. Selected cores were tested by laboratory methods and the resulting porosity values for the Hosston-Sligo ranged from 18.3 to 29.8 percent. Rock porosity was also estimated from the geophysical logs. The post-acidification logs reveal a high porosity zone from 495 to 525 feet. Thin zones in these areas reach 50 percent; however, in general the range is 30 to 35 percent. Between 525 and 550 feet, the porosity decreases and ranges from 15 to 25 percent.

The next high porosity zone is from 555 to 580 feet. This zone is characterized by large voids (porosity = 100 percent). Beneath 570 feet, two high porosity zones were identified. From 570 to 580 feet, the porosity reaches about 40 percent, while in the zone from 588 to 590 feet up to 45 percent was found.

3.4 GROUNDWATER AND FINISHED WATER QUALITY

Water quality samples were collected at several times during the field investigation. Water samples were to be collected from the Cow Creek Limestone and the Hosston-Sligo Sand. Unfortunately, the samples from the Cow Creek could not be retrieved. Difficulties with the packer system sealing off the formation and the low flow present in this unit, precluded collection of a sample.

The Hosston-Sligo was sampled during the development periods before and after acidification and at the end of the final pump test. The development samples were collected and analyzed onsite for a few water quality parameters were analyzed. The pump test sample was analyzed at the UGRA and San Antonio Testing Laboratories for a more comprehensive suite of parameters. Additional testing was conducted by the TWDB. Data sheets for all laboratory work are in Appendix E.

Table 3-4 contains the results of water quality testing during the development period. Pre-acidification waters exhibited a conductivity of about 680 umhos/cm,

Table 3-4
WATER QUALITY DURING WELL DEVELOPMENT

Period	Time (Hours)	Conductivity (umhos/cm)	(pH)	Fe (mg/L)	Cl (mg/L)	Turbidity NTU	Sulfate (mg/L)
Pre Acid	7	--	--	--	--	49	--
Pre Acid	8	684	8.22	--	--	12	--
Pre Acid	10	680	8.23	0.34	--	4.4	--
Pre Acid	11.5	682	--	--	--	2.3	33
Pre Acid	14.5	670	8.19	0.60	--	4.2	--
Pre Acid	15.5	--	--	--	--	2.4	--
Post Acid	1	--	6.8	--	--	--	--
Post Acid	2	12,000	6.6	--	--	--	--
Post Acid	3	7,160	6.7	--	--	--	--
Post Acid	4	--	6.6	20	2,960	--	--
Post Acid	4.5	8,100	6.8	--	--	--	--
Post Acid	5.5	7,300	6.8	20	2,450	--	--
Post Acid	6	5,530	7.0	--	1,800	--	--
Post Acid	7.5	5,400	7.1	9	1,750	--	--
Post Acid	8.5	4,820	7.1		1,500	--	--
Post Acid	9.0	4,500	7.1	3	1,350	--	--
Post Acid	9.5	4,480	--	11.5	1,320	--	--
Post Acid	11.5	3,110	--	9.9	1,000	--	--
Post Acid	14.5	2,780	--	11.7	850	--	--
Post Acid	17	2,540	7.2	6.7	--	--	--
Post Acid	20	2,320	--	--	675	--	--
Post Acid	22	2,150	7.3	5.9	--	--	--
Post Acid	24	2,180	7.4	4.5	--	--	--
Post Acid	27	1,900	7.4	--	--	--	--
Post Acid	32.5	1,367	7.4	--	260	--	--
Post Acid	39	1,203	--	--	240	35	--
Post Acid	45.5	1,020	7.5	--	160	--	--

an alkaline pH of 8.2, and iron between 0.3 and 0.6 mg/L. One sample was analyzed for sulfate and contained 33 mg/L. All of these values are within Texas Department of Health standards. Turbidity ranged from 49 NTU following 7 hours of development to only 2.4 after 15.5 hours of development.

Water samples collected during the development period following acidification exhibited an expected wide range of water quality. In the first few hours of development, conductivity ranged from 8,000 to 12,000 umhos/cm, the pH was slight acidic (6.6 to 6.8), iron was 20 mg/L, and chloride was near 3,000 mg/L. These values reflect the result of the acidification. The hydrochloric acid reacted with the dolomite in the formation and liberated calcium and magnesium and increased the dissolved solids as reflected by conductivity. The acid also reacted with the iron in the formation and well casing, thereby increasing the iron in development waters. The high chlorides are the residuals of the neutralized hydrochloric acid.

PZ-1 was developed for approximately 45 hours following acidification. During development, the monitored parameters (conductivity, pH, chloride, and iron) approached, but did not attain their pre-acidification levels. Conductivity dropped to about 1,000 umhos/cm, chloride decreased to 160 mg/L, iron decreased to about 4 mg/L, and pH rose to 7.5.

Additional development and purging of the well occurred during the 12 hours of pump testing that followed the second development period. A sample of aquifer water was collected. After 6 hours of pump testing, the Hosston-Sligo water sample was collected for detailed analysis. In addition, a sample of finished water was also collected. These samples and aquifer matrix material analyses (Section 3.2) are the basis of the plugging analyses (Section 3.5). Table 3-5 depicts the water quality of the sample from PZ-1, finished water, and typical City wells.

PZ-1 water is characterized as near-saline (TDS=583 mg/L), slightly alkaline (pH=7.3), hard water (hardness=416 mg/L). This type of water is not atypical for the Hosston-Sligo Sand as evidenced by the ranges in 17 City wells. The majority of the dissolved solids content in PZ-1 water is from bicarbonate(331 mg/L), chloride (96 mg/L), calcium (58 mg/L), and magnesium (48 mg/L).

The trace metals cadmium, copper, and selenium were below detectable levels. Other metals detected included aluminum (0.1 mg/L), iron (1.36 mg/L), manganese (0.07 mg/L), and zinc (0.04 mg/L).

Comparing PZ-1 water quality with the City wells data reveals that the majority of the parameters were below or within the range of concentration of the City wells. For the parameters analyzed, only iron (1.36 mg/L), manganese

Table 3-5
SUMMARY OF WATER QUALITY

Parameter	Units	PZ-1	Finished Water	City Wells	TDH Limits
pH	S.U.	7.3	7.6	7.3 - 8.0	>7.0[a]
Temperature	C°	23	25	--	
Specific Conductance	umhos/cm	942	399	--	
Dissolved Oxygen	mg/L	4.08	7.69	--	
Total Alkalinity	mg/L	331	169	--	
Suspended Solids	mg/L	4.4	0.21	--	1,000
Dissolved Solids	mg/L	583	262	540 - 710	
Turbidity	NTU	2.8	0.22	--	
Total Hardness	mg/L	416	206	312 - 445	
Noncarbonate Hardness	mg/L	85	37	--	
Calcium Hardness	mg/L	146	68	--	
Chloride	mg/L	96	23	12 - 109	300[a]
Fluoride	mg/L	1.0	0.9	0.9 - 1.5	1.6[b]
Nitrite (N)	mg/L	<0.01	--	--	
Iodine	mg/L	<0.1	--	--	
Nitrate (N)	mg/L	0.069	0.049	<0.4	10
Ammonia (N)	mg/L	0.1	0.1	--	
Sulfate	mg/L	24	11	27 - 92	300[a]
Ortho Phosphate	mg/L	0.041	0.011	--	
Aluminum	mg/L	0.1	0.2	--	
Cadmium	mg/L	<0.01	<0.01	<0.005	0.01
Calcium	mg/L	58	27	60 - 97	
Copper	mg/L	<0.02	<0.02	<0.02	1.0[a]
Iron	mg/L	1.36	0.05	0.06 - 1.15	0.3[a]
Magnesium	mg/L	48	19	37 - 56	
Manganese	mg/L	0.07	<0.01	<0.05	0.05[a]
Potassium	mg/L	7.5	1.3	--	
Selenium	mg/L	<0.01	<0.01	<0.002	0.01
Silica	mg/L	3.3	4.9	--	
Sodium	mg/L	37	11	12 - 34	
Zinc	mg/L	0.04	0.05	0.02	5.0[a]
H_2S	mg/L	<1	<1	--	
Total Organic Carbon	mg/L	1.4	2.3	--	
Volatile Organics	µg/L	BMDL		--	
Chloroform	µg/L		35		
Dichlorbromomethane	µg/L		23		
Color	C.U.	39	1	--	
Density	g/ml	0.992	0.991	--	
T. Coliform		0	0	--	

NOTES:

TDH = Texas Department of Health
[a]Secondary standards related to aesthetics and taste, not to health risks.
[b]For air temperature of 71° to 79°.

(0.07 mg/L), sodium (37 mg/L), and zinc (0.04 mg/L) exceeded the City well range.

Comparison with Texas Department of Health limits has revealed that only iron and manganese exceed the standards of 0.3 and 0.05 mg/L, respectively. The standards for these parameters are related to aesthetics (taste and porcelain staining) and not health risks.

Water quality for PZ-1 as depicted by the single sample still exhibits the affects of residuals from the acidification process. Conductivity in the collected sample still exceeded the pre-acidification concentrations (942 versus 680 umhos/cm). This has also resulted in a higher than expected dissolved solids concentration. Chloride, calcium, and magnesium are probably higher than normal as a result of reaction of acid (HCl) and the dolomite $[CaMg(CO_3)_2]$ in the aquifer matrix. Elevated iron levels are presumed to come from acid attack on the casing and aquifer materials and would probably decrease to less than 1 mg/L if the well were to undergo additional development.

The finished water sample is also non-saline (TDS=262 mg/L), slightly alkaline (pH=7.6), and hard (206 mg/L). With the exception of zinc (0.05 mg/L), all parameters common with the City well data were within or below City well ranges.

Comparing the PZ-1 water with finished water indicates that the finished water has less similar water quality, except that individual parameters in the finished water are present in lower concentrations.

Aluminum, zinc, silica, and dissolved oxygen were the only parameters present in the finished water in higher concentrations than in the PZ-1 water. The higher dissolved oxygen in the finished water sample is not out of the norm because surface water (source) is more aerated, especially after it has been passed through the treatment plant. The remaining three parameters were only slightly above the concentrations in PZ-1.

Organic analyses were conducted on finished water. Total organic carbon in the finished water was slightly higher than in the PZ-1 well water (2.3 versus 1.4 mg/L). Purgeable aromatic and halocarbon compounds were also analyzed. These analyses revealed the presence of chloroform (35 µg/L) and dichlorobromomethane (23 µg/L) in the finished water. No purgeable aromatics or halocarbons were detected in the well water.

Comparing the finished water with TDH requirements reveals that no standards were exceeded for the parameters analyzed.

In summary, the PZ-1 water exhibits acceptable water quality. This water is comparable to water produced from the existing City wells. Finished water quality is similar to well water quality and is within TDH standards. PZ-1 water only exceeded the aesthetic standards for iron and manganese.

3.5 PLUGGING ANALYSIS

Plugging analysis includes an assessment of geochemical, physical and biological plugging. The geochemical plugging analysis involves an interpretation of the geochemical reactions between the recharge (finished) water and the insitu groundwater. A representative water analysis of each water is entered into a chemical thermodynamic computer model called EQ3NR. EQ3NR determines the equilibrium status of each water. Model runs are included in Appendix F. The analytical accuracy of the combined field and laboratory analysis is checked but the model principally determines the compatible minerals and chemical compounds in the water systems. The groundwater and the mixture of groundwater and recharge water are then compared to the rock mineralogy to determine the degree of compatibility between the groundwater and the aquifer rock matrix. If the calculations indicate that a mineral could precipitate (supersaturated state), then an assessment of its potential to plug the aquifer must be made. The assessment involves both the physical and chemical potential for plugging, but principally centers on the likelihood that a supersaturated mineral could form under aquifer conditions and that the volume of that mineral could be significant to affect porosity and permeability. This assessment is more important in fine sand and silty sand aquifers than in rock aquifers that transmit flow through fractures, but can be important in both after a long period of time.

3.5.1 Representativeness

The groundwater and recharge water (finished plant) analyses were compared to historical water analyses in the area to assess the representativeness of the analyses. The treated Guadalupe River recharge water compares favorably with three other analyses collected in 1985 and 1986 with only a few exceptions. The calcium, bicarbonate, sulfate and nitrate are lower than the historical range and the iron is slightly higher. The Kerrville well water is only slightly lower in calcium, bicarbonate, and sulfate than 17 historical City of Kerrville well water analyses analyzed between 1963 and 1973. The sodium is slightly higher but the iron is considerably higher than the historical data. Except for the iron, these analyses are probably representative of the recharge and groundwater. The effect of the lower calcium and bicarbonate in the recharge water is addressed in the equilibrium discussion.

The higher iron concentration in the groundwater is probably a residual from the acidification procedure. The acidification increases the well production by dissolving some of the aquifer matrix. It usually takes a very long time to completely remove the dissolved material from the aquifer skeleton. In this case, an iron concentration of 0.6 milligrams per liter (mg/L) is assumed to be more representative of the groundwater. This assumption is based on the preacidification concentration of dissolved iron.

Preacidification groundwater had a pH of 8.2, the groundwater sample had a pH of 7.3, and the historical groundwater has a range of pH from 7.3 to 8.0. The preacidification pH is above historical values but is approximately that of a fresh carbonate aquifer skeleton in contact with dilute groundwater. A correction for the pH involves too many variables to be supportable. Therefore, a pH of 7.3 (measured field pH) and a pH of 8.2 (potential pH) were used in initial calculations.

The recharge water is near saturation with respect to atmospheric oxygen. This is important because if the aquifer is under reducing conditions, iron and manganese can be either relatively immobile or mobile depending on other dissolved ions. The introduction of oxidized recharge water from the surface would cause the dissolved iron to precipitate and flocculate, thereby potentially plugging the smaller pore spaces and reducing the permeability of the aquifer. This problem is particularly acute if pyrite is present in the more permeable parts of fine sand aquifer(s). The presence of pyrite in the Hosston-Sligo is considered insignificant and most of the iron is in an oxidized state. Since the aquifer is under oxidizing conditions, this potentially adverse effect should not occur.

The relatively high chloroform (35 micrograms per liter) and dichlorobromomethane (23 micrograms per liter) in the UGRA WTP finished water suggest that the residual chlorine should be maintained at a minimum concentration in the recharge water. Higher values may enhance the formation of trihalomethane, which, however, may be reduced during aquifer storage.

3.5.2 Thermodynamic Equilibrium Modeling

The EQ3NR computer model was run twice for the groundwater (pH differences), once for the recharge water and twice for the mixed recharge and groundwater (Eh differences). The groundwater at a pH of 7.3 resulted in the finding of 15 minerals that are at or near saturation, which are potential plugging problems if the minerals precipitate under specific temperature and pressure conditions. The remaining 835 minerals are undersaturated and will not precipitate.

Dolomite (calcium magnesium carbonate) is the major control on the calcium, magnesium and alkalinity. The magnesium is in equilibrium with magnesite (magnesium carbonate). Calcium is in equilibrium with aragonite and calcite (calcium carbonate). Iron is in equilibrium with siderite (iron carbonate). The analysis at pH 7.3 indicates excellent correlation with the carbonates. Silica is in equilibrium with quartz and along with other ions (smectite and potassium feldspar).

Aluminum is in equilibrium with boehmite (aluminum hydroxide), a weathering product of the clay mineral kaolinite. The illitic/micaceous clay is probably a phengite (a silica-rich illite). Manganese and phosphate are in equilibrium. Zinc is in equilibrium with adsorption onto exposed iron oxyhydroxides. The glauconite pellets may also contain the clay mineral chamosite.

Undersaturation is a common situation when a suite of 850 minerals are being scanned for equilibrium and no explanation is necessary. Oversaturation is unusual and needs to be considered for potential plugging material. A scan of the equilibrium minerals indicate that as many as 40 minerals may be potential plugging material. However, most of these are clays, zeolites and metamorphic minerals that are either kinetically too slow to form before other simpler minerals (like those above) or do not form at the anticipated conditions of temperature and pressure in any significant amount. Therefore, plugging by equilibrium minerals is not expected.

The recharge water has a very similar equilibrium to the groundwater. Most of the minerals are slightly less saturated but still well within equilibrium. The iron and manganese have lower concentrations. Iron is present as iron oxyhydroxide typical of the oxidized surface conditions. The manganese concentration is too low to be indicative of any equilibrium. The orthophosphate is in equilibrium with calcium.

The mixture of recharge and groundwater on a 50-50 basis was analyzed for both oxidizing and reducing conditions. In both cases the mixture resembles the groundwater equilibrium mineralogy. The oxidation-reduction ratio mostly affects the iron and manganese equilibrium mineralogy, and only indirectly affects the other equilibria. When iron and manganese are present in concentrations below approximately one mg/L at a pH near neutral, they do not have a significant effect on the equilibria.

Given the above data there does not appear to be a problem with plugging the aquifer by geochemical reactions either between the recharge and groundwater or between the 50-50 mixture and the aquifer minerals. The data are limited and do not cover the extreme conditions of either the water or probably the spectra of aquifer mineralogy, but do probably represent the average conditions for the aquifer. No additional testing is necessary due to this consistent geochemical and mineralogical data.

3.5.3 Summary

The plugging analysis indicates no significant geochemical plugging potential based on the physical, chemical and mineralogical data and the thermodynamic equilibrium data for the groundwater and a 50-50 mixture of recharge water and groundwater. The recharge and groundwater are in equilibrium with one another and the mixture is in equilibrium with the aquifer mineralogy. Therefore, precipitation of new minerals in pore spaces is unlikely. These are expected to represent near average conditions in the aquifer and for the recharge process. There may be parts of the aquifer that have not been defined by core analysis and water quality extremes that would be outside the assumptions in this analysis. The data are so consistent in their characterization, however, that no significant deviations are expected.

The geochemical and mineralogical data analyses indicate that no further geochemical testing is necessary.

Although aquifer plugging due to geochemical reactions is not expected, other mechanisms may also occur that can plug the aquifer if adequate precautions are not taken. In particular, biological and physical plugging potential have to be taken into consideration.

Biological plugging can occur when conditions in the ASR well are conducive to growth of bacteria, generally iron and sulfur bacteria. These occur naturally underground or can be introduced with the recharge water or during drilling operations. Bacterial growth can be stimulated by the introduction of nutrients in the recharge water or by release of nutrients in the aquifer through geochemical action. A proven approach to controlling bacterial activity is to treat the ASR well very similar to a dead-end in a water distribution system. Recharge will occur with treated drinking water, similar in geochemical composition to the native water in the storage zone. The recharge water will have a disinfectant residual that will prevent bacterial activity in the well. During storage periods when this residual would normally disappear after a few days, a trickle flow of treated water should be allowed to flow into the well to maintain a disinfectant residual. This approach, combined with selection of non-ferrous or coated casing and wellhead materials, should be sufficient to control bacterial plugging at the UGRA site.

Physical plugging can occur when solid matter in the recharge water is present at sufficient concentrations as to form a mat on the formation walls. Every 1 milligram per liter (mg/L) of total suspended solids (TSS) can introduce about 3 cubic feet of solid material into a well per 100 million gallons of recharge. A general rule of thumb is that recharge water TSS should be less than 2 mg/L to avoid frequent plugging and the resultant need for backflushing or redevelopment. Data collected by UGRA at the water treatment plant during

October 1989 indicated TSS values ranging from 0.014 to 0.075 mg/L, and turbidity values ranging from 0.06 to 0.16 NTU. The average ratio for TSS to turbidity was 0.51. If these values are representative of those that would occur during a recharge season, physical plugging should not be a problem. Backflushing the well to waste or to the raw water supply for up to one hour at the beginning of recharge and recovery operations should be adequate.

Physical plugging can also occur due to air entrainment during recharge. If water is allowed to cascade into a well in such a way as to induce air, the air may tend to move into the formation and air-bind the aquifer. Several design alternatives are available at the UGRA site to ensure that this will not occur.

4.0 CONCLUSIONS AND RECOMMENDATIONS FOR ASR PROGRAM

4.1 CONCEPTUAL DESIGN OF ASR WELL

A significant finding of this investigation is the thickness of the Hosston-Sligo formation at the UGRA site, totalling 135 feet. This is about twice the expected thickness based upon available records from existing wells in the Kerrville area. Furthermore, it appears that the middle section of this formation yields most of the water to the well. One possible explanation is that existing Hosston-Sligo wells are generally constructed with open boreholes, which remain open only in the upper part of the formation but may fill in with sand if constructed deeper. If wells were designed to produce from the full thickness of the aquifer, well yield and efficiency may increase, as would the cost of well construction.

For ASR purposes, it would be appropriate to construct wells through the full thickness of the formation, possibly requiring screen and gravel pack well construction methodology. Based upon data from well PZ-1, the following ASR well conceptual design appears appropriate:

- Set 40 feet of 24-inch steel surface casing.
- Drill nominal 24-inch hole to 495 feet and obtain geophysical logs.
- Set 495 feet of 16-inch casing, cemented to the surface.
- Drill 14-inch hole to 620 feet.
- Develop open borehole with eductor techniques and obtain geophysical logs.
- If the hole remains open, acidize the well with 15,000 gallons of 15 percent hydrochloric acid, develop the acid residues from the well with an eductor, and obtain final geophysical logs.
- If the hole fails to remain open either before or after acidization, set approximately 100 feet of 8-inch stainless steel screen and gravel pack, centered in the formation between 505 and 605 feet.

The ASR well should be constructed about 100 feet from well PZ-1.

Following well completion, wellhead facilities would be constructed. Once the permanent pump is installed in the well, a long-term pump test of at least 72 hours' duration would be conducted to estimate aquifer hydraulic characteristics, including storativity and leakance. This test would also serve to purge any residual acidization products from the well prior to commencement of recharge testing.

A monitor well will be required to permit measurement of water level and water quality changes in the first productive zone overlying the Hosston-Sligo formation at the site. While this was originally anticipated to be constructed in the Cow Creek formation, results from well PZ-1 suggest that this well should also penetrate the Hensell Sands with an open hole interval between 400 and 450 feet. The construction sequence for this well is as follows:

- Set 10-inch surface casing to 40 feet.
- Drill nominal 10-inch hole to 400 feet.
- Set and cement 400 feet of 4-inch steel casing.
- Drill 4-inch hole to 450 feet.
- Develop well with air.

A monitor well in the Lower Glen Rose formation will be required to detect water level changes during ASR testing at the UGRA site. The resulting data will be helpful in assessment of potential ASR storage volume beneath Kerrville. The construction sequence for this 4-inch well is as follows:

- Set 10-inch casing to 40 feet.
- Drill nominal 10-inch hole to 270 feet.
- Set 270 feet of 4-inch steel casing and cement up to 80 feet, leaving an annular space to monitor Glen Rose water level fluctuations.
- Drill 4-inch hole to 320 feet.
- Develop well with air.

A conceptual design of the ASR test facility is shown in Figure 4-1.

4.2 STORAGE POTENTIAL

An important issue pertaining to the long-term value of ASR facilities to the Kerrville area is the volume potentially available for storage of UGRA treated water. Depending upon this volume, it should be possible to provide seasonal storage and thereby enable UGRA to meet peak water demands above the 5 mgd capacity of the present water treatment plant. This would enable UGRA to defer plant expansion, currently planned for about 1992. It may also be possible to provide additional storage underground in lieu of surface storage in the planned offstream reservoir. To meet different objectives, reservoir capacity estimates have ranged from 500 to 8,000 acre feet. To the extent that ASR storage is available, it would probably represent a significant savings to UGRA compared to the cost of constructing the offstream reservoir.

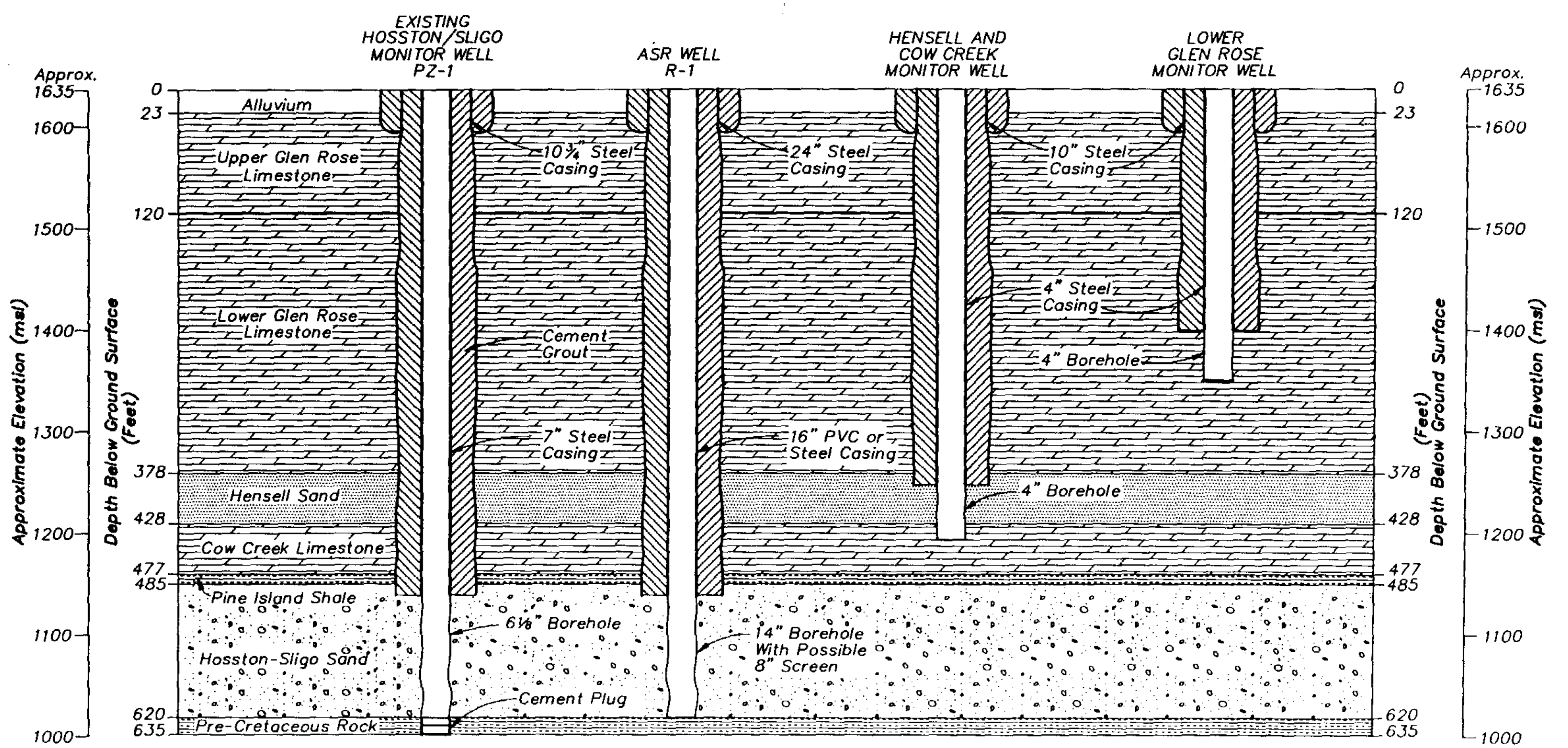

FIGURE 4-1
CONCEPTUAL DESIGN OF
ASR TEST FACILITY

At this time, it appears most likely that ASR storage would permit reduction, but not elimination of the need for offstream reservoir construction. Further investigation of the most cost-effective combination of diversion, treatment, surface reservoir storage, and ASR storage will be required in order to meet water supply and low flow augmentation objectives, once Phase II ASR testing is completed. Such investigations could show that offstream storage is not required, however, a more prudent assumption at this time is that offstream storage will be required, but with a significantly reduced capacity.

With the exception of determining the true thickness of the aquifer, construction of well PZ-1 has not added much information of significance for the estimation of potential ASR storage volume. However, the next phase of the ASR test program includes planned construction and testing of an ASR well. The results of this test will include an estimate of the degree of hydraulic connection between the Hosston-Sligo formation and overlying formations. It will also provide an estimate of the volume available for storage at that site due to compressibility of the formation materials under expected recharge pressures. This test requires measurement of water levels in monitor wells independent of the ASR wells. Hence, it was not possible to conduct the test on well PZ-1 alone.

Until such time as additional data is available to support an estimate of storage potential, a preliminary approximation can be made using indirect methods, to be confirmed through Phase II-B construction, testing, ASR cycles, and subsequent extended operation.

In 1955, the U.S. Geological Survey (USGS) conducted a recharge test on Kerrville well 7. As discussed in the April 1988 report, recharge occurred at rates of 400 to 500 gpm for 72 hours. Based upon the test results, a water level rise of about 40 feet would have occurred as a result of recharging for 8 months at 350 gpm. An aquifer computer simulation model could be prepared, based upon available USGS data plus the results of ASR testing, and would indicate the water level rise that would occur if some or all of the Kerrville wells were converted to ASR operational capability, supplemented by the new ASR well at the UGRA water treatment plant and additional ASR wells in the service area. Some interference would be expected between wells such that the water level rise in any well would be affected not only by recharge in that well but also to a lesser extent by recharge in other wells. Until such a model can be prepared, an appraisal of the wellfield layout and probable well interference suggests that recharge for 8 months at a combined rate exceeding 5 mgd should be possible, if treated water were available for recharge. This is equivalent to seasonal storage of over 3,700 acre feet of water. The water level rise need not be limited to land surface or pre-development conditions since further pressurization would provide additional storage volume. However, care would be required to avoid hydraulic fracturing of any confining layers that retard vertical movement of poor quality water. Once the available storage volume is established through testing and operational experience, recovery rates can be established to meet seasonal and peak demands. Through ASR operations, the present natural recharge rate, estimated at 0.5 mgd, would be increased substantially. This would enable higher sustained production rates during dry periods.

A second approach is to assume a value for aquifer storativity between 10^{-4} and 10^{-5}. This is probably a reasonable range and represents the volume of water which a unit volume of the aquifer can release from storage in response to expansion of water and compression of the formation materials under a one-foot change in head. Storativity has been calculated by the USGS from the results of several aquifer pumping tests on Hosston-Sligo wells in this area. Values ranged from 7.4×10^{-4} to 5×10^{-5}. The tests were all conducted within a relatively concentrated area and, while very useful, are not necessarily representative of values that may be found from pumping tests at more dispersed sites in the east, south, and west parts of the City. The area affected by ASR operations would exceed 15 square miles, which is the approximate area within the city limits of Kerrville. Assuming that the thickness of the aquifer that would be pressurized during recharge would exceed 250 feet, and the allowable increase in head would be at least 150 feet, the resultant storage volume is 3,600 to 36,000 acre feet. Further investigations could show that increased area, thickness and water level rise is achievable, in which case the storage volume would increase.

An interesting frame of reference for judging the range of storage volumes discussed above is to consider the volume of water contained locally within the Hosston-Sligo formation. Assuming conservatively an area of 15 square miles, an average thickness of at least 75 feet and an effective porosity of at least 10 percent, the volume stored in the aquifer is at least 72,000 acre feet. If the Cow Creek and Hensell formations are hydraulically connected with the Hosston-Sligo formation, as suggested by limited available information, the combined volume would approximately double. The two zones are presently saturated and it would probably be unwise to produce groundwater at rates or durations that would dewater any portion of these aquifers. Consequently, this water is not practically available for direct water supply purposes. However, the calculation provides a benchmark for judging the reasonableness of estimated potential increases in volume attainable by raising water levels.

As shown above, this present storage volume can be increased by raising the water levels in an aquifer already saturated with water. It is also possible that in some areas along the north side of Kerrville, further increase in storage volume can be achieved by raising water levels in shallow formations that are presently unsaturated. In this case, a very large increase in volume can occur with a small change in water level.

In summary, insufficient data exists to determine potential volume available for ASR storage. Planned testing will provide the data needed to support reasonable estimates of these important parameters. Until such testing is completed, preliminary approximations suggest that the range of storage volumes potentially available is between 3,600 and 36,000 acre feet, and possibly higher. The volume required for initial ASR operations to enable deferral of water treatment plant expansion is well below the range of estimated storage volume availability for ASR purposes.

4.3 PHASE II-B WORK PLAN

The following tasks are proposed for the next phase in the UGRA aquifer storage recovery test program:

Task 1--Plans and Specifications

Prepare plans and specifications ready for bidding for construction of

- ASR well to 620 feet.
- Monitor well to 400-450 feet
- Monitor well to 270-320 feet
- Wellhead facilities at the ASR well to provide for recharge and recovery test operations

Task 2--Bid Assistance

Assist UGRA during the bidding process, including preparation of an advertisement for bids, review of bids, recommendation of award, and issuance of notice to proceed.

Task 3--Permitting

Prepare permit applications for submittal by UGRA to the Texas Water Commission and the Texas Department of Health. Respond to agency questions and attend meetings as required to obtain these permits prior to beginning well construction.

Task 4--Well Construction

Provide resident observation services to monitor key construction activities according to the plans and specifications. Obtain data during construction to include water level, water quality, formation samples, geophysical logs, and pump testing. Prepare well completion reports for each well.

Task 5--Contract Administration

Provide services during construction of ASR facilities to support field activities including pay estimate reviews and submittal to UGRA, shop drawing review, preparation of construction record drawings, and cost estimates.

Task 6--Aquifer Testing

Conduct one aquifer test of at least 72 hours' duration at the UGRA site, pumping the ASR well and measuring water levels in each of the onsite monitor wells, plus additional available wells offsite. Collect water samples for analysis. Analyze pump test results to determine aquifer transmissivity, storativity, leakance; vertical hydraulic conductivity of overlying confining layers; specific capacity, efficiency, and water quality in the well.

A second similar test in Kerrville Well No. 9, monitoring water levels in available nearby Hosston-Sligo wells 11, 13, and/or 14, whichever is not being pumped. If any private, shallower wells are close to this site, monitoring of water levels in such wells would also be useful.

These two tests will provide storativity estimates near the south and east parts of the City and other valuable data to support the ASR investigation objectives.

Task 7--ASR Testing

Conduct two ASR test cycles to assess recharge and recovery flow rates, operational performance, recovery water quality and effect upon water levels. The initial cycle would be designed to confirm satisfactory operation of all facilities, with a storage volume of about ten million gallons (30 acre-feet). Water would be recovered to the raw water side of the water treatment plant. Monitoring of well PZ-1 would establish mixing characteristics in the storage zone. This would be followed by a long cycle simulating full operational conditions. Recharge volume would be about 50 to 100 million gallons (150 to 300 acre-feet), with recovery to the distribution system.

Depending upon initial cycle results, it may prove beneficial to repeat this cycle prior to performing the long cycle.

Task 8--Aquifer Simulation Model

Based upon hydraulic characteristics of the aquifer determined from available data supplemented by the pump tests and ASR cycles, develop a computer simulation model of the aquifer system at Kerrville. Use the model to evaluate the range of potential storage volume available for ASR operations, pressure and water level effects, and potential increase in river baseflow due to seasonal restoration of aquifer water levels to or above historic conditions.

Task 9--Offstream Reservoir Evaluation

Evaluate an appropriate combination of water facilities' capacity including offstream reservoir, water treatment plant intake and treatment, ASR and Kerrville wellfield capacity, to achieve an efficient and cost-effective water supply while also meeting low flow requirements in the Guadalupe River. This will be based upon the range of storage volumes estimated to be available in the aquifer.

Task 10--Report Preparation

Prepare a final report covering Tasks 1 through 9 and including a feasibility assessment, costs for ASR expansion, and recommendations for subsequent action.

Task 11--Operations Manual and Startup Assistance

Prepare an operating manual for ASR facilities recommending field procedures and monitoring activities. Review operating data collected during initial operations and respond to requests for assistance with interpretation of data or operational performance.

Conversion of Well No. 7 (Optional Task)

In addition to these 11 tasks, it is recommended that UGRA and Kerrville plan for testing at a second ASR site if results from the first cycle at well R-1 prove encouraging. The recommended site is Kerrville Well 7, which is currently out of service. Effort would be required to modify this well for ASR operations, including engineering design and well construction activities. This task would be authorized separately and would proceed concurrently with Cycle Two testing at Well R-1. If ASR proves feasible at Kerrville, as expected, the two ASR wells would probably provide the recovery capacity needed to defer water treatment plant expansion for several years. Testing at Well 7 would also address the need for confirming ASR operational performance of modified existing supply wells within the Kerrville water service area.

4.4 PHASE II-B SCHEDULE

Figure 4-2 shows the estimated schedule for tasks in Phase II-B. Once the project is initiated, well construction activities should begin after about 5 months and will require about 4 months to complete. ASR cycles would begin in the 11th month. Depending upon when in the year this occurs, cycles would continue for up to about 12 months. The first cycle would be completed within about 2 months, while the second cycle would be completed during the dry season following completion of recharge activities. The aquifer simulation model and evaluation of offstream storage reservoir requirements would be completed about month 18, while the final report would be completed by about month 26.

4.5 ASR PROGRAM COSTS

The cost of Phase II-B investigations is expected to be in the range of $550,000 to $765,000, comprised as follows:

Well Construction	$225,000 - $250,000
Wellhead Facilities Construction	80,000 - 120,000
Engineering Design/Investigations	200,000 - 325,000
ASR Testing	40,000 - 60,000
Permitting	5,000 - 10,000
TOTAL	$550,000 - $765,000

Upon completion of Phase II-B in early 1992, UGRA will have one operational ASR well with a recovery capacity estimated at 0.7 mgd. Total investment by UGRA to that point will be in the range of $750,000 to $900,000 including all Phase I and II activities. Tentatively, an additional ASR well may be required within a few years to meet increasing system demand. Equipping Kerrville Well No. 7 should be given strong consideration as the second ASR well. With the sucessful completion of these two wells, UGRA should be able to defer water treatment plant expansion by about 10 years. During or after this time, additional effort may be appropriate to construct expanded ASR facilities in lieu of offstream reservoir storage, to meet future water supply and minimum Stream Plan requirements.

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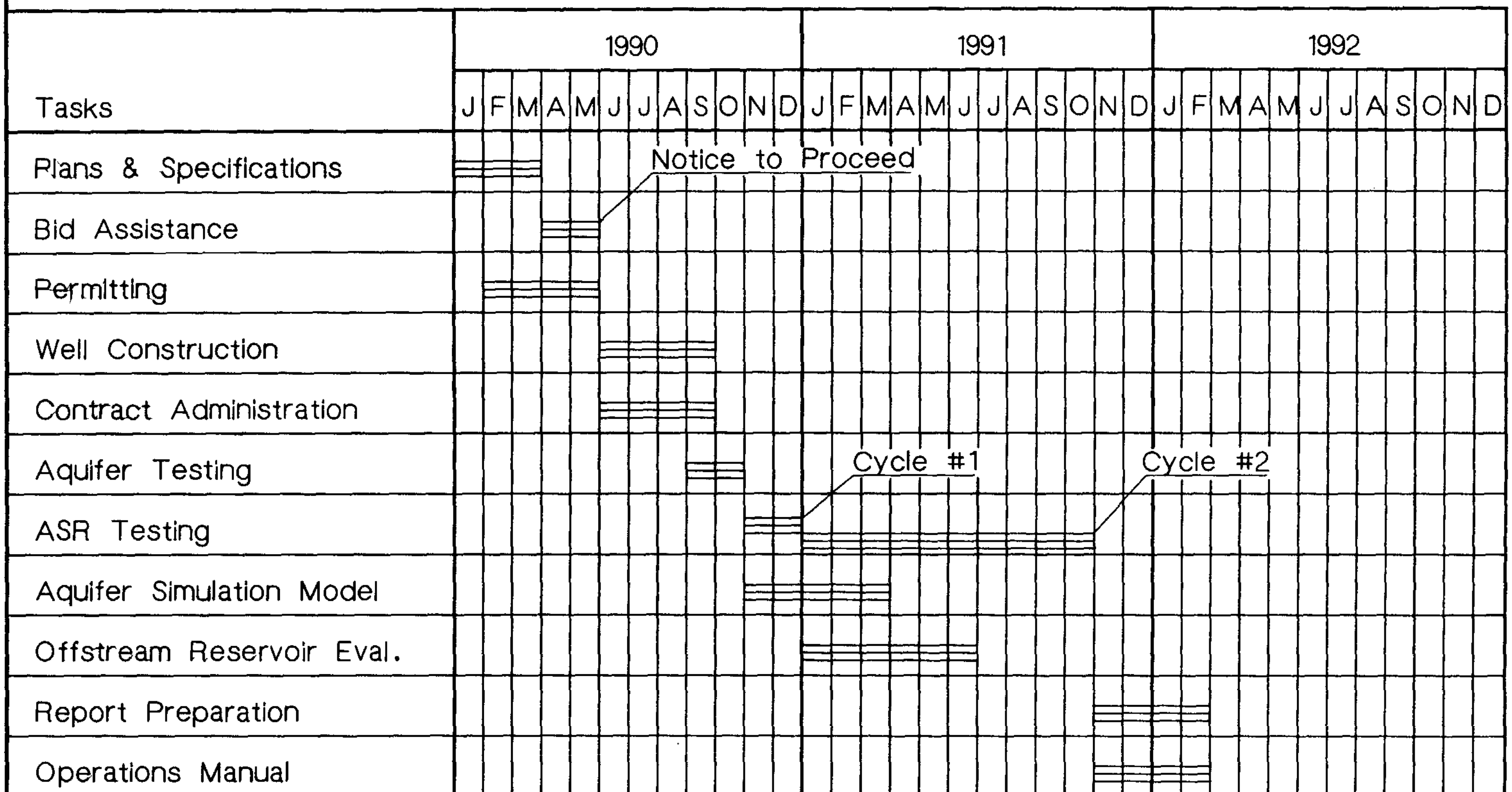

FIGURE 4-2
PHASE II-B SCHEDULE
UGRA ASR PROJECT