

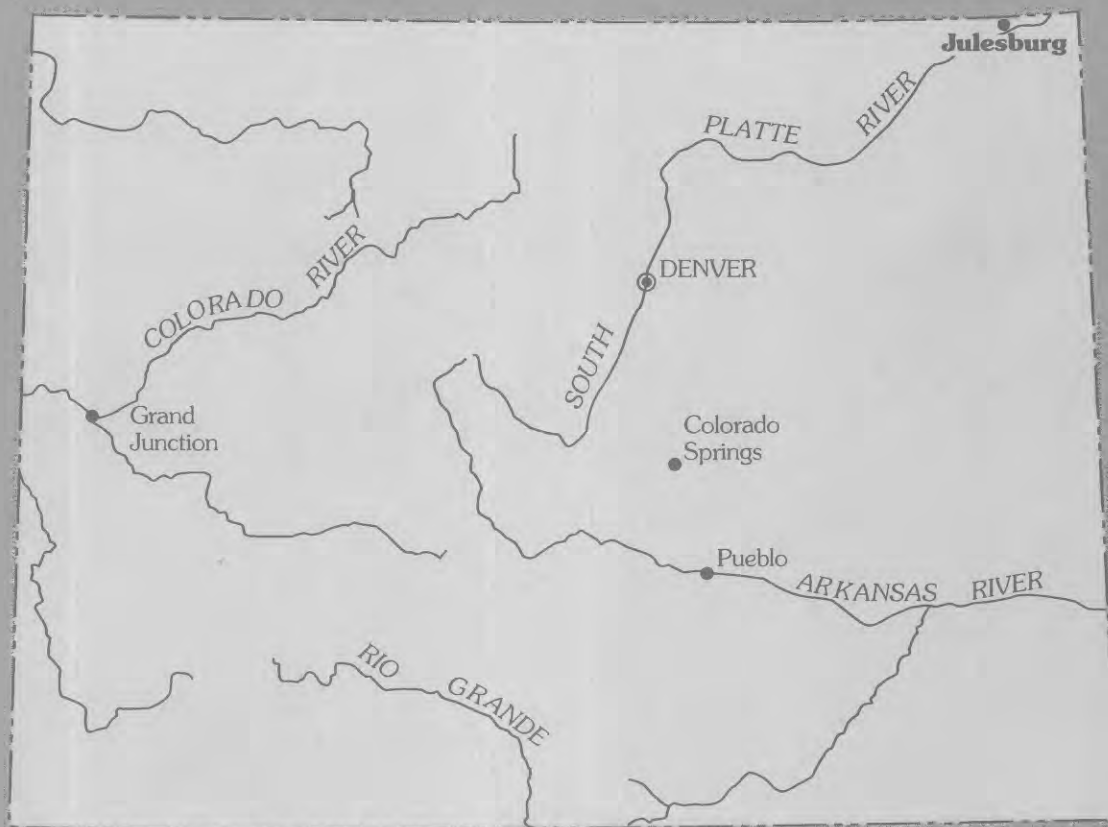


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IN-SITU BIOREMEDIATION OF NITRATE-CONTAMINATED GROUND WATER—A PILOT TEST, JULESBURG, COLORADO, 1996-97

U.S. GEOLOGICAL SURVEY



Water-Resources Investigations Report 98-4046

Prepared in cooperation with the
TOWN OF JULESBURG, COLORADO

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By P.B. McMahon, K.F. Dennehy, *and* B.W. Bruce

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1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS

	Multiply	By	To obtain
Length			
	inch	2.54	centimeter (cm)
	inch	25.4	millimeter (mm)
	foot (ft)	0.3048	meter (m)
	mile (mi)	1.6093	kilometer (km)
Area			
	square foot (ft ²)	929	square centimeter (cm ²)
	square foot (ft ²)	0.0929	square meter (m ²)
	square inch (in ²)	6.452	square centimeter (cm ²)
Volume			
	gallon (gal)	3.785	liter (L)
	gallon (gal)	0.003785	cubic meter (m ³)
	million gallons (Mgal)	3,785	cubic meter (m ³)
Flow			
	gallon per minute (gpm)	0.06309	liter per second (L/s)
Pressure			
	pound per square inch (psi)	6.895	kilopascal (kPa)
Hydraulic conductivity			
	foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=1.8\text{ }^{\circ}\text{C}+32$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm).

Concentrations of chemical constituents in water are given in grams per liter (g/L), milligrams per liter (mg/L), or micrograms per liter (μg/L).

ADDITIONAL ABBREVIATIONS

g	gram
L	liter
cm	centimeter
μm	micrometer
mL	milliliter
NTU	nephelometric turbidity units
mL/min	milliliter per minute
μL	microliter

ACRONYMS

DOC	dissolved organic carbon
SOC	suspended organic carbon
THM	trihalomethane compound
MCL	maximum contaminant level
SMCL	secondary maximum contaminant level
USGS	U.S. Geological Survey
PVC	polyvinyl chloride

In-Situ Bioremediation of Nitrate-Contaminated Ground Water—A Pilot Test, Julesburg, Colorado, 1996–97

By P.B. McMahon, K.F. Dennehy, and B.W. Bruce

Abstract

A pilot test was conducted using an in-situ bioremediation process to remove nitrate from ground water of the South Platte River alluvial aquifer in Julesburg, Colorado. The bioremediation system was based on the process of heterotrophic denitrification, in which denatured alcohol (5 gallons of methanol in 100 gallons of ethanol) was added to the ground water to support the reduction of nitrate to harmless substances by the denitrifying microbes naturally present in the aquifer. The alcohol was circulated through the aquifer using a central pumping well surrounded by nine injection wells. The bioremediation system was operated from January 9 through September 29, 1997.

No alcohol was added to the injection water during the first 5 weeks of system operation to determine the baseline injection rates (110 to 120 gallons per minute) and pressures (10.2 to 12.4 pounds per square inch). The injection rates decreased slightly but the pressures did not change during a 2-month period when ethanol concentrations in the injection water were gradually increased from 0 to about 40 milligrams per liter (mg/L). However, about 1.5 months after ethanol concentrations reached their maximum levels, injection rates decreased to less than 105 gallons per minute and injection pressures increased to about 14.5 pounds per square inch. The change in injection rates and pressures resulted from biomass buildup in and around the injection wells. Injection rates and pressures returned to pre-treatment levels after the biomass

was removed from the injection wells by using a commercially available chemical formulation. An additional chemical treatment was required about 2.5 months after the first treatment because changes in the injection rates and pressures indicated that biomass was beginning to plug the wells again. However, injection rates and pressures did not recover to pre-treatment levels after the second treatment.

Concentrations of dissolved oxygen in water from the pumping well (production water) decreased from about 5.6 mg/L to a median value of 3.4 mg/L after alcohol injections began, indicating that the oxygen-removal efficiency of the bioremediation system was about 40 percent. In contrast, the nitrate-removal efficiency of the system was about 16 percent because nitrate concentrations were reduced from about 24.5 mg/L as nitrogen to a median value of 20.6 mg/L (a reduction of 3.9 mg/L). These results indicated that most of the injected alcohol was used by microbes in the aquifer to remove dissolved oxygen from ground water; therefore, the bioremediation system might be more effective in a ground-water system containing less dissolved oxygen.

Ethanol, methanol, dissolved iron, and hydrogen sulfide were not detected in the production water during operation of the bioremediation system. Dissolved manganese was measured in the production water at a concentration of 0.06 mg/L prior to alcohol injections, and the median manganese concentration in production water after alcohol injections was about 0.10 mg/L. No coliform bacteria were detected in

the production water during operation of the bioremediation system. The concentration of heterotrophic bacteria in the production water was 101 colony-forming units per milliliter of water before alcohol injections began, and concentrations ranged from 77 to 610 colony-forming units per milliliter of water after alcohol injections began.

The pilot test demonstrated that a bioremediation system using microbes naturally present in the aquifer could remove some nitrate from ground water without creating additional water-quality problems. The primary concern with the system was aquifer plugging by biomass buildup at the points of organic-substrate injection. Biomass buildup might be controlled by periodic cleaning of the wells. However, additional work is needed to determine the optimal frequency of well cleaning and if that cleaning will allow for long-term operation of the bioremediation system.

INTRODUCTION

Dissolved nitrate is present in the ground water of the South Platte River alluvial aquifer in concentrations that exceed the U.S. Environmental Protection Agency's maximum contaminant level (MCL) for drinking water. The MCL for nitrate is 10 mg/L as nitrogen (U.S. Environmental Protection Agency, 1996; information also available on the World Wide web at <http://www.epa.gov/OGWDW/wot/appa.html>). For example, a 1992 survey of nitrate concentrations in water collected from domestic wells screened in the alluvial aquifer from Brighton to Julesburg, Colo., indicated that about 34 percent of the wells (33 of 96 wells) had nitrate concentrations that exceeded the MCL (Austin, 1993). The town of Julesburg (fig. 1) operates three water-supply wells that are screened in the alluvial aquifer and that produce water with nitrate concentrations that generally exceed the MCL (Allen Coyne, town of Julesburg, written commun., 1996). In 1996, the town of Julesburg entered into a cooperative agreement with the U. S. Geological Survey (USGS) to test an in-situ (that is, in the aquifer) bioremediation process for removing nitrate from ground water. The

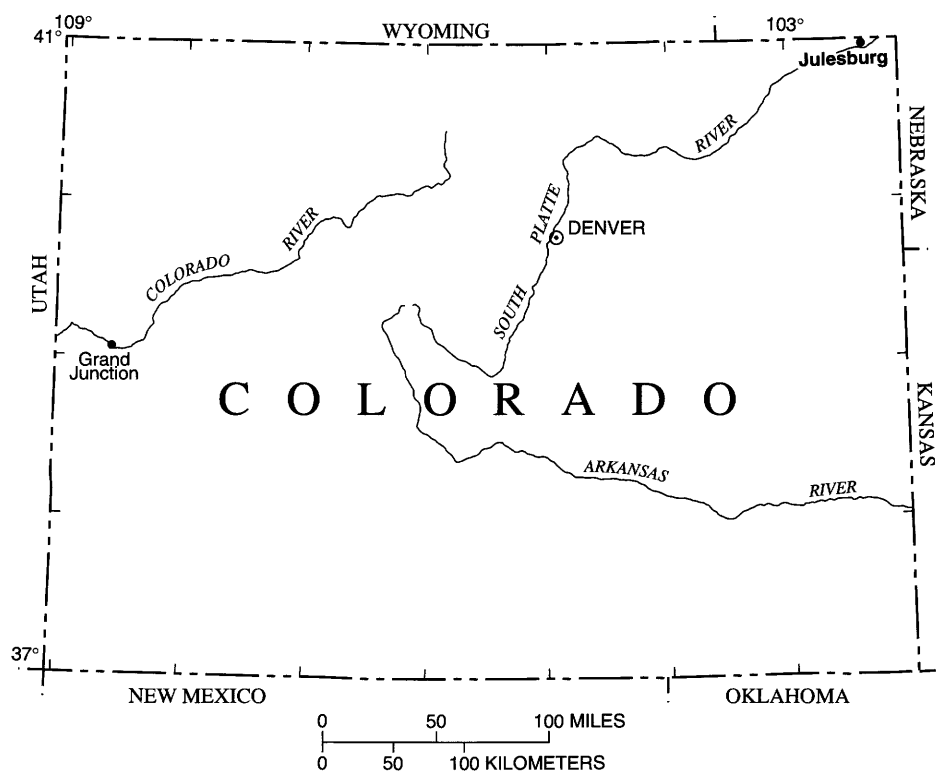


Figure 1. Location of Julesburg, Colorado.

pilot test was conducted on a well that supplies cooling water to the Julesburg Power Plant.

The in-situ bioremediation system used in the pilot test was based on the process of heterotrophic denitrification. In the process of heterotrophic denitrification, microorganisms couple the reduction of nitrate to the oxidation of organic carbon. Nitrate is reduced to dinitrogen gas (N_2), a harmless substance and major component of the atmosphere, and the organic carbon is oxidized to carbon dioxide. For heterotrophic denitrification to occur in situ, denitri-

fying microorganisms, nitrate, and a biodegradable form of organic carbon must be present. The necessary microorganisms and nitrate already are present in the aquifer (Pfenning and McMahon, 1996; Bruce and McMahon, 1997); therefore, only organic carbon needed to be added to the aquifer during the pilot test to support denitrifying activity. Organic carbon was added to the alluvial aquifer through nine injection wells surrounding a central pumping well (fig. 2). Water for the injection wells was diverted from the pumping-well discharge line, through injection-water

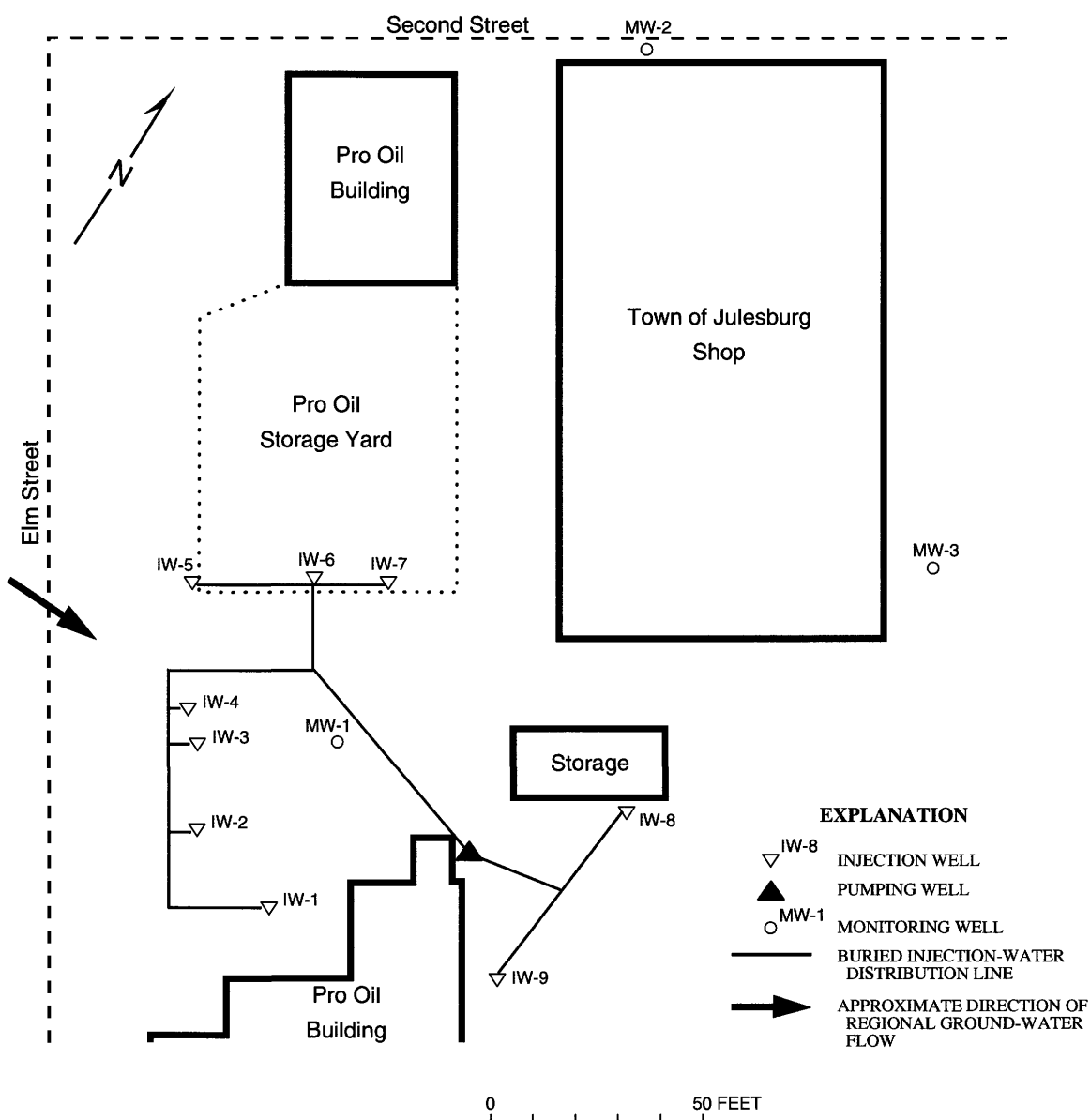


Figure 2. Diagrammatic map of locations of injection, pumping, and monitoring wells and injection-water distribution lines at the study area in Julesburg, Colorado.

distribution lines, and to the injection wells. Specially denatured alcohol (formula SDA-3A, 5 gal methanol per 100 gal ethanol) was used as the organic substrate in this pilot test. Similar in-situ bioremediation systems have been used to remove nitrate from ground water at other sites (Janda and others, 1988; Mercado and others, 1988; Hamon and Fustec, 1991; Hiscock and others, 1991). Forms of organic carbon that have been used in other bioremediation systems include acetate, corn oil, ethanol, methanol, and sucrose.

Purpose and Scope

This report describes the hydraulic, chemical, and biological performance of the in-situ nitrate-bioremediation system used in the pilot test. This report presents hydraulic, chemical, and biological data collected during the pilot test that was conducted from July 1996 through September 1997. Data were collected from one pumping well, three monitoring wells, and nine injection wells.

Description of Study Area

The study area was located in Julesburg, Colo. Julesburg is in northeastern Colorado (fig. 1) and has a population of about 1,300. The town obtains its drinking water from three wells screened in the South Platte River alluvial aquifer. The alluvial aquifer consists primarily of unconsolidated sands and gravels that are adjacent and parallel to the South Platte River. Detailed descriptions of the hydrology and chemistry of the alluvial aquifer in northeastern Colorado are in publications by Hurr and others (1975), Dennehy and others (1995), and McMahon and Bohlke (1996). The depth to ground water at the study area was about 12 ft, and the saturated thickness of the aquifer was about 23 ft. The alluvial aquifer is underlain by clay of the Brule Formation (Bjorklund and Brown, 1957) at a depth of about 35 ft. The water-supply wells operated by the town are located about 0.8 mi north of the study area. In that area, the alluvial aquifer is about 200 ft deep, and the total depths of the water-supply wells range from 107 to 205 ft.

Concentrations of dissolved nitrate in water from Julesburg's supply wells generally exceeded the MCL (fig. 3). The relatively large concentrations of dissolved nitrate in ground water indicated that there

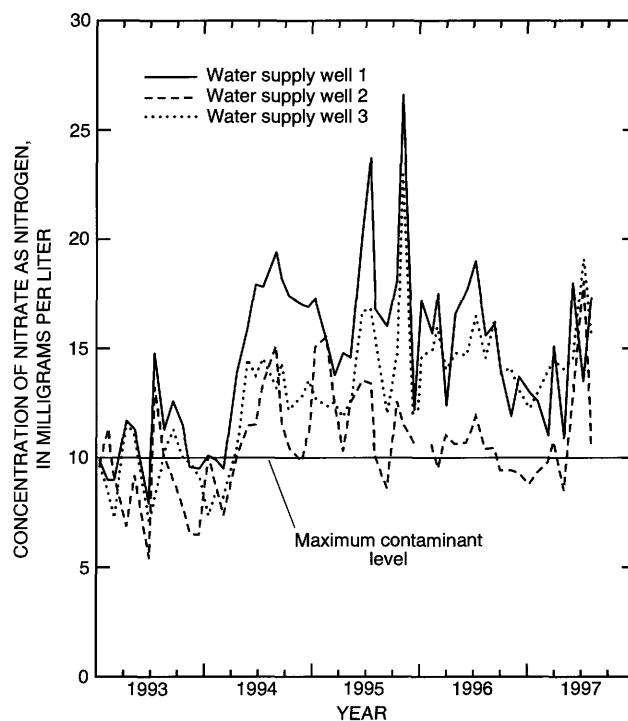


Figure 3. Concentrations of nitrate in water from water-supply wells operated by the town of Julesburg, Colorado, 1993-97.

was a lack of organic carbon, or other electron donors like pyrite, in the aquifer to support microbially mediated denitrification (McMahon and Bohlke, 1996). Without active denitrification, nitrate persists in the aquifer and potentially could become a water-quality problem.

Acknowledgments

The authors thank the employees of the town of Julesburg who helped install and operate the bioremediation system. The authors would also like to thank Archer, Daniels, Midland Company for donating the alcohol used in the bioremediation system. Permission to install wells on property owned by Pro Oil Company is gratefully acknowledged.

METHODS OF DATA COLLECTION

A variety of data-collection activities were required to design and monitor the hydraulic, chemical, and biological performance of the bioremediation system. Descriptions of the data-collection methods are discussed in the following sections.

Organic-Substrate Tests

Microorganisms can couple the reduction of nitrate to the oxidation of a variety of forms of organic carbon. However, some forms of organic carbon support faster rates of denitrification than others (Pfenning and McMahon, 1996). The ideal carbon substrate is one that supports a fast rate of denitrification and is inexpensive. Seven organic substrates were tested for their ability to support denitrification. The tested substrates were acetate, ethanol, corn syrup, dextrose, and three forms of corn oil (unrefined, partially refined, and refined). To test the organic substrates for their capacity to support denitrification, samples of aquifer sediment were collected from the study area and brought to a laboratory where they were amended with nitrate and organic carbon. Aquifer sediment was collected near well MW-1 (fig. 2) using a hollow-stem auger and split-spoon sampler. Each organic substrate was tested as follows:

1. To each of four sterile, 150-mL glass serum bottles was added 15 g of sediment and 100 mL of an aqueous solution containing 28 mg/L of dissolved nitrate (as nitrogen) and 48 mg/L of dissolved organic carbon (DOC) (in the form of one of the seven substrates). The bottles were then capped with thick butyl stoppers.
2. The headspace and solution in the serum bottles were flushed with helium for 5 minutes to remove oxygen, then 2.5 mL of acetylene was added to the headspace. Acetylene blocks the conversion of nitrous oxide to N_2 during the denitrification process (Yoshinari and others, 1977). One of the four serum bottles containing sediment and solution was used as a control by autoclaving the bottle and its contents for 30 minutes at 15 psi and 121°C.
3. The bottles were incubated in the dark at 15°C (expected ground-water temperature). Accumulation of nitrous oxide in the headspace of the bottles over time was measured using gas chromatography with thermal conductivity detection. The rate of denitrification supported by each substrate was calculated from the slope of the least squares linear-regression line plotted through the nitrous-oxide-versus-time data. The component of nonbiological denitrification was determined by measuring nitrous-oxide production in the autoclaved bottles. No nitrous-oxide

production was detected in the autoclaved bottles.

Additional details of the laboratory methods were provided by Pfenning and McMahon (1996). The organic-carbon content of the substrates was determined by Huffman Laboratories of Golden, Colo.

Results from these tests were used to select an organic substrate to use in the pilot test. Additional laboratory tests were conducted on the selected substrate prior to injecting it into the aquifer. The tests were designed to determine the required residence time of the substrate in the aquifer to achieve the target amount of nitrate reduction (15 mg/L). The tests were conducted as described previously, with the following exceptions:

1. No acetylene was added to the headspace of the glass bottles, and
2. nitrite and nitrate concentrations in the water were measured over time rather than nitrous oxide in the headspace.

Aquifer Test

An aquifer test was conducted at the site on November 5 and 6, 1996, to determine the hydraulic conductivity of the aquifer sediments. The test was conducted using the pumping well and monitoring wells MW-1 and MW-3 (fig. 2). Wells MW-1 and MW-3 were located 40 and 131 ft from the pumping well, respectively. The total depth of the pumping well was 40 ft. The pumping well consisted of a metal screen (18-inch diameter) from 20 to 40 ft below the land surface and a metal casing (18-inch diameter) from 0 to 20 ft below the land surface. The total depth of well MW-1 was 35 ft. It consisted of a PVC screen (2-inch diameter) from 15 to 35 ft below the land surface and a PVC casing (2-inch diameter) from 0 to 15 ft below the land surface. Construction information was not available for well MW-3 except that it was known to be screened in the alluvial aquifer. A flow meter was installed on the pumping well to monitor the discharge rate during the test. The well was pumping continuously for 24 hours at 200 gpm while water levels in the monitoring wells were measured using pressure transducers. Water-level measurements were recorded using a data logger. The time-drawdown data from the monitoring wells were analyzed using the Cooper and Jacob method (Cooper and Jacob, 1946), which was corrected for unconfined

conditions (Waterloo Hydrogeologic, 1996a) to calculate the hydraulic conductivity of the aquifer sediments. Data analysis was done using the Aquifer-Test software (Waterloo Hydrogeologic, 1996a).

Tracer Test

Nine injection wells were installed around the pumping well, and injection-water distribution lines were installed between the pumping and injection wells to divert some of the production water (water from the pumping well) back into the aquifer through the injection wells (fig. 2). During normal operation of the bioremediation system, alcohol was pumped into the distribution line before the water was injected into the aquifer. However, prior to the first injections of alcohol into the aquifer, a tracer test was conducted to determine the residence time of injection water in the aquifer. The tracer test was conducted from January 28, 1997, to February 6, 1997.

The pumping and injection wells were operated for about 6 hours during each day of the tracer test, excluding the weekend, to simulate the anticipated operation of the bioremediation system. The pumping well produced 270 gpm, and 110 gpm of this water was diverted to the injection-water distribution lines for injection into the aquifer through the nine injection wells. On the first day of the tracer test, an aqueous solution containing 250 g/L of bromide was pumped into the injection-water distribution line at a rate of 218 mL/min for 2 hours. This resulted in the injection of 13,200 gal of an aqueous solution containing about 131 mg/L of bromide into the aquifer. During and after the injection of bromide into the aquifer, samples of water from the pumping well were collected for the analysis of bromide to determine the time required for injected water to reach the pumping well and to determine the residence time of injected water in the aquifer.

Potential Trihalomethane Formation

There is a potential for trihalomethane (THM) compounds to form in drinking water if that water contains DOC and is disinfected using chlorine (Cl_2). Trihalomethanes, which include chloroform, bromodichloromethane, dibromochloromethane, and bromoform, are potential cancer-causing chemicals.

Although the water from the pumping well used in this pilot test was not chlorinated or used for drinking water, there was a possibility that concentrations of DOC in the production water could increase because of the alcohol that was injected into the aquifer. Laboratory tests were conducted to determine the potential for THM formation in water from the pumping well. Tests were run on samples collected in January 1997 prior to the first injections of alcohol into the aquifer and again in July 1997 after alcohol injections had been occurring for 5 months.

The test used in this study was a modification of the procedure by Krasner and Scilimenti (1993). The test involved the addition of Cl_2 , in the form of sodium hypochlorite, to a sample of water, incubating the water in a closed vessel at room temperature for 24 hours, and analyzing the water for THM's. The test measured potential THM formation because a Cl_2 residual was maintained in the sample during the test. The amount of Cl_2 added to maintain a residual was determined using equation 1 (Krasner and Scilimenti, 1993):

$$\text{Cl}_2(\text{mg/L}) = \text{DOC} + (7.6 \times \text{NH}_4\text{-N}) \quad (1)$$

DOC is the concentration of dissolved organic carbon in the water (in milligrams per liter) and $\text{NH}_4\text{-N}$ is the concentration of dissolved ammonium in the water (in milligrams per liter as nitrogen).

Concentrations of THM's in the water were determined using gas chromatography with electron-capture detection. The THM's were separated using a stainless-steel column (1/8 inch \times 8 ft) packed with 60/80 Carbopack B/1% SP-1000. The carrier gas was 95-percent argon/5-percent methane. The inlet temperature was 200°C; the detector temperature was 300°C; and the oven temperature was programmed at 50°C (hold 3 minutes), 8°C per minute to 150°C (hold 15 minutes). The THM detection levels were about 1 $\mu\text{g/L}$.

Water-Quality Sampling and Analytical Procedures

Samples of water from the pumping well (fig. 4) were collected about once each week when the bioremediation system was in operation. Water samples were analyzed for various physical properties, and

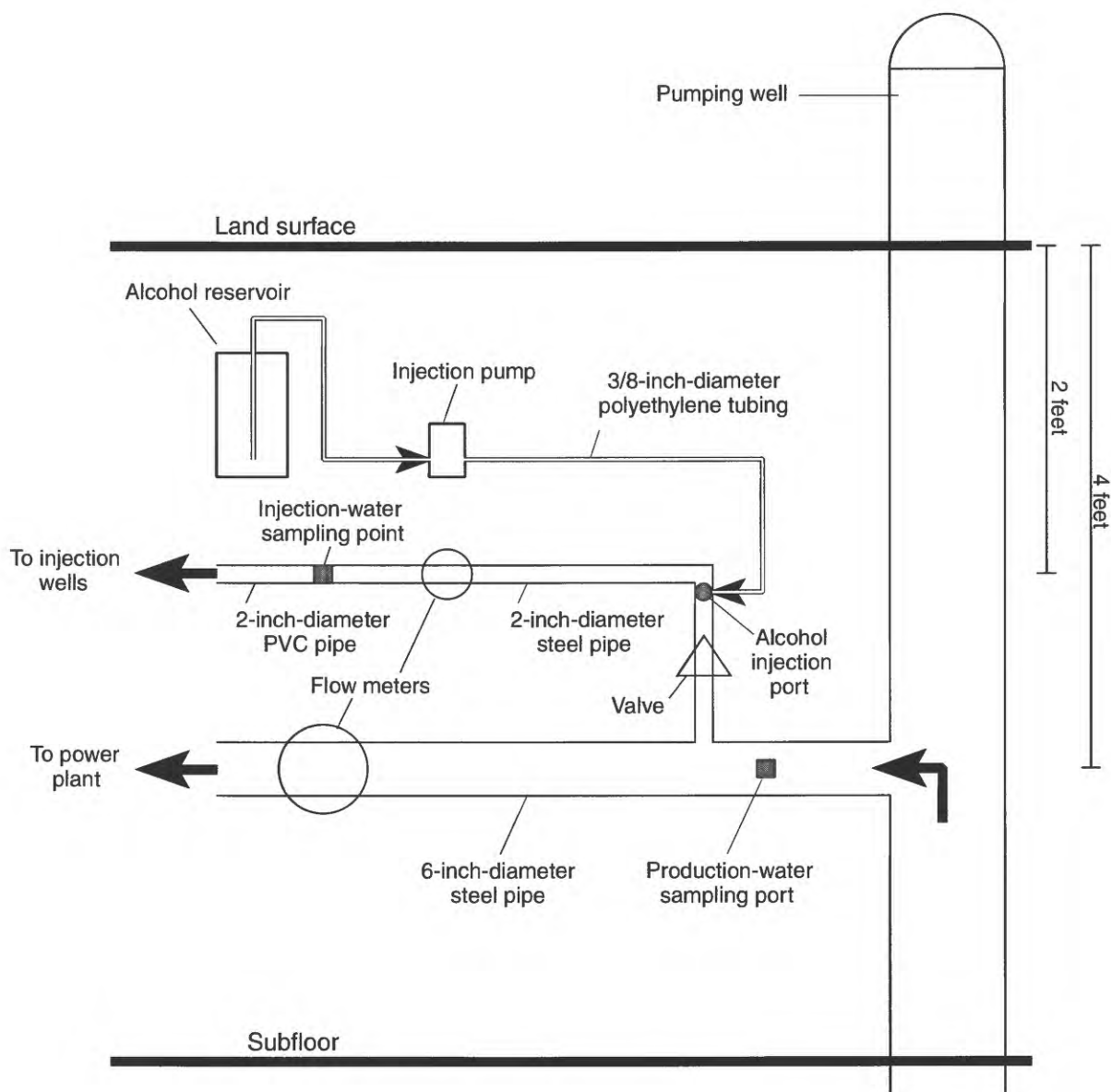


Figure 4. Diagrammatic cross section of plumbing for pumping well.

concentrations of selected dissolved inorganic and organic constituents and total coliform and heterotrophic bacteria. Physical properties of the water measured were specific conductance, pH, water temperature, turbidity, dissolved oxygen, and alkalinity. Dissolved inorganic constituents analyzed were calcium, magnesium, sodium, potassium, sulfate, chloride, bromide, nitrite, nitrate, ammonium, iron, hydrogen sulfide, and manganese. Organic constituents analyzed were methane, ethanol, methanol, suspended organic carbon (SOC), and DOC. Water samples also were collected from the injection-water

distribution line (fig. 4) for the analysis of ethanol and methanol. Water samples for the analysis of nitrate were collected from wells MW-1 and MW-2 using a bailer.

Physical properties of the water were measured at the wellhead at the time of sampling using methods described by Bruce and McMahon (1997). Concentrations of dissolved hydrogen sulfide and manganese also were measured at the well head using a spectrophotometer (Hach Company, 1991). Water samples collected for the analysis of dissolved inorganic constituents were filtered through 0.45- μ m capsule

filters. Cation samples were acidified with hydrochloric acid (iron) or nitric acid (all other cations). Anion samples were kept chilled at 4°C until analyzed. Iron was measured using the ferrozine method by Lovley and Phillips (1986). Other dissolved inorganic constituents were analyzed using ion chromatography with suppressed conductivity detection. All samples were analyzed in duplicate. Detection limits were about 0.1 mg/L, and precisions were plus or minus 5 percent for analyses by ion chromatography. An internal nitrate standard (10 mg/L as nitrogen) was included in the anion analyses to evaluate the nitrate data. The average calculated concentration of the internal nitrate standard was 9.6 mg/L as nitrogen, which represents a 4-percent deviation from the actual concentration. In addition, replicate water samples were collected on March 13 and July 18, 1997, for the analysis of nitrate at the USGS National Water Quality Laboratory. The average percent difference in nitrate concentrations between the project laboratory and the USGS National Water Quality Laboratory was 4.5.

Water samples collected for the analysis of DOC were filtered through 0.45-μm silver filters and kept chilled at 4°C until analyzed (Wershaw and others, 1987). Concentrations of suspended organic carbon were determined by measuring the amount of organic carbon retained on the silver filter. Water samples collected for the analysis of dissolved ethanol, methane, and methanol were filtered through 0.45-μm nylon syringe filters and kept chilled at 4°C until analyzed. Methane was analyzed using gas chromatography with flame-ionization detection, following the method by Baedeker and Cozzarelli (1992). Ethanol and methanol also were measured using gas chromatography with flame-ionization detection. Five-microliter water samples were injected on a column, and ethanol and methanol were separated on a PoraPlot Q capillary column (0.021 inch × 82 ft). The carrier gas was helium. The inlet temperature was 250°C; the detector temperature was 250°C; and the oven temperature was 150°C. All samples were run in duplicate and detection limits for methane, ethanol, and methanol were 0.02, 2, and 5 mg/L, respectively. Analytical precisions were plus or minus 5 percent.

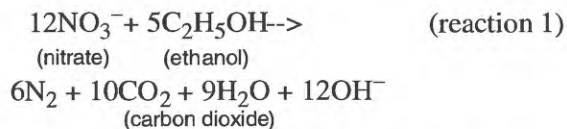
Water samples for the analysis of total coliform and total heterotrophic bacteria were collected in sterile plastic bags and preserved with sodium thiosulfate. The samples were analyzed at Industrial Laboratories in Denver, Colo.

DESIGN AND INSTALLATION OF BIOREMEDIATION SYSTEM

The design of the bioremediation system was based on results from the organic-substrate tests, aquifer test, and ground-water flow modeling. The organic-substrate tests were used to select which organic substrate to inject into the aquifer. The aquifer test was used to determine the hydraulic conductivity of the aquifer sediments. The hydraulic-conductivity value was used in a generalized model of ground-water flow to determine the distance between the pumping and injection wells required to obtain an injection-water residence time of about 7 days. Results from these activities and construction details for the bioremediation system are described in this section.

Organic Substrates

In the process of heterotrophic denitrification, nitrate is reduced to N₂ and organic carbon is oxidized to carbon dioxide. Reaction 1 describes the denitrification reaction involving nitrate and ethanol:



Organic substrates that supported a fast rate of nitrous-oxide production were preferred for the bioremediation system because they would require a shorter residence time in the aquifer, thereby allowing for a shorter distance between the pumping and injection wells. Results from the substrate tests indicated that ethanol and acetate supported the fastest rates of nitrous-oxide production (fig. 5A). Ethanol was chosen rather than acetate for use in the bioremediation system because it is less corrosive on plumbing than acetic acid.

Ethanol was tested further in the laboratory to determine the required residence time of ethanol in the aquifer to achieve a target amount of nitrate reduction. The target amount of nitrate reduction was 15 mg/L, which was the difference between the nitrate concentration in the pumping well (25 mg/L) and the MCL of nitrate. Results of this laboratory test are shown in figure 5B. The results indicated that about 7 days were required to achieve a 15-mg/L reduction in nitrate concentrations. Therefore, the required residence time

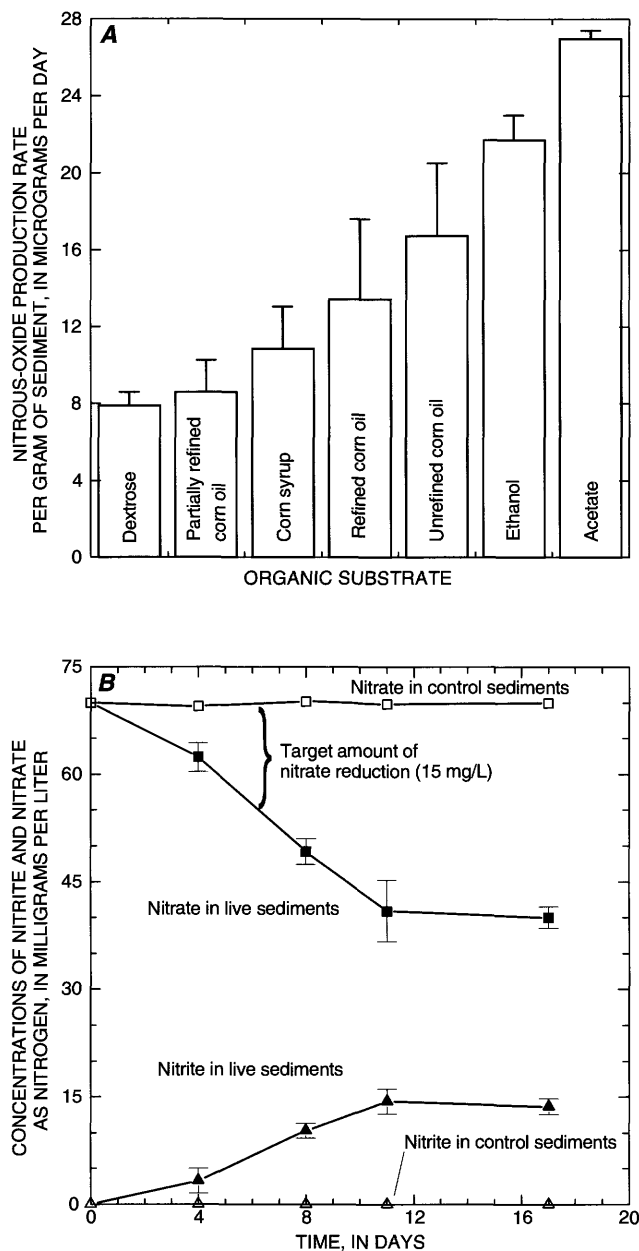


Figure 5. (A) Laboratory-measured rates of nitrous-oxide production in aquifer sediments amended with different organic substrates and (B) concentrations of dissolved nitrite and nitrate in aquifer sediments amended with ethanol. Columns in (A) represent the average of three measurements, and the error bars represent one standard deviation. Data points for live sediments in (B) are the average of three measurements plus or minus one standard deviation.

based on this test was about 7 days. Note that there was no uptake of nitrate or production of nitrite in control sediments that were autoclaved (fig. 5B), indicating that nitrate degradation in the aquifer sediments was due to microbial activity.

Aquifer Test

A hydraulic-conductivity value of 720 ft/d was calculated for the aquifer sediments using the time-drawdown data from well MW-1 and the Cooper and Jacob method (Cooper and Jacob, 1946) corrected for unconfined conditions (Waterloo Hydrogeologic, 1996a) (fig. 6). A hydraulic-conductivity value of 740 ft/d was calculated using the time-drawdown data from well MW-3. These values of hydraulic conductivity are representative of coarse sand and gravel sediments (Freeze and Cherry, 1979) similar to those at the study area.

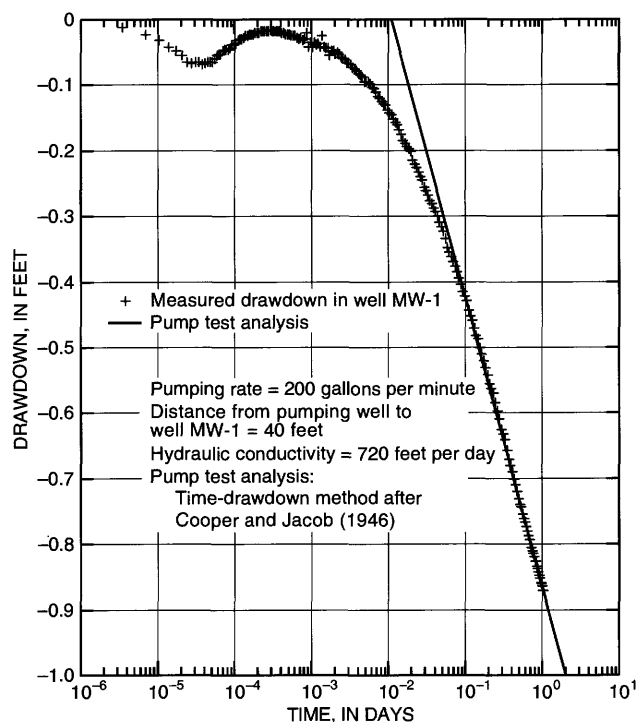


Figure 6. Time-drawdown data from monitoring well MW-1.

Ground-Water Flow Model

A generalized two-dimensional areal model of ground-water flow was developed using the visual MODFLOW software (Waterloo Hydrogeologic, 1996b) and the hydraulic-conductivity data. The model was used to determine the required distance between the central pumping well and 10 injection wells to provide a 7-day residence time of injected water in the aquifer. A square grid 10,000 ft on each side was created to represent the flow field. The grid was aligned parallel to the direction of regional ground-water flow as defined by Hurr and Schneider (1972). The pumping and injection wells were located in the middle of the grid where the smallest cells were 2 ft \times 2 ft. Cell sizes were expanded outside the area of the wells, with the largest cells being 800 ft \times 800 ft. Other hydraulic parameters of the model are listed in table 1. An initial steady-state model with no pumping or injection was developed to produce a water-table map of the simulated area. The water table from this simulation was used as the initial condition in a transient model that simulated pumping (190 gpm) and injection (10 wells, each injecting 10 gpm). The pumping and injection simulation was 6 hours of pumping and injection during each of 5 consecutive days, followed by no pumping or injection for 2 days. This simulation was run for 365 days.

Results of the transient simulation are shown in figure 7. Shown in the figure are the flow paths of water moving from the injection wells to the pumping well. Each arrowhead on the flow-path lines represents

24 hours of residence time of injected water in the aquifer. The arrowhead points in the direction of ground-water flow. Flow paths were straight for injection wells placed directly upgradient from the pumping well. Flow paths for wells downgradient from the pumping well were circuitous because injected water moved toward the pumping well when it was operating, but the water moved away from the pumping well when it was not operating. The placement of the injection wells around the pumping well in the model was constrained by the known locations of buildings at the site. Because of the buildings, an even spacing between injection wells could not be achieved. The transient simulation indicated that the residence time of water in the aquifer would be from 5 to 10 days for the injection-well locations shown in figure 7. These residence times are similar to the required residence time determined from laboratory tests to achieve the target amount of nitrate reduction in the aquifer sediments (fig. 5B).

Installation of Injection Wells and Injection-Water Distribution Lines

The generalized ground-water flow model indicated the possible locations for 10 injection wells around the central pumping well. However, the physical layout of the site (primarily locations of buildings and utilities) prevented installation of the wells in the exact locations indicated in the model (fig. 7). In fact, the injection well located directly downgradient from

Table 1. Hydraulic parameters used in the ground-water flow model

Parameter	Value
Saturated thickness	20 feet
Porosity	0.3
Horizontal hydraulic conductivity	720 feet per day
Vertical hydraulic conductivity	72 feet per day
Pumping rate	190 gallons per minute
Injection rate per well	10 gallons per minute
Storage coefficient	0.2
Specific storage	0.02 per foot
Boundary condition along upgradient edge of model	Constant head
Boundary condition along downgradient edge of model	Constant head
Boundary condition along bottom of model	No flow
Boundary conditions along sides of model	No flow

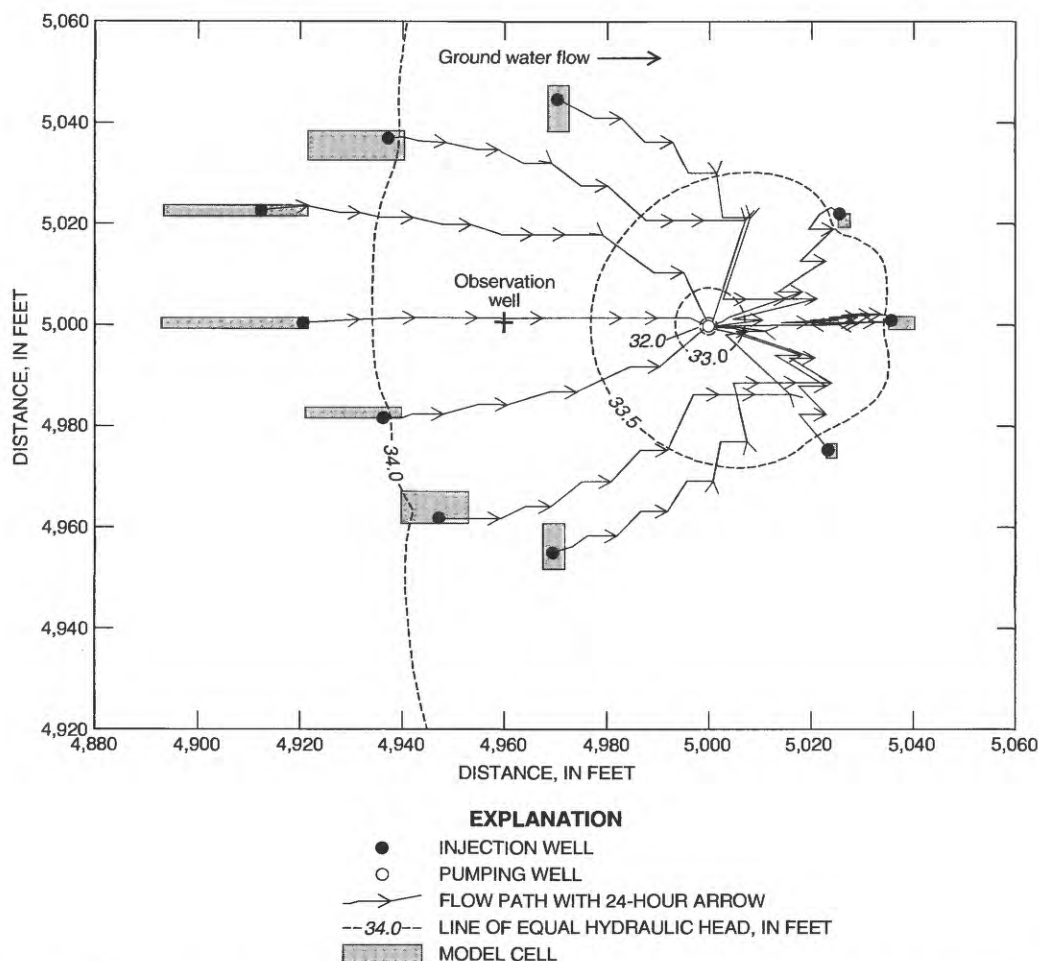


Figure 7. Output from transient ground-water flow simulation showing locations of injection wells around pumping well and flow paths for injection water with 24-hour arrows. Pumping rate was 190 gallons per minute, and the injection rate for each well was 10 gallons per minute.

the pumping well in the model could not be installed because a water tower was located in that area. Distances from the injection wells to the pumping well ranged from 31 to 94 ft.

Nine of 10 planned injection wells were installed around the central pumping well (fig. 2). The injection wells were installed using a rotary drill rig and water as the drilling fluid. Each well was 35 ft deep and had 20 ft of 2-inch-diameter PVC-wire wrapped screen (0.040-inch slot size). Well construction details are illustrated in figure 8. There were relatively large distances between injection wells IW-1 and IW-9, IW-7 and IW-8, and IW-8 and IW-9 because of the presence of buildings or utilities in those areas. These gaps between injection wells represented areas of the aquifer that could not be treated by the bioremediation system.

Water used for injection in the aquifer was provided by the pumping well. About 30 percent of the production water was diverted from the main (6-inch diameter) discharge line to a smaller (2-inch diameter) injection-water distribution line (fig. 4). The injection-water distribution line, which was buried about 2 ft below land surface, connected the injection wells to the pumping well (fig. 2). A 20-percent solution of denatured alcohol in water was pumped into the injection-water distribution line downstream from a valve that isolated that line from the main discharge line (fig. 4). The alcohol, when injected into the aquifer, served as the electron donor for the denitrifying microorganisms. Specially denatured alcohol, formula SDA-3A, was used in this pilot test. Formula SDA-3A contains 5 gal of methanol in 100 gal of ethanol (minimum 199 proof). Pure ethanol was not used in the pilot test because of the tax liability associ-

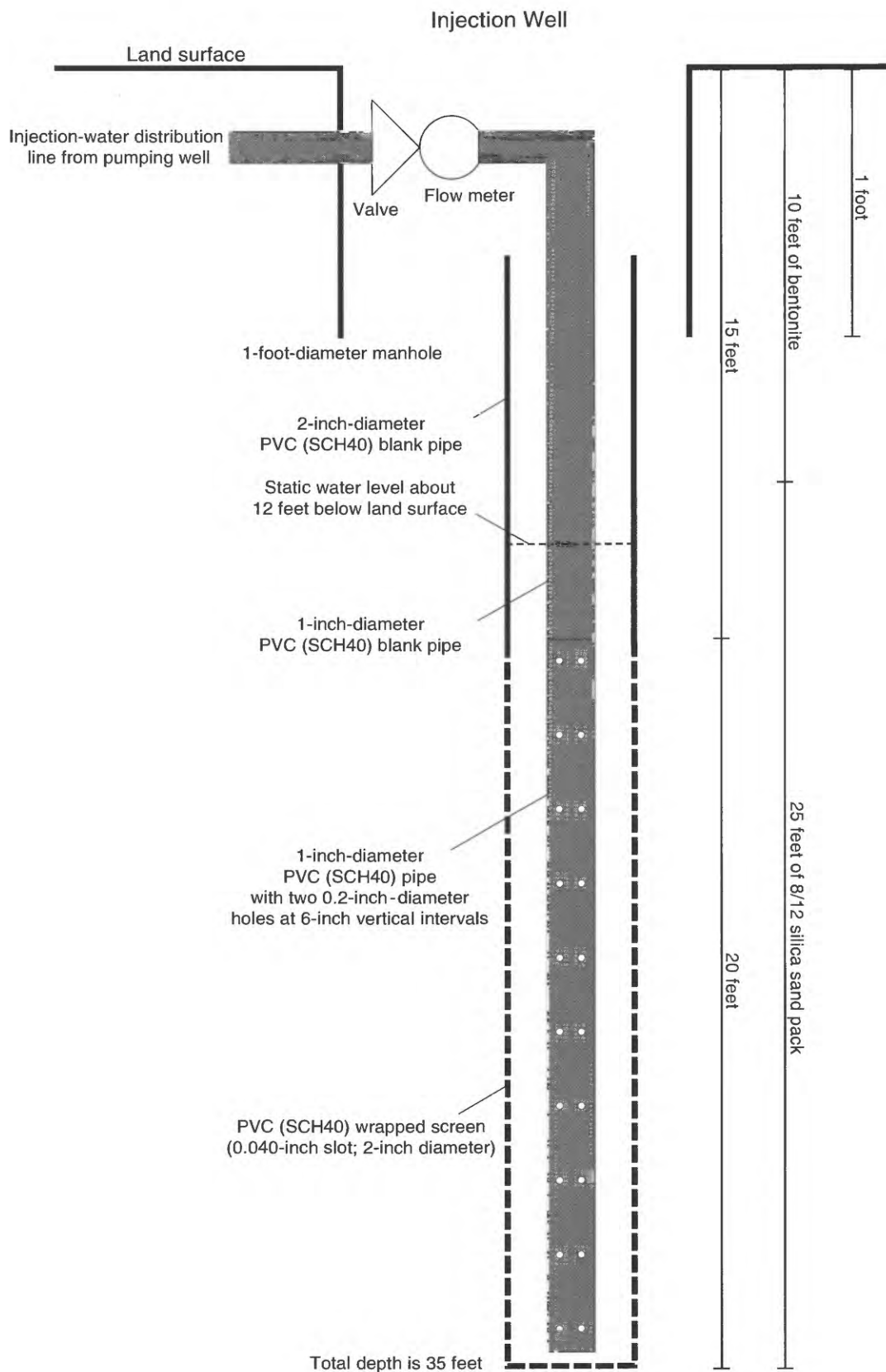


Figure 8. Diagrammatic cross section showing construction of injection wells.

ated with distilled spirits. However, pure ethanol may be the preferred substrate for treating an actual drinking-water-supply well because of the potential toxicity of methanol.

HYDRAULIC PERFORMANCE OF BIOREMEDIATION SYSTEM

Two aspects of the hydraulic performance of the bioremediation system were studied in this pilot test. One was the residence time of injection water in the aquifer. Residence time in the aquifer is the time it takes for injection water to travel from the injection wells to the pumping well. If the rate of denitrification in the aquifer is slow relative to the residence time, there is a possibility that components of the denatured alcohol (ethanol and methanol) will appear in the production water because the denitrifying microorganisms did not have time to degrade it completely. The second aspect of hydraulic performance studied in this pilot test was the injection rates and pressures. The primary obstacle to successfully operating in-situ bioremediation systems that rely on organic-carbon injections is the plugging of the injection well or aquifer sediments around the well (Pyne, 1995). The plugging is an artifact of biomass buildup at the point of organic-carbon injection. As biomass accumulates around injection wells, injection rates may decrease and injection pressures may increase. These aspects of hydraulic performance are discussed in this section.

Injection-Water Residence Times

The bromide-tracer test was used to determine the residence time of injection water in the aquifer. Bromide above background concentrations was detected in the production water as early as 1 hour and as late as 9 days after the injection (fig. 9). However, most of the tracer mass was recovered 1 to 3 days after injection. Arrival of the maximum bromide concentrations 1 to 3 days after injection was sooner than predicted by the ground-water flow model. The earlier than expected breakthrough of the tracer probably was due to an increase in the pumping rate after the injection-water distribution line was installed. A pumping rate of 190 gpm was measured at the well prior to installation of the injection-water distribution line, and this pumping rate was used in the model for injection-

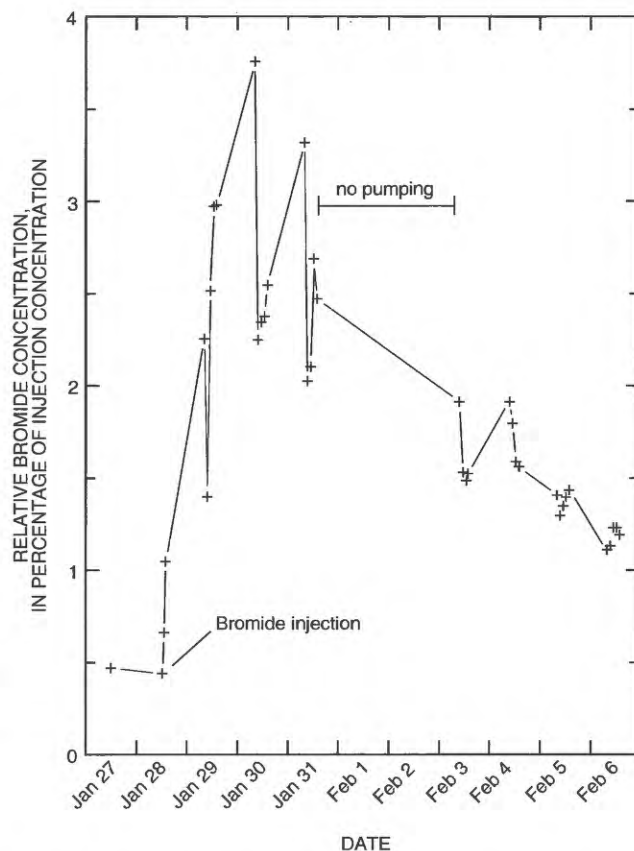


Figure 9. Relative concentrations of bromide in water collected from the pumping well during the tracer test (test was from January 28 to February 6, 1997).

well placement. After installing the injection-water distribution line, the pumping rate increased to about 270 gpm (fig. 10A). Apparently, the increased opening in the discharge line provided by the injection-water distribution line allowed for the increased pumping rate. Therefore, the tracer test was conducted at a pumping rate of about 270 gpm instead of at the simulation rate of 190 gpm.

The maximum concentration of bromide in the production water (4.9 mg/L) was about 3.75 percent (fig. 9) of the bromide concentration in the injection water (131 mg/L). These results indicated that there was substantial dilution of the bromide solution after it was injected into the aquifer. The large amount of bromide dilution may stem from the relatively large distances between injection wells IW-1 and IW-9, IW-7 and IW-8, and IW-8 and IW-9 (fig. 2). Water entering the capture zone of the pumping well between these injection wells contained no added bromide. This means that nitrate entering the capture zone in

these areas probably was not treated during operation of the bioremediation system. A more effective deployment of the injection wells could be achieved at a site with fewer buildings and utilities.

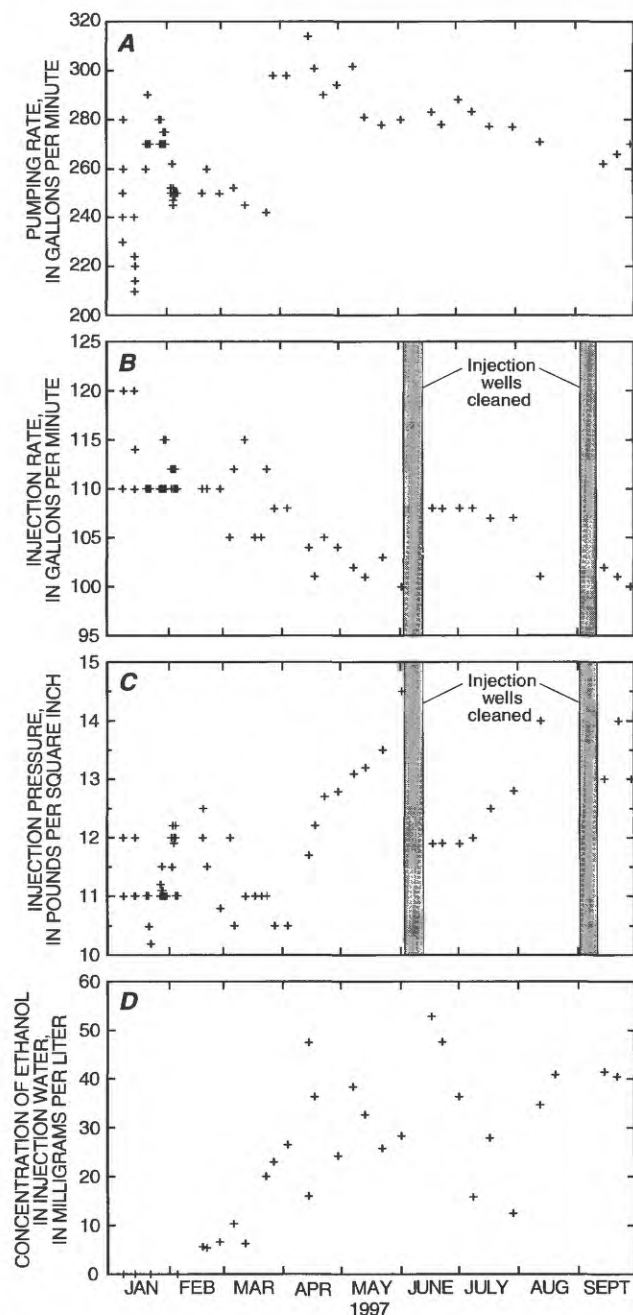


Figure 10. (A) pumping rates, (B) injection rates, (C) injection pressures, and (D) concentrations of ethanol in the injection water during operation of the bioremediation system.

Injection Rates and Pressures

Operation of the bioremediation system began on January 9, 1997, and ended on September 29, 1997. The system was operated Monday through Friday of each week until the beginning of June. From June through September, the system operated on Mondays, Wednesdays, and Fridays. The pumping and injection wells were run for 6 hours during each day of system operation. A total of 8,160,000 gal of water was pumped from the aquifer, and 4,626,400 gal of water was injected into the aquifer during the pilot test.

No alcohol was added to the injection water until February 19, 1997, about 5 weeks after system start up, so that baseline injection rates and pressures could be determined. Injection rates ranged from about 110 to 120 gpm during this period (fig. 10B), and injection pressures ranged from about 10.2 to 12.4 psi (fig. 10C). The variability in the data soon after start up probably represented a period when equilibration had not been reached in the pumping and injection wells.

Injections of alcohol began on February 19, 1997, by alternately starting and stopping the alcohol injection pump (fig. 4) during the 6-hour operating period. The alcohol injection pump was operated during the first two hours, stopped for 1 hour, operated for 2 hours, and then stopped for the final 1 hour of operation. The purpose of pulsed alcohol injections was to minimize biomass growth around the injection wells by forcing the alcohol-amended water away from the well and into the aquifer using unamended injection water (Mercado and others, 1988; Hamon and Fustec, 1991). Also, concentrations of ethanol in the injection water were increased gradually over a period of about 2 months (fig. 10D) to minimize the rate of biomass buildup around the injection wells. An attempt was made to maintain the maximum ethanol concentration in the injection water at about 40 mg/L. However, occasional maintenance problems with the alcohol injection pump resulted in ethanol concentrations in the injection water that ranged from about 12 to 52 mg/L (fig. 10D).

The injection rates decreased slightly but the pressures did not change from the pre-alcohol levels during the 2-month period when ethanol concentrations were increased (figs. 10B through 10D). However, about 1.5 months after ethanol concentrations reached their maximum levels, injection rates decreased to less than 105 gpm and injection pressures

increased to about 14.5 psi. These changes in injection rates and pressures were indicative of injection-well plugging. Inspection of the 1-inch diameter injection pipes inside the injection wells (fig. 8) confirmed that the injection wells were becoming plugged with biomass. The injection wells were redeveloped using commercially available chemical formulations designed to detach biomass from casing and aquifer solids so that the biomass could be pumped from the wells (Johnson Screens, St. Paul, Minnesota, formulations NW-110 and NW-310). Injection rates and pressures returned to pre-treatment levels after the chemical treatment of the injection wells (figs. 10B and 10C). An additional chemical treatment was required about 2.5 months after the first treatment because changes in the injection rates and pressures indicated that biomass was beginning to plug the wells again. However, injection rates and pressures did not recover to pre-treatment levels after the second treatment (figs. 10B and 10C). This non-recovery indicated that the growth of biomass probably occurred outside of the treatment zone around the injection wells. More frequent cleaning of the injection wells might reduce the biomass buildup, although additional work is needed to determine the optimal cleaning frequency.

The longevity of the pilot test was the result of several factors, including (a) pulsed injections of alcohol, (b) gradual increases in the amount of alcohol in the injection water, (c) periodic cleaning of the injection wells, and (d) relatively large hydraulic conductivity of the aquifer sediments. These factors need to be considered in the design of future in-situ nitrate-bioremediation systems.

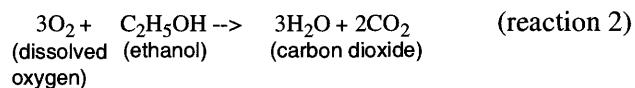
CHEMICAL AND BIOLOGICAL PERFORMANCE OF BIOREMEDIATION SYSTEM

The chemical and biological performance monitoring was focused on selected physical properties and concentrations of inorganic and organic constituents and bacteria in the production water. The production water was monitored because it is the water that would be used for human consumption in a full-scale bioremediation system.

Physical Properties of Production Water

Physical properties monitored during the pilot test included specific conductance, pH, water temperature, turbidity, dissolved oxygen, and alkalinity. Time-series measurements of the physical properties of the production water are listed in table 3 at the back of the report. Specific conductance of the production water ranged from 2,410 to 2,490 $\mu\text{S}/\text{cm}$ and did not increase during the test. The same is true for the pH, which ranged from 7.1 to 7.3, and turbidity, which generally ranged from less than 1 to 1 NTU. The low turbidity in the production water during the test indicated that there was not substantial breakthrough of bacterial cells or suspended sediment in the production water, as has been observed in some other in-situ nitrate-bioremediation systems (Mercado and others, 1988). High turbidity of the production water is undesirable because the water would need to be filtered before use. Water temperatures increased during the test from about 13.5 to 14.7°C. However, this increase was the result of increases in the air temperature from winter to summer and was not an artifact of the bioremediation system.

Dissolved oxygen and alkalinity were the only physical properties of the production water that changed in concentration as a result of the bioremediation process. Concentrations of dissolved oxygen in the production water decreased from about 5.6 mg/L prior to alcohol injections to concentrations as small as 2.6 mg/L during the period when ethanol concentrations in the injection water were largest (figs. 11A and 11B). In contrast to the production water, water from well MW-2 contained more than 6 mg/L of dissolved oxygen. Well MW-2 was located outside the area of influence of the bioremediation system (fig. 2). Like nitrate, dissolved oxygen can be an electron acceptor during the microbial oxidation of ethanol to carbon dioxide (reaction 2).



The dissolved-oxygen concentration of 5.6 mg/L in the production water prior to alcohol injections and a median dissolved-oxygen concentration of 3.4 mg/L after the start of alcohol injections (table 3) indicated that the efficiency of reaction 2 was about 40 percent. The efficiency of oxygen consumption is an important consideration in the denitrification process because

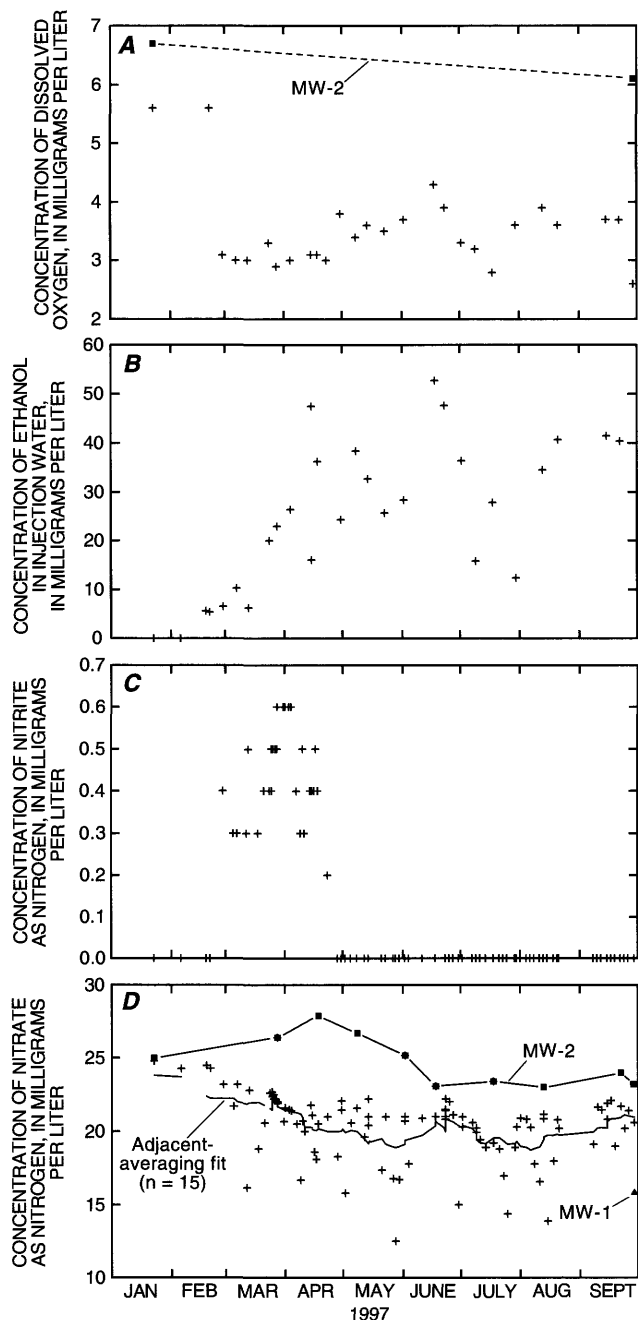


Figure 11. Concentrations of (A) dissolved oxygen in production water and in water from well MW-2, (B) ethanol in injection water, (C) nitrite in production water, and (D) nitrate in production water and in water from wells MW-1 and MW-2 during operation of the bioremediation system.

denitrifying activity is inhibited by large concentrations of dissolved oxygen (Chapelle and others, 1995). Therefore, more organic carbon is required to achieve a target level of nitrate reduction in water with large concentrations of dissolved oxygen than in water with small concentrations of dissolved oxygen. Concentrations of dissolved oxygen and nitrate in the South Platte River alluvial aquifer generally decrease with depth (McMahon and Bohlke, 1996; Dennehy and others, 1995); therefore, deep wells may be easier to bioremediate than shallow wells such as the one used in this pilot test.

Reaction 2 indicates that carbon dioxide is produced when ethanol is oxidized. Alkalinity is produced when carbon dioxide dissolves in water and reacts to form bicarbonate and carbonate anions. Concentrations of alkalinity in the production water increased from about 240 mg/L prior to alcohol injections to concentrations as large as 338 mg/L after the alcohol injections started (table 3). Alkalinity produced by the bioremediation process increased the hardness of the production water.

Concentrations of Nitrite and Nitrate in Production Water

Concentrations of dissolved nitrite and nitrate in the production water are listed in table 3 and illustrated in figures 11C and 11D. Nitrite is an intermediate product of the denitrification process, and it generally does not occur in ground water in concentrations that exceed the MCL of 1 mg/L as nitrogen. Nitrite was not present in the ground water prior to the injection of alcohol to the aquifer. Nitrite concentrations increased to as much as 0.6 mg/L after alcohol injections began, but they never exceeded the MCL. The presence of nitrite in the ground water after alcohol injections began indicated that the denitrification process was actively reducing nitrate in the ground water. Similar results were observed in the laboratory tests (fig. 5B). Nitrite concentrations generally decreased to less than 0.1 mg/L after about 2 months, possibly indicating that a balance between nitrite and nitrate reduction in the aquifer was achieved. It is common for ground water, in which denitrifying microbes have been active for extended periods of time, to contain only small concentrations of nitrite (McMahon and Bohlke, 1996).

The average concentration of nitrate in the production water was about 24.5 mg/L as nitrogen prior to the injection of alcohol on February 19, 1997 (fig. 11D and table 3). The concentration of nitrate in water from monitoring well MW-2 was about the same as the nitrate concentrations in water from the pumping well prior to alcohol injections (fig. 11D and table 3). Therefore, concentrations of nitrate in water from well MW-2 were used to represent nitrate concentrations in undenitrified ground water at the site. The historical variability in nitrate concentrations in water from the pumping well and from well MW-2 is not known, so it is uncertain how accurately nitrate concentrations from well MW-2 represented pre-denitrification concentrations from the pumping well during the 9-month test.

Concentrations of nitrate in the production water after alcohol injections began ranged from 12.5 to 24.3 mg/L (fig. 11D). The median nitrate concentration was 20.6 mg/L as nitrogen. In contrast, nitrate concentrations in water from well MW-2 ranged from 23.0 to 27.9 mg/L as nitrogen, with a median value of 24.5 mg/L as nitrogen. The difference between the median nitrate concentrations in the two wells was 3.9 mg/L as nitrogen. Based on this difference in median nitrate concentrations, the efficiency of nitrate removal by the bioremediation system was about 16 percent.

This level of efficiency in removing nitrate from ground water was considerably less than the oxygen-removal efficiency (40 percent) of the bioremediation system, indicating that most of the alcohol added to the aquifer was used to remove dissolved oxygen from ground water. As previously stated, the nitrate-removal efficiency could be increased for ground water containing less dissolved oxygen. Another factor contributing to the relatively low nitrate-removal efficiency was the location of the injection wells. The large distances between some of the wells resulted in more untreated ground water entering the capture zone of the production well than was desired. To illustrate this point, the concentrations of nitrate in water samples from well MW-1 (fig. 2) and the pumping well were 15.8 and 20.6 mg/L, respectively, on September 29, 1997 (fig. 11D and table 3). The nitrate concentration in MW-1 was 4.8 mg/L less than the nitrate concentration in the production water. Well MW-1 was more effectively surrounded by injection wells than the pumping well; therefore, the small nitrate concentration in well MW-1 may indicate

more complete denitrification in the aquifer near that well.

The nitrate-removal efficiency of the bioremediation system was relatively low for the pumping well. However, if the same amount of nitrate removal (3.9 mg/L as nitrogen) was achieved in the town's water-supply wells, the nitrate-removal efficiency would have been much greater for the water-supply wells. This is because the concentrations of nitrate in water from the water-supply wells were considerably smaller than the concentrations in water from the pumping well (compare figs. 3 and 11D). The measured average nitrate concentrations and the hypothetical average nitrate concentrations in water from the water-supply wells are shown in figure 12 for years 1993–97. The hypothetical average nitrate concentrations were calculated by subtracting the amount of nitrate removal measured in the pilot test (3.9 mg/L as nitrogen) from the measured average nitrate concentrations in water from the three water-supply wells. Based on these calculations, the nitrate-removal

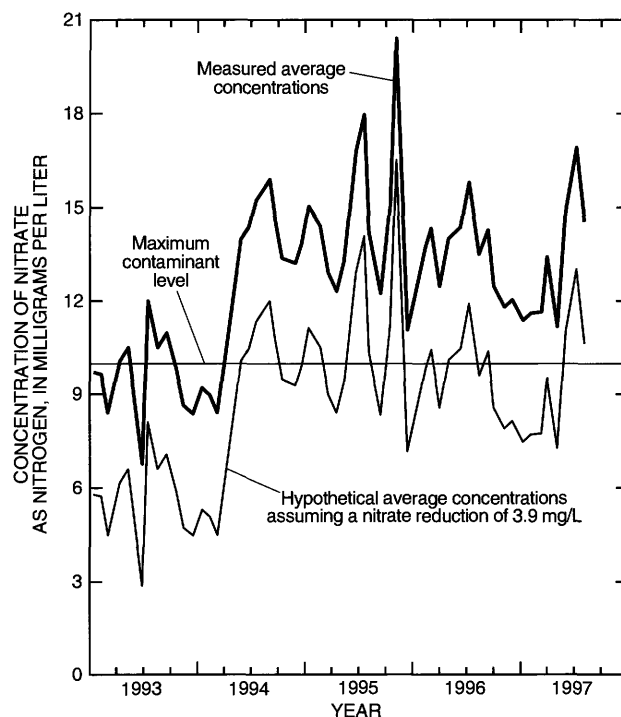


Figure 12. Measured and hypothetical average concentrations of nitrate in water from water-supply wells operated by the town of Julesburg, Colorado, 1993–97.

efficiency would have been about 30 percent, and the number of times the nitrate concentrations exceeded the MCL would have been reduced by 56 percent. These calculations indicated that relatively small reductions in the concentrations of nitrate in water from the water-supply wells potentially could produce substantial improvements in the compliance record for these wells.

Concentrations of Selected Organic Constituents in Production Water

Selected organic constituents were analyzed for in the production water during the pilot test, including methane, ethanol, methanol, SOC, and DOC (table 3). There were no detections of methane, ethanol, or methanol in the production water. Some previous studies have reported the appearance of added organic substrates at the pumping well (Janda and others, 1988; Hamon and Fustec, 1991). The appearance of organic substrates in the production water in those studies probably resulted from inadequate residence time of the carbon in the aquifer or injection of organic substrates in the aquifer at concentrations that exceeded the metabolic capacity of the microbes. A maximum ethanol concentration of 40 mg/L was the target level for the injection water in this pilot test because it was only slightly more than the stoichiometric amount of ethanol (36 mg/L) required to remove 5.6 mg/L of dissolved oxygen and 24.5 mg/L of nitrate as nitrogen from the ground water (reactions 1 and 2).

Suspended and dissolved organic carbon were detected in the production water at average concentra-

tions of 0.1 and 4.4 mg/L, respectively (data in table 3). There was no measurable concentration increase in the three SOC samples collected during the test. The concentration of DOC was 4.3 mg/L prior to alcohol injections, and it was 4.2 mg/L after 5 months of alcohol injections. The maximum measured concentration of DOC was 4.5 mg/L after 2 months of alcohol injections. These data indicated that alcohol injections did not substantially increase concentrations of DOC in the production water.

Potential Trihalomethane Formation in Production Water

There is a potential for THM's to be formed when water containing DOC is chlorinated. Therefore, any water-treatment process that has the potential to increase concentrations of DOC also has the potential to increase THM formation if that water is chlorinated. The potential for THM formation in water from the pumping well was evaluated using water samples collected in January 1997 (before alcohol injections) and in July 1997 (after 5 months of alcohol injections). The concentrations of DOC in these water samples were 4.3 and 4.2 mg/L (table 3).

Results of the THM tests are listed in table 2. None of the THM's were detected in the unchlorinated water samples from January and July. However, three of the four THM's were detected in the chlorinated sample from January. These results indicated that the DOC naturally present in the aquifer formed THM's when the water was chlorinated. Concentrations of the THM's in the July water sample were somewhat larger than the concentrations in the January sample, even

Table 2. Concentrations of trihalomethane compounds in unchlorinated and chlorinated water from the pumping well

[µg/L, micrograms per liter; <, less than; --, not applicable]

Trihalomethane	January 1997		July 1997		State of Colorado ground-water standard ¹ (µg/L)
	Unchlorinated (µg/L)	Chlorinated (µg/L)	Unchlorinated (µg/L)	Chlorinated (µg/L)	
Chloroform	< 1	< 1	< 1	4	6.0
Bromodichloromethane	< 1	3	< 1	11	0.3
Dibromochloromethane	< 1	15	< 1	23	14.0
Bromoform	< 1	32	< 1	42	4.0
Sum of concentrations ²	--	50	--	80	--

¹Colorado Department of Public Health and Environment, 1995.

²U.S. Environmental Protection Agency (1996) standard for total trihalomethanes is 100 µg/L.

though there was slightly less DOC in the July sample. It is possible that compositional differences in the DOC in the two samples resulted in the different THM concentrations. However, only two THM tests were conducted as part of this study. Additional THM tests should be conducted on treated and untreated ground water to determine how THM formation varies over time.

Except for chloroform, the THM concentrations in the January and July chlorinated samples exceeded the ground-water standards established by the Colorado Department of Public Health and Environment (1995) (table 2). However, neither sample exceeded the U.S. Environmental Protection Agency (1996) standard for total THM's, which is 100 µg/L. It should be emphasized that the THM concentrations measured in these samples probably are maximum concentrations. It is likely that THM concentrations in the town's water-supply system would be smaller because of aeration in water-supply lines and in storage tanks.

Concentrations of Manganese, Iron, and Hydrogen Sulfide in Production Water

If ground water contains an excess of biodegradable organic carbon, such as ethanol, a sequence of microbial processes may occur that can produce undesirable water-quality conditions. The sequence of microbial processes begins with oxygen reduction (removes dissolved oxygen from water) and is followed by denitrification, manganese reduction (adds manganese to the water), ferric-iron reduction (adds iron to the water), sulfate reduction (adds hydrogen sulfide to the water), and finally methanogenesis (adds methane to the water). Denitrification is desirable; however, large concentrations of manganese, iron, and hydrogen sulfide in ground water are not. Therefore, it is important to add enough organic carbon to the aquifer to support denitrification, but not so much organic carbon that other undesirable microbial processes also are induced.

Manganese was detected in all of the water samples, but iron and hydrogen sulfide were not (table 3). The single water sample collected from the pumping well (before alcohol injections began) contained 0.06 mg/L of dissolved manganese. Manganese concentrations in water samples collected from the pumping well after alcohol injections began ranged from 0.06 to 0.23 mg/L, with a median value of

0.10 mg/L. These data indicated that the bioremediation system probably caused a small increase in manganese concentrations in the ground water. The secondary drinking-water standard (SMCL) for manganese in ground water is 0.05 mg/L (Colorado Department of Public Health and Environment, 1995). Therefore, ground water from the site contained manganese concentrations that exceeded the SMCL before and after the bioremediation system was installed. The increase in manganese concentrations caused by the bioremediation system might be lessened by injecting smaller concentrations of ethanol in a larger number of wells.

Concentrations of Bacteria in Production Water

Total coliform and total heterotrophic bacteria were analyzed in water samples collected from the pumping well (table 3). Coliform bacteria are associated with human and animal fecal waste. Heterotrophic bacteria include many groups of bacteria that are naturally present in soil and aquifer sediment. Examples of groups of heterotrophic bacteria are the oxygen-reducing and denitrifying bacteria. The bioremediation system tested in this pilot study relied on the presence of oxygen-reducing and denitrifying bacteria in the aquifer to remove oxygen and nitrate from the ground water.

No coliform bacteria were detected in the three water samples. In contrast, heterotrophic bacteria were detected in water samples collected before (101 colony-forming units per milliliter of water) and after (77 to 610 colony-forming units per milliliter of water) alcohol injections began. These numbers of heterotrophic bacteria are typical for natural ground water (Chapelle, 1993) and did not necessarily indicate an increase in bacterial numbers because of the bioremediation system. However, in the vicinity of the injection wells, the numbers of bacteria in the aquifer did increase. In general, the small numbers of bacteria and small turbidity values in water samples from the pumping well indicated that the presence of bacteria in production water was not a problem during operation of the bioremediation system.

SUMMARY

The bioremediation system was operated from January 9 through September 29, 1997. The system consisted of a central pumping well surrounded by nine injection wells. The pumping rate was about 270 gpm, and about 105 gpm of this production water was injected into the aquifer through the nine wells. A total of 8,160,000 gal of water was pumped from the aquifer, and 4,626,400 gal of water was injected into the aquifer. Specially denatured alcohol (formula SDA-3A, 5-gal methanol in 100-gal ethanol) was added to the injection water and served as the electron donor for denitrification in the aquifer. Injection rates and pressures were affected by biomass buildup in the aquifer after about 3.5 months of alcohol injections. Biomass buildup was controlled by periodic cleaning of the injection wells. However, additional work is needed to determine the optimal frequency of well cleaning and if well cleaning can ensure long-term operation of the injection wells.

Concentrations of dissolved oxygen in the production water were reduced from about 5.6 mg/L to a median value of 3.4 mg/L by the bioremediation system, which represented an oxygen-removal efficiency of about 40 percent. Nitrate concentrations in the production water were reduced from about 24.5 mg/L as nitrogen to a median value of 20.6 mg/L, a nitrate-removal efficiency of about 16 percent. These results indicated that most of the injected alcohol was used by microbes in the aquifer to consume dissolved oxygen. Therefore, the bioremediation system would be more effective in a ground-water system containing less dissolved oxygen. The bioremediation system also would be more effective at a site where the placement of injection wells is not restricted by buildings and utilities, as was the case at the study site. Although the amount of nitrate reduction achieved in the pilot test was relatively small, it would represent a substantial decrease in the nitrate concentrations in water from the water-supply wells operated by the town of Julesburg. An average reduction of 3.9 mg/L in the nitrate concentrations from these wells would have reduced the number of MCL exceedances by about 56 percent.

Turbidity in the production water did not change during operation of the bioremediation system. In addition, ethanol, methanol, dissolved iron, hydrogen sulfide, and total coliform bacteria were not detected in the production water. Concentrations of suspended and dissolved organic carbon and concentrations of

total heterotrophic bacteria did not change appreciably during operation of the bioremediation system.

However, concentrations of dissolved manganese exceeded the SMCL before and after alcohol injections began and increased slightly during operation of the system. The results of the pilot study indicated that the bioremediation system successfully removed some nitrate from ground water without causing significant water-quality problems in the production water.

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SUPPLEMENTAL DATA

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; $\text{MPN}/100\text{ mL}$, most probable number per 100 milliliters; CFU/mL , colony-forming units per milliliter; <, less than; --, no data]

Date	Specific conductance ($\mu\text{S}/\text{cm}$)	pH	Water temperature ($^{\circ}\text{C}$)	Turbidity (NTU)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO_3)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Bromide (mg/L)
Pumping well													
01/23/97	2,460	7.3	13.5	<1	5.6	240	278	59.3	188	32.0	844	107	0.5
02/06/97	--	--	--	--	--	--	--	--	--	--	849	106	1.4
02/19/97	--	--	--	--	--	--	--	--	--	--	850	106	0.7
02/21/97	2,450	7.2	13.6	1	5.6	218	279	59.9	187	35.4	845	104	0.6
02/28/97	2,450	7.2	13.3	3	3.1	296	277	59.4	185	35.2	828	104	0.6
03/05/97	--	--	--	--	--	--	--	--	--	--	817	98	0.6
03/07/97	2,440	7.2	13.8	<1	3.0	302	277	59.5	186	35.3	843	106	0.6
03/12/97	--	--	--	--	--	--	--	--	--	--	771	74	0.4
03/13/97	2,430	7.2	13.4	<1	3.0	326	277	59.6	186	35.4	837	104	0.5
03/18/97	--	--	--	--	--	--	--	--	--	--	789	87	0.4
03/21/97	--	--	--	--	--	--	--	--	--	--	806	94	0.4
03/24/97	2,480	7.3	13.4	1	3.3	304	276	59.3	185	35.2	824	103	0.4
03/25/97	--	--	--	--	--	--	--	--	--	--	833	104	0.5
03/26/97	--	--	--	--	--	--	--	--	--	--	837	105	0.5
03/27/97	--	--	--	--	--	--	--	--	--	--	840	105	0.5
03/28/97	--	--	--	--	--	--	--	--	--	--	837	105	0.5
03/31/97	--	--	--	--	--	--	--	--	--	--	821	99	0.5
04/01/97	--	--	--	--	--	--	--	--	--	--	839	105	0.5
04/03/97	--	--	--	--	--	--	--	--	--	--	840	105	0.5

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; $\text{MPN}/100\text{ mL}$, most probable number per 100 milliliters; CFU/mL , colony-forming units per milliliter; <, less than; --, no data]

Date	Specific conductance ($\mu\text{S}/\text{cm}$)	pH	Water temperature ($^{\circ}\text{C}$)	Turbidity (NTU)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO_3)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Bromide (mg/L)
Pumping well—Continued													
04/04/97	2,490	7.2	13.4	1	3.0	298	272	58.1	181	34.4	844	106	0.5
04/07/97	--	--	--	--	--	--	--	--	--	--	823	101	0.5
04/09/97	--	--	--	--	--	--	--	--	--	--	781	83	0.4
04/10/97	--	--	--	--	--	--	--	--	--	--	832	102	0.5
04/11/97	--	--	--	--	--	--	--	--	--	--	818	99	0.4
04/14/97	--	--	--	--	--	--	--	--	--	--	837	--	0.5
04/15/97	2,480	7.2	13.4	<1	3.1	304	269	57.5	179	34.0	826	102	0.4
04/16/97	--	--	--	--	--	--	--	--	--	--	808	92	0.4
04/17/97	--	--	--	--	--	--	--	--	--	--	810	90	0.4
04/18/97	2,480	7.2	13.4	1	3.1	338	268	57.2	179	33.8	825	103	0.5
04/23/97	2,450	7.3	13.5	<1	3.0	302	267	57.1	178	33.9	829	102	0.6
04/28/97	--	--	--	--	--	--	--	--	--	--	782	85	0.7
04/30/97	2,460	7.3	13.4	<1	3.8	286	270	58.6	187	33.8	832	103	0.5
05/02/97	--	--	--	--	--	--	--	--	--	--	773	77	0.4
05/05/97	--	--	--	--	--	--	--	--	--	--	811	100	0.5
05/08/97	2,410	7.2	13.4	1	3.4	308	270	59.1	187	34.0	828	102	0.5
05/12/97	--	--	--	--	--	--	--	--	--	--	802	96	0.5
05/14/97	--	--	--	--	3.6	--	--	--	--	--	813	101	0.5
05/21/97	--	--	--	--	--	--	--	--	--	--	789	87	0.7

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; $\text{MPN}/100\text{ mL}$, most probable number per 100 milliliters; CFU/mL , colony-forming units per milliliter; $<$, less than; --, no data]

Date	Specific conductance ($\mu\text{S}/\text{cm}$)	pH	Water temperature ($^{\circ}\text{C}$)	Turbidity (NTU)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO_3)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Bromide (mg/L)
Pumping well—Continued													
05/23/97	2,410	7.2	13.5	<1	3.5	300	271	59.6	187	34.1	829	104	0.5
05/27/97	--	--	--	--	--	--	--	--	--	--	779	84	0.4
05/28/97	--	--	--	--	--	--	--	--	--	--	719	62	0.5
05/30/97	--	--	--	--	--	--	--	--	--	--	776	83	0.4
06/02/97	2,410	7.2	13.5	<1	3.7	292	270	59.6	187	34.2	817	102	0.5
06/04/97	--	--	--	--	--	--	--	--	--	--	803	90	0.4
06/11/97	--	--	--	--	--	--	--	--	--	--	829	102	0.5
06/18/97	--	--	--	--	4.3	--	--	--	--	--	824	101	0.5
06/23/97	2,430	7.1	13.8	1	3.9	292	273	59.8	187	34.3	836	102	0.5
06/25/97	--	--	--	--	--	--	--	--	--	--	848	110	0.6
06/27/97	--	--	--	--	--	--	--	--	--	--	836	107	0.5
06/30/97	--	--	--	--	--	--	--	--	--	--	767	77	0.4
07/02/97	2,430	7.1	13.6	<1	3.3	298	273	59.9	188	34.4	844	107	0.6
07/07/97	--	--	--	--	--	--	--	--	--	--	844	108	0.5
07/09/97	2,430	7.1	14.0	<1	3.2	284	273	59.9	188	34.4	834	106	0.5
07/11/97	--	--	--	--	--	--	--	--	--	--	843	108	0.5
07/14/97	--	--	--	--	--	--	--	--	--	--	839	105	0.5
07/18/97	2,420	7.2	13.9	1	2.8	300	271	59.6	187	34.4	843	107	0.5
07/21/97	--	--	--	--	--	--	--	--	--	--	838	105	0.6

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; $\text{MPN}/100\text{ mL}$, most probable number per 100 milliliters; CFU/mL , colony-forming units per milliliter; <, less than; --, no data]

Date	Specific conductivity ($\mu\text{S}/\text{cm}$)	pH	Water temperature ($^{\circ}\text{C}$)	Turbidity (NTU)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO_3)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Bromide (mg/L)
Pumping well—Continued													
07/23/97	--	--	--	--	--	--	--	--	--	--	815	97	0.5
07/25/97	--	--	--	--	--	--	--	--	--	--	777	83	0.4
07/29/97	--	--	--	--	--	--	--	--	--	--	838	104	0.5
07/30/97	2,420	7.2	14.2	<1	3.6	284	263	57.9	181	33.3	846	107	0.5
08/01/97	--	--	--	--	--	--	--	--	--	--	830	102	0.7
08/04/97	--	--	--	--	--	--	--	--	--	--	831	102	0.6
08/06/97	--	--	--	--	--	--	--	--	--	--	831	100	0.5
08/08/97	--	--	--	--	--	--	--	--	--	--	795	88	0.5
08/11/97	--	--	--	--	--	--	--	--	--	--	776	80	0.8
08/13/97	2,420	7.2	14.3	1	3.9	288	269	59.1	185	34.1	837	102	0.6
08/15/97	--	--	--	--	--	--	--	--	--	--	728	68	0.6
08/18/97	--	--	--	--	--	--	--	--	--	--	802	89	0.9
08/20/97	--	--	--	--	--	--	--	--	--	--	834	104	0.9
08/21/97	--	--	--	--	3.6	--	--	--	--	--	837	103	0.7
09/08/97	--	--	--	--	--	--	--	--	--	--	811	87	0.4
09/10/97	--	--	--	--	--	--	--	--	--	--	849	100	0.4
09/12/97	--	--	--	--	--	--	--	--	--	--	849	101	0.5
9/15/97	2,430	7.1	14.6	<1	3.7	306	270	59.3	185	33.8	853	102	0.6
9/17/97	--	--	--	--	--	--	--	--	--	--	860	105	0.5

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S/cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; MPN/100 mL, most probable number per 100 milliliters; CFU/mL, colony-forming units per milliliter; <, less than; --, no data]

Date	Specific conductivity ($\mu\text{S/cm}$)	pH	Water temperature ($^{\circ}\text{C}$)	Turbidity (NTU)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO_3)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Bromide (mg/L)
Pumping well—Continued													
9/19/97	--	--	--	--	--	--	--	--	--	--	816	90	0.4
09/22/97	2,440	7.2	14.3	<1	3.7	321	273	60.2	186	34.4	854	102	0.4
09/24/97	--	--	--	--	--	--	--	--	--	--	831	96	0.4
09/26/97	--	--	--	--	--	--	--	--	--	--	839	102	0.4
09/29/97	2,450	7.1	14.7	1	2.6	296	--	--	--	--	848	102	0.4
Well MW-1													
09/29/97	--	--	--	--	--	--	--	--	--	--	840	101	0.5
Well MW-2													
01/23/97	--	--	--	--	6.7	--	--	--	--	--	--	--	--
03/28/97	--	--	--	--	--	--	--	--	--	--	--	--	--
04/18/97	--	--	--	--	--	--	--	--	--	--	783	107	0.6
05/08/97	--	--	--	--	--	--	--	--	--	--	796	108	0.6
06/02/97	--	--	--	--	--	--	--	--	--	--	796	106	0.6
06/18/97	--	--	--	--	--	--	--	--	--	--	763	101	0.6
07/18/97	--	--	--	--	--	--	--	--	--	--	812	109	0.5
08/13/97	--	--	--	--	--	--	--	--	--	--	804	103	0.7
09/22/97	--	--	--	--	--	--	--	--	--	--	796	102	0.6
09/29/97	--	--	--	--	6.1	--	--	--	--	--	789	103	0.6

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S/cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; MPN/100 mL, most probable number per 100 milliliters; CFU/mL, colony-forming units per milliliter; <, less than; --, no data]

Date	Nitrite (mg/L as N)	Nitrate (mg/L as N)	Ammo- nium (mg/L as N)	Iron (mg/L)	Hydro- gen sulfide (mg/L)	Manga- nese (mg/L)	Methane (mg/L)	Ethanol (mg/L)		Methanol (mg/L)		Sus- pended organic carbon (mg/L)	Dissolved organic carbon (mg/L)	Total coliforms (MPN/100 mL)	Total hetero- trophs (CFU/mL)
								Produc- tion water	Injec- tion water	Produc- tion water	Injec- tion water				
Pumping well															
01/23/97	<0.1	24.8	<0.1	<0.05	<0.01	0.06	<0.02	<2	<2	<5	<5	0.1	4.3	<2	101
02/06/97	<0.1	24.3	--	--	--	--	--	--	--	--	--	--	--	--	--
02/19/97	<0.1	24.5	--	--	--	--	--	<2	5.6	<5	<5	--	--	--	--
02/21/97	<0.1	24.3	<0.1	<0.05	<0.01	0.12	<0.02	<2	5.4	<5	<5	--	--	--	--
02/28/97	0.4	23.2	<0.1	<0.05	<0.01	0.11	<0.02	<2	6.6	<5	<5	--	--	--	--
03/05/97	0.3	21.7	--	--	--	--	--	--	--	--	--	--	--	--	--
03/07/97	0.3	23.2	<0.1	<0.05	<0.01	0.10	<0.02	<2	10.4	<5	<5	--	--	--	--
03/12/97	0.3	16.2	--	--	--	--	--	--	--	--	--	--	--	--	--
03/13/97	0.5	22.8	<0.1	<0.05	<0.01	0.09	<0.02	<2	6.3	<5	<5	0.1	4.4	<2	610
03/18/97	0.3	18.8	--	--	--	--	--	--	--	--	--	--	--	--	--
03/21/97	0.4	20.6	--	--	--	--	--	--	--	--	--	--	--	--	--
03/24/97	0.4	22.6	<0.1	<0.05	<0.01	0.07	<0.02	<2	20.0	<5	<5	--	--	--	--
03/25/97	0.4	22.7	--	--	--	--	--	--	--	--	--	--	--	--	--
03/26/97	0.5	22.2	--	--	--	--	--	--	--	--	--	--	--	--	--
03/27/97	0.5	22.2	--	--	--	--	--	--	--	--	--	--	--	--	--
03/28/97	0.6	22.0	--	--	--	--	--	--	--	--	--	--	--	--	--
03/31/97	0.6	20.7	--	--	--	--	--	--	--	--	--	--	--	--	--
04/01/97	0.6	21.6	--	--	--	--	--	--	--	--	--	--	--	--	--

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; MPN/100 mL, most probable number per 100 milliliters; CFU/mL, colony-forming units per milliliter; $<$, less than; --, no data]

Date	Nitrite (mg/L as N)	Nitrate (mg/L as N)	Ammonium (mg/L as N)	Iron (mg/L)	Hydro- gen sulfide (mg/L)	Manga- nese (mg/L)	Ethanol (mg/L)		Methanol (mg/L)		Sus- pended organic carbon (mg/L)	Dissolved organic carbon (mg/L)	Total coliforms (MPN/100 mL)	Total hetero- trophs (CFU/mL)		
							Methane (mg/L)	Product- ion water		Produc- tion water					Injec- tion water	
								Produc- tion water	Injec- tion water	Produc- tion water						Injec- tion water
Pumping well—Continued																
04/03/97	0.6	21.5	--	--	--	--	--	--	--	--	--	--	--	--		
04/04/97	0.6	21.4	<0.1	<0.05	<0.01	0.08	<2	26.5	<5	<5	--	--	--	--		
04/07/97	0.4	20.5	--	--	--	--	--	--	--	--	--	--	--	--		
04/09/97	0.3	16.7	--	--	--	--	--	--	--	--	--	--	--	--		
04/10/97	0.5	20.7	--	--	--	--	--	--	--	--	--	--	--	--		
04/11/97	0.3	20.0	--	--	--	--	--	--	--	--	--	--	--	--		
04/14/97	0.4	21.8	--	--	--	--	--	--	--	--	--	--	--	--		
04/15/97	0.4	21.1	<0.1	<0.05	<0.01	0.07	<2	16.1	<5	<5	0.1	4.5	<2	260		
04/16/97	0.4	18.6	--	--	--	--	--	--	--	--	--	--	--	--		
04/17/97	0.5	18.1	--	--	--	--	--	--	--	--	--	--	--	--		
04/18/97	0.4	20.5	<0.1	<0.05	<0.01	0.08	<2	36.2	<5	<5	--	--	--	--		
04/23/97	0.2	21.0	<0.1	<0.05	<0.01	0.09	<2	--	<5	<5	--	--	--	--		
04/28/97	<0.1	18.3	--	--	--	--	--	--	--	--	--	--	--	--		
04/30/97	<0.1	22.1	<0.1	<0.05	--	0.10	<2	24.3	<5	<5	--	--	--	--		
05/02/97	<0.1	15.8	--	--	--	--	--	--	--	--	--	--	--	--		
05/05/97	<0.1	20.6	--	--	--	--	--	--	--	--	--	--	--	--		
05/08/97	<0.1	21.6	<0.1	<0.05	--	0.07	<2	38.4	<5	<5	--	--	--	--		
05/12/97	<0.1	19.6	--	--	--	--	--	--	--	--	--	--	--	--		

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; $\text{MPN}/100\text{ mL}$, most probable number per 100 milliliters; CFU/mL , colony-forming units per milliliter; $<$, less than; --, no data]

Date	Nitrite (mg/L as N)	Nitrate (mg/L as N)	Ammo- nium (mg/L as N)	Iron (mg/L)	Hydro- gen sulfide (mg/L)	Manga- nese (mg/L)	Ethanol (mg/L)		Methanol (mg/L)		Sus- pended organic carbon (mg/L)	Dissolved organic carbon (mg/L)	Total coliforms (MPN/100 mL)	Total hetero- trophs (CFU/mL)		
							Methane (mg/L)	Product- ion water		Product- ion water					Injec- tion water	
								Produc- tion water	Injec- tion water	Produc- tion water						Injec- tion water
Pumping well—Continued																
05/14/97	<0.1	20.4	--	--	--	--	--	--	--	--	--	--	--	--		
05/21/97	0.6	17.4	--	--	--	--	--	--	--	--	--	--	--	--		
05/23/97	<0.1	21.0	<0.1	<0.05	--	0.11	<2	25.8	<5	<5	--	--	--	--		
05/27/97	<0.1	16.8	--	--	--	--	--	--	--	--	--	--	--	--		
05/28/97	<0.1	12.5	--	--	--	--	--	--	--	--	--	--	--	--		
05/30/97	<0.1	16.7	--	--	--	--	--	--	--	--	--	--	--	--		
06/02/97	<0.1	20.7	<0.1	<0.05	--	0.08	<2	28.4	<5	<5	--	--	--	--		
06/04/97	<0.1	17.8	--	--	--	--	--	--	--	--	--	--	--	--		
06/11/97	<0.1	20.9	--	--	--	--	--	--	--	--	--	--	--	--		
06/18/97	<0.1	21.0	--	--	--	--	<2	52.8	<5	<5	--	--	--	--		
06/23/97	<0.1	21.4	<0.1	<0.05	--	0.15	<2	47.6	<5	<5	--	--	--	--		
06/25/97	<0.1	22.0	--	--	--	--	--	--	--	--	--	--	--	--		
06/27/97	<0.1	21.1	--	--	--	--	--	--	--	--	--	--	--	--		
06/30/97	<0.1	15.0	--	--	--	--	--	--	--	--	--	--	--	--		
07/02/97	<0.1	21.0	<0.1	<0.05	--	0.20	<2	36.4	<5	<5	--	--	--	--		
07/07/97	<0.1	20.6	--	--	--	--	--	--	--	--	--	--	--	--		
07/09/97	<0.1	20.2	<0.1	<0.05	--	0.23	<2	15.9	<5	<5	--	--	--	--		
07/11/97	<0.1	19.4	--	--	--	--	--	--	--	--	--	--	--	--		

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; MPN/100 mL, most probable number per 100 milliliters; CFU/mL, colony-forming units per milliliter; <, less than; --, no data]

Date	Nitrite (mg/L as N)	Nitrate (mg/L as N)	Ammo- nium (mg/L as N)	Iron (mg/L)	Hydro- gen sulfide (mg/L)	Manga- nese (mg/L)	Ethanol (mg/L)		Methanol (mg/L)		Sus- pended organic carbon (mg/L)	Dissolved organic carbon (mg/L)	Total coliforms (MPN/100 mL)	Total hetero- trophs (CFU/mL)
							Produc- tion water	Injec- tion water	Produc- tion water	Injec- tion water				
Pumping well—Continued														
07/14/97	<0.1	18.9	--	--	--	--	--	--	--	--	--	--	--	--
07/18/97	<0.1	19.2	<0.1	<0.05	--	0.10	<2	27.9	<5	<5	<0.2	4.2	<2	77
07/21/97	<0.1	18.8	--	--	--	--	--	--	--	--	--	--	--	--
07/23/97	<0.1	17.0	--	--	--	--	--	--	--	--	--	--	--	--
07/25/97	<0.1	14.4	--	--	--	--	--	--	--	--	--	--	--	--
07/29/97	<0.1	18.9	--	--	--	--	--	--	--	--	--	--	--	--
07/30/97	<0.1	20.3	<0.1	<0.05	--	0.11	<2	12.5	<5	<5	--	--	--	--
08/01/97	<0.1	20.9	--	--	--	--	--	--	--	--	--	--	--	--
08/04/97	<0.1	20.8	--	--	--	--	--	--	--	--	--	--	--	--
08/06/97	<0.1	20.3	--	--	--	--	--	--	--	--	--	--	--	--
08/08/97	<0.1	17.8	--	--	--	--	--	--	--	--	--	--	--	--
08/11/97	<0.1	16.6	--	--	--	--	--	--	--	--	--	--	--	--
08/13/97	<0.1	21.2	<0.1	<0.05	--	0.14	<2	34.6	<5	<5	--	--	--	--
08/15/97	<0.1	13.9	--	--	--	--	--	--	--	--	--	--	--	--
08/18/97	<0.1	18.0	--	--	--	--	--	--	--	--	--	--	--	--
08/20/97	<0.1	20.8	--	--	--	--	--	--	--	--	--	--	--	--
08/21/97	<0.1	20.2	--	<0.05	--	--	<2	40.7	<5	<5	--	--	--	--
09/08/97	<0.1	19.1	--	--	--	--	--	--	--	--	--	--	--	--

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; $\text{MPN}/100\text{ mL}$, most probable number per 100 milliliters; CFU/mL , colony-forming units per milliliter; $<$, less than; --, no data]

Date	Nitrite (mg/L as N)	Nitrate (mg/L as N)	Ammo- nium (mg/L as N)	Iron (mg/L)	Hydro- gen sulfide (mg/L)	Manga- nese (mg/L)	Ethanol (mg/L)		Methanol (mg/L)		Sus- pended organic carbon (mg/L)	Dissolved organic carbon (mg/L)	Total coliforms (MPN/100 mL)	Total hetero- trophs (CFU/mL)	
							Methane (mg/L)	Injec- tion water		Produc- tion water					Injec- tion water
								Produc- tion water	Injec- tion water						
Pumping well—Continued															
09/10/97	<0.1	21.7	--	--	--	--	--	--	--	--	--	--	--	--	
09/12/97	<0.1	21.5	--	--	--	--	--	--	--	--	--	--	--	--	
09/15/97	<0.1	21.9	<0.1	<0.05	--	0.06	<2	41.4	<5	<5	--	--	--	--	
09/17/97	<0.1	22.1	--	--	--	--	--	--	--	--	--	--	--	--	
09/19/97	<0.1	19.0	--	--	--	--	--	--	--	--	--	--	--	--	
09/22/97	<0.1	21.7	<0.1	<0.05	--	0.11	<2	40.4	<5	<5	--	--	--	--	
09/24/97	<0.1	20.2	--	--	--	--	--	--	--	--	--	--	--	--	
09/26/97	<0.1	21.4	--	--	--	--	--	--	--	--	--	--	--	--	
09/29/97	<0.1	20.6	--	<0.05	--	0.11	--	--	--	--	--	--	--	--	
Well MW-1															
09/29/97	<0.1	15.8	--	--	--	--	--	--	--	--	--	--	--	--	
Well MW-2															
01/23/97	<0.1	25.0	--	--	--	--	--	--	--	--	--	--	--	--	
03/28/97	<0.1	26.4	--	--	--	--	--	--	--	--	--	--	--	--	
04/18/97	<0.1	27.9	--	--	--	--	--	--	--	--	--	--	--	--	
05/08/97	<0.1	26.7	--	--	--	--	--	--	--	--	--	--	--	--	
06/02/97	<0.1	25.2	--	--	--	--	--	--	--	--	--	--	--	--	
06/18/97	<0.1	23.1	--	--	--	--	--	--	--	--	--	--	--	--	

Table 3. Physical properties, concentrations of selected inorganic and organic constituents, and concentrations of bacteria in water from the pumping well, well MW-1, and well MW-2—Continued

[Alcohol injections began on February 19, 1997. $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $^{\circ}\text{C}$, degrees Celsius; NTU, nephelometric turbidity units; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; N, nitrogen; $\text{MPN}/100\text{ mL}$, most probable number per 100 milliliters; CFU/mL , colony-forming units per milliliter; <, less than; --, no data]

Date	Nitrite (mg/L as N)	Nitrate (mg/L as N)	Ammo- nium (mg/L as N)	Iron (mg/L)	Hydro- gen sulfide (mg/L)	Manga- nese (mg/L)	Ethanol (mg/L)		Methanol (mg/L)		Sus- pended organic carbon (mg/L)	Dissolved organic carbon (mg/L)	Total coliforms (MPN/100 mL)	Total hetero- trophs (CFU/mL)
							Produc- tion water	Injec- tion water	Produc- tion water	Injec- tion water				
Well MW-2—Continued														
07/18/97	<0.1	23.4	--	--	--	--	--	--	--	--	--	--	--	--
08/13/97	<0.1	23.0	--	--	--	--	--	--	--	--	--	--	--	--
09/22/97	<0.1	24.0	--	--	--	--	--	--	--	--	--	--	--	--
09/29/97	<0.1	23.2	--	--	--	--	--	--	--	--	--	--	--	--