FORMATION HYDROFRACTURING IN THE PALEOZOIC AQUIFER CORINTH MUNICIPAL WATER WELL PROJECT CORINTH, MISSISSIPPI

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INTRODUCTION

The occurrence of groundwater in extreme northeastern Mississippi is very different from that of the rest of the state. It is derived from hard sedimentary rocks, occurring near the surface in the region, which are known to produce high quality water. Water well engineering design and groundwater production techniques for these hardrock aquifers differ from sandy unconsolidated aquifers, which are more typical to the remainder of the state. Over the last decade, the Mississippi Mineral Resources Institute (MMRI) has had a continuing interest in the groundwater production in northeast Mississippi with primary focus on the Corinth district, where MMRI has assisted the Corinth Gas and Water Department (CGWD) in locating water production wells. The source of the public water supply in Corinth is the Paleozoic aquifer. Groundwater from this aquifer is more desirable than that from the shallower Cretaceous aquifer because of its lower iron and manganese content. Although deeper wells are required, it is more economical to produce groundwater from the Paleozoic aquifer than to remove these unwanted materials from water produced from the Cretaceous formations.

In the past, the standard method of developing a new municipal water source for Corinth has been to drill a well and test its production capabilities. This approach often resulted in one or more test wells (producing sub-economic volumes of groundwater) which then had to be plugged and abandoned. This system of groundwater exploration is both expensive and time-consuming. Several years ago, the MMRI began investigating the feasiblity of utilizing hydrofracturing for water well development. The technology had been used successfully in other parts of the country, but never attempted in Mississippi. Hydrofracturing involves the controlled application of water under pressure at selected intervals in the boring. Contrary to the implication of the term, the process does not induce new fractures in the rocks, but expands existing natural fractures, thereby increasing water transmissivity in these pre-existing zones. Recognizing the potential advantages of this technology as a means of enhancing well production, the MMRI began investigating the feasibility of applying it to the geologic/hydrologic conditions of the Corinth district. Over two years of evaluation and planning (in conjunction with the CGWD and pertinent state agencies) preceeded the implementation of a test project in Corinth. The opportunity to test the hydrofracturing procedure occurred when the CGWD planned to install a new well at the site of an abandoned one located in the city's southern industrial area during the summer of 1993. The project involved the installation of one municipal water supply well, referred to as the Production Well, and one Test Well, to be used as a piezometer for monitoring water levels. Formation hydrofracturing was performed in both wells under the direction of the MMRI and the CGWD. The MMRI performed the following tasks to assist in this project: (1) submitted a Workplan to the CGWD to assist in project planning and implementation; (2) provided the CGWD with technical support in the form of presentations to the Mississippi Department of Health and other State agencies; (3) assisted the CGWD in selecting a hydrofracturing contractor and subsequently acted as liaison between the two entities; (4) provided drill site geologists during on site drilling operations; (5) scheduled and directed geophysical borehole logging performed by the U.S. Geological Survey (USGS) and the Mississippi Office of Geology (MOG); (7) provided technical support and water level monitoring during aquifer and well performance testing at the site, and (8) submitted a technical report to the CGWD documenting the results of the hydrofracturing procedure.

Herndon Well and Supply Company of Shannon, Mississippi, was contracted by the CGWD to perform the drilling and well installation. Cook Coggin Engineers, Inc., of Tupelo, Mississippi, was selected by the CGWD as the Engineer for the project. Northeastern Water Production, Inc., of Sterling, Massachusetts, performed the hydrofracturing. The U.S. Geological Survey and the Mississippi Office of Geology aided in the collection and analysis of borehole geophysical data.

SITE DESCRIPTION

Field activities were conducted during the installation of two water wells at Corinth, Mississippi. One of the wells was completed as a municipal water supply well and is referred to in this report as the Production Well. The second well was installed as a piezometer and is referred to in this report as the Test Well. The piezometer is used for monitoring water levels and is administered by the CGWD.

The site of this investigation is referred to in this report as the Well-19 site and is located on Golding Street in Corinth, Mississippi. The Well-19 site is also the location of Corinth Well-8. Well-8 was installed in 1968 and was completed in the Paleozoic aquifer. After 24 years of service, Well-8 was plugged and abandoned in 1992 due to casing failure. The casing failure allowed lower quality groundwater from overlying Cretaceous sediments to enter the well, resulting in iron and manganese concentrations above the drinking water standards established by the Environmental Protection Agency and Mississippi Department of Health (Lilly 1993).

GEOLOGIC SETTING

Regional Geology

In northeastern Mississippi, units of Cretaceous and Paleozoic age crop out in an arcuate band extending from the Mississippi-Tennessee state line on the northwest to the Mississippi-Alabama state line on the southeast. Alcorn County and the city of Corinth are entirely within the Cretaceous outcrop belt, as the Paleozoic outcrop belt is further east in adjoining Tishomingo County. The Cretaceous-Paleozoic contact is the major regional unconformity upon which erosional relief can be significant. Jennings et al. (1991) emphasized the importance of this unconformity to water production in northeastern Mississippi.

Paleozoic Stratigraphy. Geological age assignments of the buried Paleozoic strata in northeastern Mississippi vary. Those in the Corinth area are somewhat debatable. Henderson (1991) states that these Paleozoic units are Silurian-Devonian, while Jennings (1993) considers them to be entirely Devonian in age. Saunders and Swann (1991, 1992) prefer a Mississippian age for the Paleozoic chert section in unconformable contact with the Eutaw and with the Silurian in place below. These Paleozoic cherts form the principal aquifer from which Corinth produces groundwater for its public water supply.

In this report, the Paleozoic section is subdivided into two units. The youngest (uppermost) consists of sparsely fossiliferous light gray chert and interbeded white tripoli and is assigned to the Fort Payne Formation of Mississippian age, based on lithology and regional stratigraphic relationships. The second unit, which is the oldest unit sampled during the investigation, consists of interbedded, ferruginous, kaolinitic clay, chert, tripoli, and minor sandstones and shales. This unit has been assigned to Niagaran series, which includes all Silurian rocks in Mississippi. The upper contact was chosen at the top of the first ferruginous clay bed and neither boring penetrated the entire thickness of the unit.

Cretaceous Stratigraphy. The Ripley Formation, Demopolis Chalk, Coffee Sand Formation, and the Eutaw Groups all occur at the surface in Alcorn County. The Demopolis and Coffee Sand outcrop is within the Corinth city limits, but the Eutaw is present only in the subsurface. The Demopolis consists of argillaceous chalks which are typically of low permeability. The Coffee Sand consists primarily of glauconitic sands which produce some groundwater for domestic use. The Eutaw consists of clays with subordinate sand beds which are sufficient for domestic water supply. The Eutaw is unconformable to the Paleozoic section in the Corinth area.

Site Stratigraphy

During drilling operations at the site, lithologic sampling and geophysical borehole logging were conducted. Both sets of data were utilized in stratigraphic interpretation and characterization. Figures 1 and 2 illustrate the stratigraphy, along with details on well construction, elevations, borehole depths. For additional, more detailed geological discussions, the reader is referred to the Corinth Water Well Project Supplemental Report (SP-1), available upon request from MMRI.

METHODOLOGY

Drilling Operations and Well Construction

Production Well. The boring was drilled with a trailer-mounted, Gardner Denver 2000 drilling rig, using mud rotary techniques. The pilot hole was drilled to 95 feet below ground level (bgl) and reamed to a final diameter of 30 inches. Following stabilization of the borehole, a 20 inch diameter, steel surface casing was installed. Portland Type II Cement was used to produce a grout mixture with a slurry weight of 14 lbs/gal. Slurry placement was achieved by the casing method (also known as the Halliburton Method) in which grout is forced down the casing and into the wellbore/casing annulus using a floatshoe and pumpdown plug. Cutting returns were visible at the surface during grout placement. The grout was allowed to cure for 24 hours prior to resumption of drilling operations.

Below the surface casing, the boring was advanced as a pilot hole to a depth of 383 feet bgl. A 14 inch, epoxy-coated, steel inner casing was installed from the surface to 383 feet and slurry placement conducted. Three hundred ninety sacks of cement were used in the grouting operation. The grout was allowed to cure for 48 hours prior to resumption of drilling operations.

Following installation of the inner casing, drilling was resumed to a total depth of 539 feet bgl (as measured by the U.S. Geological Survey Logging Services on June 15, 1993). This boring was completed as an open well. Final well completion was supervised by the engineer.

Test Well. The Test Well pilot boring was advanced using a Gardner Denver 1500 truck-mounted drilling rig and mud rotary techniques. A pilot hole was drilled to 95 feet bgl.

Following stabilization of the borehole, a 12 inch diameter, steel surface casing was installed. A 14 lbs/gal grout slurry mixture of Portland Type II Cement was injected to seal the wellbore/casing annulus (via the Halliburton Method), and allowed to cure for 48 hours prior to resumption of drilling operations.

Drilling continued beyond the surface casing as an 11 3/4-inch diameter boring to a depth of 383 feet bgl. Six inch steel inner casing was installed from the surface to 383 feet. Portland Type II Cement was again employed to produce a grout mixture with a slurry. Grout returns were observed at the surface during grout placement, and the grout was allowed to cure for 48 hours prior to resumption of drilling operations. One hundred sacks of cement were used grouting the Test Well.

Following installation of the inner casing, drilling was resumed as a 7 7/8-inch diameter boring to total depth. This portion of the well was completed as an open hole. The total depth of the boring was 533 feet bgl as measured by the Herndon Well and Supply Company.

Lithological Sampling and Analysis

Herndon Well and Supply Company performed lithological sampling under the direction of the MMRI drillsite geologists. Drill cuttings were collected from the Production Well, and cuttings, shelby tube samples, and cores were collected from the Test Well. Drill cuttings were collected by stopping the boring operations at the end of each sample interval and catching cuttings from the returns in the circulating drilling fluid. Approximately 500 grams of cuttings were collected in each sample. Following descriptions on site by the geologist, the samples were transported to the University of Mississippi for microscopic analyses. Lithologic samples were also collected using shelby tubes. Coring was conducted using a double tube core barrel. The shelby tube samples were wrapped with plastic and transported to the University of Mississippi Department of Civil Engineering for testing and analyses. Cores were boxed and taken to the MMRI facilities for analysis. All cuttings from both wells and the core samples from the Test Well were examined and described at MMRI.

Geophysical Borehole Logging

An extensive suite of geophysical logs was run on each boring by the USGS and the MOG. The digital geophysical logging data are available from the MMRI.

Geotechnical Testing of Shelby Tube Samples

Permeability analyses were performed in the Department of Civil Engineering, University of Mississippi. These tests followed ASTM Designation D5084-90 with a constant head of 2.9 pounds per square inch (psi). A laboratory report containing the methods and results of these tests are available from the MMRI.

Formation Hydrofracturing

The hydrofracturing technique implements both single packer and zone isolation (straddle packer) operations. The single packer hydrofracture is accomplished by lowering an inflatable packer to the desired depth and inflating the packer to seal the borehole to total depth. After the single packer operation, zone isolation operations utilize two inflatable packers to seal and isolate a selected interval (zone). Water is pumped into the isolated portion of the borehole and pressure is allowed to build. When hydrostatic pressure exceeds local lithostatic pressure, pre-existing fractures are opened or blockages of pre-existing fractures are removed. The straddle packers are then deflated and moved to the next isolation zone.

Northeast Water Production, Inc. (NEWP), of Sterling, Massachusetts, was contracted by the CGWD to perform hydrofracturing on the two wells during the period of August 16-20, 1993. Nontoxic, food grade, polypropylene glycol antifreeze and water from the municipal supply were used by NEWP to inflate all packers. Zone isolation hydrofracturing was performed on zones of 10 foot lengths in both wells. No propants were used in these hydrofracturing operations. Geophysical logs, boring logs, and lithological descriptions were used to select the zones for hydrofracturing.

Groundwater Sampling

Groundwater samples were collected by MMRI geologists prior to and after hydrofracturing. Samples were taken directly from the discharge pipe no sooner than four hours into the constant capacity pump test. This time period allowed a minimum of 40 casing volumes to be purged from the well at a discharge rate of 190 gpm. One-half gallon samples were collected in plastic containers which had been washed with biodegradable detergent and rinsed with distilled water. Each sample was then transferred to a glass sample bottle containing nitric acid as a preservative. Samples were initially stored on ice before being transported to the University of Mississippi, Research Institute of Pharmaceutical Sciences, Environmental Toxicology Laboratory, for chemical analyses. The groundwater samples were analyzed for the following elements: barium, iron, arsenic, manganese, copper, zinc, lead, chromium, silver, and mercury.

Aquifer Testing

Pump tests were conducted by Herndon Well and Supply Company under the supervision of the MMRI drillsite geologist. Pump tests conducted on the Production and Test Wells included pre-fracture step-drawdown pump tests, pre-fracture constant capacity pump tests, post-fracture step-drawdown pump tests, and post-fracture constant capacity pump tests. A 24-hour constant capacity pump test was performed at the Production Well.

Pump tests were conducted on the Production Well using a 3-stage, 40 horsepower submersible pump with a nominal pumping capacity of 600 gallons per minute (gpm). The Test Well pump tests were conducted using an 8-stage, 20 horsepower submersible pump with a nominal pumping capacity of 225 gpm. Submersible pumps were hard-wired to existing power at the site and no pump or power failures were experienced during testing. A gate valve in the pump discharge line maintained a constant discharge rate and allowed for variation of discharge during the step-drawdown tests. Measurement of the pumping rate was accomplished using an orifice weir and piezometer. Head in the piezometer was measured using a scale graduated to 0.1-inch. A 3-inch inside diameter (i.d.) discharge pipe with a 2-1/2 inch orifice plate was used at the Test Well for the pre-fracture pumping test. A 4-inch i.d. discharge pipe with a 3-inch i.d. orifice plate was used on all Production Well pump tests and on the Test Well post-fracture pump tests. Discharge was directed via trenches to a drainage ditch at the site, which carried it to an intermittent creek located approximately 25 yards to the west.

Changes in water levels prior to and during pumping were measured in both the pumping well and the onsite observation well during all of the pump tests. Offsite observation wells which were monitored during some of the pump tests included Corinth Well-5, Corinth Well-17, and INTEX Well MW-2.

Changes in water levels at the pumping well and the onsite observation well were recorded using either an electric (E-line) water level indicator graduated to 0.01 feet or pressure transducers and a data logger. Water level data were collected at offsite observation wells using either the E-line water level indicator or a steel tape graduated to 0.01 feet. Strict decontamination procedures were followed when collecting water level data to prevent possible contamination of wells. Water level measurement devices were washed with a biodegradable detergent followed by a distilled water rinse prior to each use.

RESULTS

Lithologic Sampling and Analysis

Paleozoic Sediments. The Fort Payne Formation generally consists of sparsely fossiliferous, light gray chert and interbedded white tripoli. This unit was encountered from 61 to -45 ft msl at the Production Well, and from 53 ft msl to total depth (-103 ft msl) of the Test Well.

The Niagaran Series at the Production Well consists of interbedded ferruginous, kaolinitic clay, chert, tripoli, and minor sandstone and shale. This unit was not fully penetrated by drilling operations at the site. The top of the Niagaran occurs at an elevation of -45 ft msl at the Production Well.

Cretaceous Sediments. The Coffee Sand Formation is the surface unit at the Well-19 site and extends to a depth of 213 feet above mean sea level (ft msl) at the Production Well, and a depth of 216 ft msl at the Test Well. This unit primarily consists of glauconitic, fine-grained sands with thin clay beds and minor limestone beds and/or stringers. Phosphate is present in several intervals as well-rounded, often polished grains. Bivalve fragments are present in concentrated fossiliferous zones. Bone fragments and shark teeth were also noted in scattered samples. Clay beds typically consist of gray, carbonaceous, micaceous clays with glauconite contained in some intervals.

The Eutaw Group is the basal Cretaceous unit encountered in the borings at the Well-19 site. The Eutaw occurs from a depth of 114 to 61 ft msl at the Production Well. At the Test Well the Eutaw occurs from 107 to 53 ft msl. This unit typically consists of olive gray clays with minor sand beds. The clays are micaceous, carbonaceous, and contain locally abundant fragments of carbonized/pyritized wood. The sand beds are fine-grained, glauconitic, and closely resemble the sands of the Coffee Sand Formation. Some of the clay cuttings contain very fine-grained glauconite.

Geophysical Logs

The results of the geophysical borehole logs and interpretations are contained in a separate report (SP-1) and are available from the MMRI.

Geotechnical Testing

Permeability analyses performed on three samples collected from the Test Well have vertical permeabilites of 3.62×10^{-5} centimeters per second (cm/s) at a depth of 340 ft. bgl, 1.75×10^{-6} cm/s at 367 ft. bgl, and 2.85×10^{-6} cm/s at a depth of 370 ft. bgl.

Formation Hydrofracturing

Hydrofracturing operations were conducted at the site during the week of August 16, 1993. Table 1 illustrates the results of those operations. The difference between maximum and minimum pressure in each interval is a good indication of success in increased fracture size for isolated portions of the boring (McDonald 1993).

Single packer hydrofracturing operations in the bottom portion of both wells experienced a pressure differential of 75 pounds per square inch (psi). The maximum pressure differential obtained in the Production Well was 125 psi in the interval from 510 to 520 ft. bgl. Borehole conditions at the Production Well prevented the contractor from hydrofracturing the interval from 490 to 510 ft. bgl. The maximum pressure differential observed in the Test Well was 250 psi in the 470 to 480 ft. bgl interval. The contractor was not able to hydrofracture between 480 and 520 ft. bgl, due to borehole conditions.

Groundwater Sampling and Analysis

Analytical results from groundwater samples collected by the MMRI during the project are presented in Table 2. Pre-fracture and post-fracture groundwater sampling at the site showed an increase in iron concentration of 170 ug/L at the Production Well and a decrease of 80 ug/L at the Test Well. Manganese concentrations remained the same in both wells before and after hydrofracturing.

Pump Test Results

The Jacob Straight-Line Method (Jacob 1950) was used to calculate transmissivity (T) and the storage coefficient (S) from the pump test data. It was noted by Jacob, and by Freeze and Cherry (1979), that after steady state conditions have been reached, the original Theis equation can be closely approximated.

Transmissivities calculated from constant capacity pump tests from both pumping and observation well data range from a maximum of 6,710 gallons per day per foot (gpd/ft) to a minimum of 4,050 gpd/ft. Hydraulic conductivities range between 69.4 gpd/ft^2 and 40.5 gpd/ft^2. Table 3 presents the aquifer characteristics calculated from the constant capacity pump tests performed by MMRI at the Well-19 site.

EFFECTS OF FORMATION HYDROFRACTURING

Aquifer Characteristics

Aquifer parameters for transmissivity and hydraulic conductivity calculated from observation well data are more accurate and reliable than those calculated from pumping wells (Driscoll 1989). The following results do not take into account the effects of continued well development as the hydrofracturing process is a well development process.

Hydrofracturing at the Test Well improved transmissivity by 1,210 gpd/ft between the pre- and post-fracture pump test. Transmissivity at the Production Well increased by 1,070 gpd/ft as a result of hydrofracturing. The Test Well hydraulic conductivity improved by 12.1 gpd/ft^2 and the Production Well hydraulic conductivity improved by 10.7 gpd/ft^2. Specific capacity improved by 1.0 gpm/ft and 0.2 gpm/ft for the Test Well and Production Well, respectively.

Projected Increases in Production

Using specific capacity to project yields before and after hydrofracturing, the following conditions are assumed: (1) pump is set at 370 feet below ground level to allow for 240 feet of drawdown during production; (2) borehole diameter is 7 7/8 inches and; (3) the well is completed as an open hole. The Test Well increase in specific capacity is 1.0 gpm/ft and the well is projected to have a net gain in production of 250 gpm (400 gpm to 650 gpm) due to hydrofracturing. The Production Well increase in specific capacity is 0.2 gpm/ft and is projected to improve production 50 gpm, from 425 gpm to 475 gpm.

A predictive model was run using QuickFlow® (Rumbaugh 1991) to predict production rates at the Production Well due to under-reaming of the borehole. The predictive model used the following conditions: (1) reference head is +310 feet mean sea level; (2) reference head is located 4,250 feet from the well; (3) final borehole diameter after under-reaming is 16 inches; (4) well is completed as an open hole; (4) pump is set at 370 feet below ground level to allow for 240 feet of drawdown during production; and (5) pumping period is 24 hours.

The results of the model differ from the previous figures primarily because of the inclusion of the reference head as a recharge boundary. Results of the model indicate that after under-reaming, but prior to hydrofracturing, the Production Well produces 461 gpm. After under-reaming, and after hydrofracturing, the model results in an increase production to 617 gpm, a gain of 156 gpm.

Inter-Aquifer Hydraulics

Offsite Observation Well Data. Water level data were collected from three observation wells located offsite during the 24-hour constant capacity pump test performed September 28-29, 1993. Corinth Well-5 and Corinth Well-17 are both completed in the Paleozoic Aquifer and INTEX MW-2 is a monitoring well completed in the upper portion of the Coffee Sand Formation. Production from the City of Corinth wells was halted 24-hours prior to the beginning of the 24-hour pump test to allow the wells to recover to static water level.

The Coffee Sand observation well (INTEX MW-2) had a rise in water level of 0.11 feet in the 24-hour period of the constant capacity pump test. These data indicate that at a pumping rate of 190 gpm there is no hydraulic connection between the upper Coffee Sand and the Paleozoic Aquifer at the site. This is significant because INTEX MW-2 is located within the zone of influence of the pumping well.

Corinth Well-5 and Well-17 had a net rise in water level of 0.78 and 2.11 feet, respectively. The 2.11 foot rise in the water level at Well-17 may be attributed to recovery from termination of pumping at Well-17 or from pumping effects at another nearby water supply well.

Groundwater Chemistry. Table 2 summarizes the concentration in micrograms per liter (ug/L) of the ten chemical elements chosen for analysis and shows the changes in the pre- and post-fracture groundwater chemistry in the two wells. Manganese and iron concentrations were used to determine if hydrofracturing affected the integrity of the aquatard between the Cretaceous and Paleozoic aquifer systems. No significant (order of magnitude) changes in the concentrations of these two tracer elements occurred as a result of the hydrofracturing performed at the Well-19 site.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It can be safely concluded that the hydrofracturing technique as applied during this investigation at the Well-19 site resulted in no deleterious effects to the integrity of the Paleozoic aquifer. The absence of drawdown in monitoring well INTEX MW-2 during the 24-hour pump test illustrates that no inter-aquifer communication was initiated between the upper Cretaceous aquifers and the deeper Paleozoic aquifer as a result of the hydrofracturing operations as conducted.

The hydrofracturing procedure improved the transmissivity, hydraulic conductivity, and specific capacity, with the overall result being an increase in the ability of the well to produce water.

Recommendations

To increase understanding of the chemical, physical, and geologic properties of the Paleozoic aquifer in northeastern Mississippi. the MMRI recommends the following: (1) drilling should continue deeper into the Paleozoic section, where the rocks are more competent, therefore allowing a greater pressure differential during hydrofracturing; (2) groundwater samples should be collected with depth within the Paleozoic aquifer and analyzed to better define the water chemistry and sources of its major components; and (3) flowmeter logging should be performed at regular intervals (less than or equal to 5 feet) to properly characterize the yield of particular zones within the aquifer. The MMRI also recommends that hydrofracturing be given serious consideration as a means of well rehabilitation on existing water wells.

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Table 1. HYDROFRACTURING RESULTS.

Isolation Set No.	Zone Top (ft bgl)	Zone Bottom (ft bgl)	Maximum Pressure (psi)	Minimum Pressure (psi)	Pressure Change (psi)	Total Volume (gallons)
PRODUCTION WELL						
Single	526	535	450	375	75	3600
1	510	520	500	375	125	2500
2	480	490	300	300	0	1800
3	470	480	350	300	0	1800
4	460	470	400	400	0	1800
5	450	460	450	400	0	1800
6	440	450	400	400	0	1800
7	430	440	400	400	0	1800
8	420	430	350	350	0	1800
9	410	420	350	350	0	1800
10	400	410	350	300	0	1800
TEST WELL						
Single	526	533	450	375	75	3600
1	470	480	600	350	250	2500
2	460	470	500	400	100	2500
3	450	460	400	400	0	1800
4	440	450	400	400	0	1800
5	430	440	350	350	0	1800
6	420	430	350	350	0	1800
7	410	420	300	300	0	1800

Notes: *ft bgl - feet below ground level*
psi - pounds per square inch

Table 2. SUMMARY OF ANALYTICAL RESULTS GROUNDWATER SAMPLES.

Element	Production Well Pre-Fracture (ug/L)	Production Well Post-Fracture (ug/L)	Test Well Pre-Fracture (ug/L)	Test Well Post-Fracture (ug/L)
Barium	220	180	220	200
Iron	130	300	410	330
Arsenic	1.1	2.8	1.5	3.2
Manganese	30	30	20	20
Copper	nd	nd	nd	nd
Zinc	10	220	20	350
Lead	1.1	0.5	2.1	1.2
Chromium	0.13	0.3	0.7	0.35
Silver	3.2	2.7	1.8	1.7

Notes: *nd - occurs in concentrations below the detection limits of the analytical procedure*
ug/L - micrograms per liter (equal parts per billion)

Table 3. SUMMARY OF CONSTANT CAPACITY PUMP TEST RESULTS.

Pump Test	Pumping Well Data	Date	Transmissivity (T) (gpd/ft)	Specific Capacity (S) (gpm/ft)	Hydraulic Conductivity (K) (gpd/sq.ft)
Pre-Fracture	Well-19P	8/13/93	4680	1.7	46.8
Pre-Fracture	Well-19T	8/15/93	5390	1.6	53.9
Post-Fracture	Well-19P	9/22/93	4460	1.9	44.6
Post-Fracture	Well-19T	9/23/93	6940	2.6	69.4
24-Hour	Well-19P	9/28/93	4050	1.9	40.5
Pump Test	**Observation Well Data**	**Date**	**Transmissivity (T) (gpd/ft)**	**Hydraulic Conductivity (K) (gpd/sq. ft)**	**Storage Coefficient**
Pre-Fracture	Well-19T	8/13/93	5500	55	7.60e-05
Pre-Fracture	Well-19P	9/15/93	5490	54.9	5.60e-05
Post-Fracture	Well-19T	9/22/93	6710	67.1	5.20e-05
Post-Fracture	Well-19P	8/23/93	6560	65.6	5.10e-05
24-Hour	Well-19T	9/28/93	6310	63.1	5.60e-05

Notes: *Well-19P - Production Well*
Well-19T - Test Well
gpd/ft - gallons per day/foot
gpm/ft - gallons per minutes/foot
gpd/sq ft - gallons per day/square foot