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FIELD DEMONSTRATION OF IN SITU PERCHLORATE BIOREMEDIATION AT BUILDING 1419 NSWC INDIAN HEAD MD

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Field Demonstration of In Situ Perchlorate Bioremediation at Building 1419

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Shaw Environmental, Inc.

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FOREWORD

Biological treatment of perchlorate in the environment represents a promising technology for remediation of ground and surface water. Naturally occurring microbial strains with the ability to degrade perchlorate by using the molecule as a terminal electron acceptor have been identified in site samples from the Indian Head Division, Naval Surface Warfare Center at Indian Head, MD. To build upon successful laboratory studies, a field demonstration of in situ bioremediation of perchlorate was conducted in 2002 at Indian Head's Building 1419, otherwise known as the Hog-out Facility. The publication includes the field trial results of buffering the aquifer pH to make it suitable for microbial perchlorate degradation, methods for addition of an electron donor, such as acetate, and the perchlorate biodegradation data over a 6-month period.

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EXECUTIVE SUMMARY

As part of a research project (CU-1163) funded by the Strategic Environmental Research and Development Program, laboratory studies were conducted using site samples from the Indian Head Division, Naval Surface Warfare Center (IHDIV) in Indian Head, MD. The site studies revealed the following:

- Naturally occurring perchlorate-degrading bacteria are present in the groundwater aquifer underlying IHDIV.
- These organisms can be stimulated to degrade perchlorate from more than 50 mg/L to below detection using lactate as a food source (electron donor).
- The pH of the aquifer must be buffered to achieve optimal perchlorate biodegradation.

Based on the above, a field demonstration of in situ perchlorate treatment was performed at IHDIV on a shallow, narrow plume of perchlorate-contaminated groundwater behind IHDIV Building 1419, known as the Hog-out Facility. Analysis of samples from this site showed the perchlorate levels ranged from 8 to 430 mg/L with an average of approximately 170 mg/L, and nitrate levels were at 4 to approximately 50 mg/L. The groundwater pH measured in several locations was generally below pH 5.0 with some values as low as pH 4.2.

A pilot system employing a recirculation cell design was engineered based on site geochemical and hydrogeologic data. Two field plots, a test plot and a control plot, were installed; each consisted of two extraction wells, two injection wells, and nine groundwater monitoring wells. In the test plot, groundwater was extracted from the site, amended with electron donor (lactate) and buffer (carbonate/bicarbonate mixture), then re-injected into the aquifer. Groundwater was extracted and re-injected without substrate or buffer amendment in the control plot.

During the first 15 weeks of the study, approximately 20,000 gallons of groundwater was recirculated through each plot. The injected buffer elevated the pH to greater than 5.9 in all test plot wells, and perchlorate was steadily degraded during the demonstration.

Over the 20-week period, the perchlorate levels were reduced by more than 95% in eight of nine monitoring wells in the test plot, with five wells reaching less than 1 mg/L and two wells reaching below 5 µg/L. Nitrate levels in all wells were reduced to less than 1 mg/L, and seven of nine wells showed non-detectable levels within 7 weeks.

Conversely, there was no significant change in pH or reduction of either perchlorate or nitrate within the control plot.

The data from this demonstration show in situ biostimulation using lactate and buffer addition was a successful remediation option for treating high levels of perchlorate in the shallow aquifers. The results suggest that in situ perchlorate bioremediation would be a viable approach for treatment of perchlorate in aquifers containing localized, high concentrations of the oxidant.

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INTRODUCTION

Background

Ammonium perchlorate (NH_4ClO_4) has been used since the 1940s in the United States as an oxidizer in solid propellants and explosives. Discharges during the manufacture of this compound and from the demilitarization of outdated solid fuels in military missiles and rockets have resulted in substantial perchlorate contamination in groundwater in several states, including California, Texas, Utah, and Nevada (Urbansky, 1998; Damian and Pontius, 1999; Betts, 2000). Because a sensitive detection method for perchlorate was not available until 1997 (CDHS, 1997), the total scope of perchlorate contamination in the United States is not yet known. However, it is currently estimated that the drinking water of more than 15 million people may be impacted (Wu et al., 2001). According to data compiled by the California Department of Health Services (CDHS), perchlorate has been detected in 80 of 912 public water supplies tested in the state, and 292 of 5,205 private drinking water sources sampled contained measurable levels of the pollutant (CDHS, 2003). Based on current data, California has established a provisional action level of 4 μg/L for perchlorate in drinking water. Several other states, including Nevada, Maryland, Massachusetts, and Texas have also instituted advisory levels for the oxidant, and it is expected that the Environmental Protection Agency (EPA) will establish a reference dose for the compound in the near future.

Standard water treatment technologies, such as sedimentation, air-stripping, carbon adsorption, and advanced oxidation, are generally not effective at removing perchlorate from water because the compound is nonreactive and nonvolatile, its salts are highly soluble, and it cannot be reduced by common reducing agents (Urbansky, 1998; Logan, 1998; USEPA, 2001). Unlike abiotic approaches, however, biological treatment represents a promising technology for the remediation of ground and surface water. In the past few years, a wide variety of microbial strains have been isolated with the ability to degrade perchlorate by using the molecule as a terminal electron acceptor (Achenbach et al., 2001; Coates et al., 1999; Rikken et al., 1996; Logan, 1998). The enzymatic pathways involved in perchlorate reduction have yet to be fully elucidated. However, it appears that a perchlorate reductase enzyme catalyzes an initial two-step reduction of perchlorate (ClO_4^-) to chlorate (ClO_3^-) and then chlorite (ClO_2^-) (van Ginkel et al., 1996; Kengen et al., 1999). The chlorite is further reduced by chlorite dismutase to chloride (Cl^-) and oxygen (O_2) (Coates et al., 1999). Thus, microbial degradation of perchlorate yields two innocuous products, chloride and oxygen.

Ex situ biological treatment systems have been successfully developed to treat perchlorate-contaminated groundwater (Greene and Pitre, 2000; Hatzinger et al., 2000, 2002; Logan, 2001; Miller and Logan, 2000). Electron donors, such as ethanol and acetate, are supplied to perchlorate-reducing bacteria in these reactors to promote biological reduction of the propellant. The success of ex situ biological treatment of perchlorate suggests that in situ treatment through

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electron donor addition may also be possible. Research data suggest that perchlorate reducing bacteria are naturally occurring in various environments, including soils, sludge, and raw wastewater, as well as in groundwater aquifers (Coates et al., 1999; Wu et al., 2001; Hatzinger et al., 2002; Hatzinger, 2002). The key to utilizing perchlorate-reducing bacteria for in situ remediation is understanding the conditions that limit their activity in subsurface environments and then devising effective technologies to overcome these limitations and subsequently stimulate perchlorate degradation.

Until recently, little research had been conducted to develop an in situ technology for bioremediation of perchlorate in groundwater. However, in 2000, Shaw Environmental, Inc. and the Indian Head Division, Naval Surface Warfare Center (IHDIV) were awarded a Strategic Environmental Research and Development Program (SERDP) project to evaluate fundamental questions concerning the potential for in situ perchlorate treatment. The results from this project revealed the following:

1. Perchlorate-degrading bacteria are widely distributed in groundwater aquifers.

2. These organisms can be stimulated to biodegrade perchlorate under anoxic conditions using a variety of different electron donors, although the most effective donors vary on a site-specific basis.

3. Perchlorate biodegradation is inhibited in aquifers where the pH is naturally below approximately 5.5.

The detailed report from this project (CU-1163) is available from the SERDP Office, 901 N. Stuart St., Suite 303, Arlington, VA 22203. Based on the successful SERDP study, the Naval Ordnance Safety and Security Activity funded a field-pilot demonstration to evaluate the potential for in situ perchlorate treatment in a shallow aquifer behind IHDIV Building 1419, the Hog-out Facility. This document details the results of this demonstration.

SUMMARY OF LABORATORY RESULTS

As part of the SERDP-funded study (CU-1163) and as a prelude to performing the field-pilot demonstration, samples were collected from the area immediately behind Building 1419, and a series of microcosm studies were conducted to determine whether perchlorate-reducing bacteria were present at the site and which electron donors were most effective at stimulating them to degrade perchlorate in the underlying aquifer. Microcosms were prepared by mixing sediment and groundwater from the Building 1419 site under anoxic conditions. The starting perchlorate concentration in the mixed groundwater and sediment was approximately 45 mg/L. Serum bottles were amended with the following electron donors at 200 mg/L: methanol, ethanol, acetate, benzoate, lactate, sucrose, molasses, or a mixture of ethanol and yeast extract (100 mg/L each). Bottles were also prepared with hydrogen gas or propane in the headspace as gaseous substrates or with the perchlorate-degrading enrichment culture FBR2 (isolated from a fluidized bed bioreactor treating perchlorate in California). Bottles were incubated at 15 °C and samples were collected at 11, 20, 36, and 71 days of incubation for perchlorate analysis by EPA Method 314.0.

There was no appreciable loss of perchlorate during the 71-day incubation period in any of the microcosms prepared from the hog-out site samples (Table I). Ten different electron donors did not stimulate perchlorate biodegradation in the samples. These results differ from those with Building 1190 samples collected from IHDIV, where several electron donors quickly stimulated perchlorate degradation (data not shown). One possibility for this absence of biological perchlorate reduction was the absence of a native microbial population capable of carrying out this process at the Building 1419 site. However, microbial analyses conducted in the laboratory of Dr. John Coates at Southern Illinois University (Hatzinger, 2002) revealed that such bacteria are present in samples from the aquifer as well as at other locations on the IHDIV facility (Table II). The observation that bioaugmentation with an exogenous perchlorate degrading culture (FBR2) also did not reduce perchlorate levels confirmed that the absence of such organisms was not the most likely cause of the persistence of perchlorate. Rather, a geochemical factor or environmental co-contaminant was hypothesized to be the factor preventing perchlorate biodegradation.

The most apparent difference between the hog-out samples and those from Building 1190 was the comparatively low pH of the microcosms from hog-out compared to those from the second site (pH of 4.3 versus 7.0). An experiment was subsequently conducted to assess the influence of pH on perchlorate degradation in the hog-out samples. A titration curve using samples from the Building 1419 area showed that approximately 240 mg/L of carbonate was required to increase the pH of the slurry from approximately 4.3 to 7.0 (Figure 1). To evaluate the influence of pH on perchlorate degradation, groundwater and sediment were added to 160-mL bottles at a ratio of approximately 3:1 (100 mL groundwater and 30 g sediment), and acetate was added as the electron donor at 75 mg/L. In eight of the fourteen bottles prepared, the pH was increased from 4.3 to approximately 7.0 by adding sodium carbonate. The pH of the

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remaining six microcosms was not adjusted (i.e., pH 4.3). Three of the bottles at pH 4.3 and three at pH 7.0 were inoculated with the perchlorate-degrading culture FBR2, and three bottles at each pH remained uninoculated. Two bottles were treated with formaldehyde to inhibit all microbial activity. The bottles were incubated on a rotary shaker at 15 °C and periodically sampled for perchlorate analysis.

Table I. Perchlorate Degradation in Aquifer Microcosms from the Building 1419 Site

Treatment	Perchlorate concentration[a] (mg/L)				
	Day 0	Day 11	Day 20	Day 36	Day 71
Electron donors					
Killed control	42 ± 4	41 ± 1	44 ± 2	36 ± 4	37 ± 2
No substrate	42 ± 4	37 ± 1	36 ± 4	38 ± 1	39 ± 5
Nutrients only	42 ± 4	38 ± 2	41 ± 4	42 ± 1	34 ± 1
Hydrogen	42 ± 4	38 ± 2	40 ± 4	32 ± 5	35 ± 2
Propane	42 ± 4	38 ± 1	39 ± 2	34 ± 2	37 ± 2
Ethanol	42 ± 4	39 ± 2	41 ± 2	36 ± 4	36 ± 3
Methanol	42 ± 4	41 ± 2	41 ± 1	32 ± 2	34 ± 2
Acetate	42 ± 4	39 ± 1	42 ± 2	33 ± 1	37 ± 1
Benzoate	42 ± 4	40 ± 1	43 ± 0	32 ± 1	38 ± 1
Lactate	42 ± 4	38 ± 3	43 ± 3	33 ± 2	37 ± 2
Molasses	42 ± 4	43 ± 2	43 ± 2	28 ± 1	36 ± 2
Sucrose	42 ± 4	44 ± 1	45 ± 0	31 ± 0	35 ± 0
Yeast extract/ethanol	42 ± 4	43 ± 2	44 ± 2	35 ± 3	37 ± 2
Bioaugmentation					
Inoculum FBR2+ ethanol	42 ± 4	41 ± 1	44 ± 3	36 ± 2	36 ± 2

[a]Values are the mean ± standard deviation from triplicate microcosms.

Table II. Enumeration of Perchlorate Reducing Bacteria from Site Samples at IHDIV

Sample[a]	Mean practical No.	CKB type	RCB type	PS type
Pristine soil	$7.5 \pm 3.4 \times 10^3$	Negative	Negative	Negative
Bldg. 1419 soil	$9.3 \pm 4.2 \times 10^4$	Negative	Positive	Negative
Bldg. 1419 water	$4.3 \pm 2.1 \times 10^1$	Negative	Positive	Positive
Bldg. 1170 soil	$9.3 \pm 4.2 \times 10^4$	Positive	Positive	Negative
Bldg. 1170 stream	$2.4 \pm 1.7 \times 10^3$	Negative	Negative	Negative
Bldg. 1170 water	$4.3 \pm 2.1 \times 10^5$	Negative	Positive	Positive
Bldg. 760 soil (ditch)	$1.5 + 0.6 \times 10^7$	Positive	Positive	Negative

[a]Data courtesy of Dr. John Coates, currently at UC Berkeley.

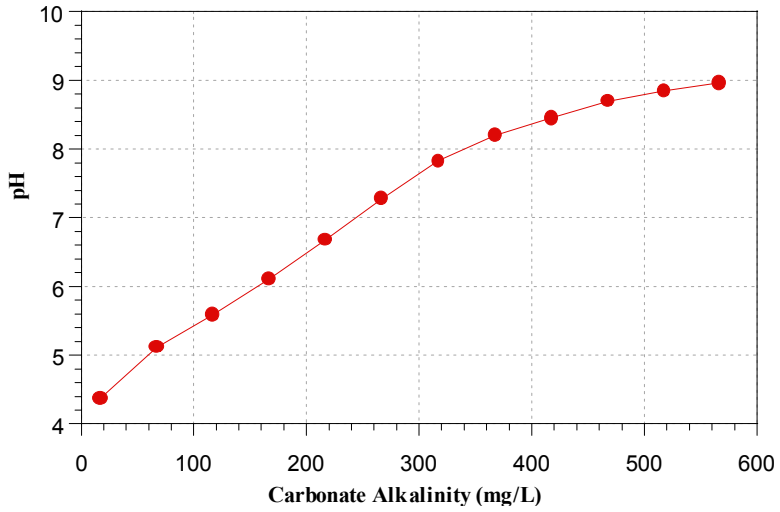

Figure 1. Carbonate Titration Curve for Sediment Slurries from the Building 1419 Site

The perchlorate levels in the samples at pH 4.3 did not decline appreciably during the study, regardless of whether the samples were bioaugmented (Figure 2). Conversely, the samples in which the pH was increased to 7.0 all showed perchlorate biodegradation. Perchlorate levels in samples receiving *Dechlorospirillum* sp. FBR2 declined from 43 to 9 mg/L from day 7 to day 16, and then to 0.16 mg/L by day 28. The perchlorate concentrations in samples that were brought to pH 7.0 but not augmented with the culture declined more slowly, but perchlorate was below detection by day 28 of the experiment. Thus, the data suggest that low pH was inhibiting perchlorate degradation in the hog-out site samples. It is interesting that indigenous perchlorate-degrading microorganisms could be stimulated to degrade the anion at a pH of 7.0 but not at a pH of 4.3. These bacteria are obviously able to survive at the low pH, which occurs naturally at this site, yet appear not to degrade perchlorate at this pH. The results suggest that (1) there may be a pH below which perchlorate biodegradation is physiologically inhibited; or (2) some other geochemical factor (e.g., heavy metal toxicity or trace metal unavailability) prevents perchlorate biodegradation at low pH.

Additional laboratory studies were conducted just prior to commencing system installation at the IHDIV site to confirm previous SERDP studies. These experiments were performed to

(1) Confirm that perchlorate degradation did not occur in unbuffered samples

(2) Determine if any electron donors other than acetate were effective for stimulating perchlorate reduction in buffered samples

(3) Quantify the expected lag period prior to the onset of perchlorate biodegradation after electron donor addition

(4) Assess whether nutrient addition would increase the rate of perchlorate reduction.

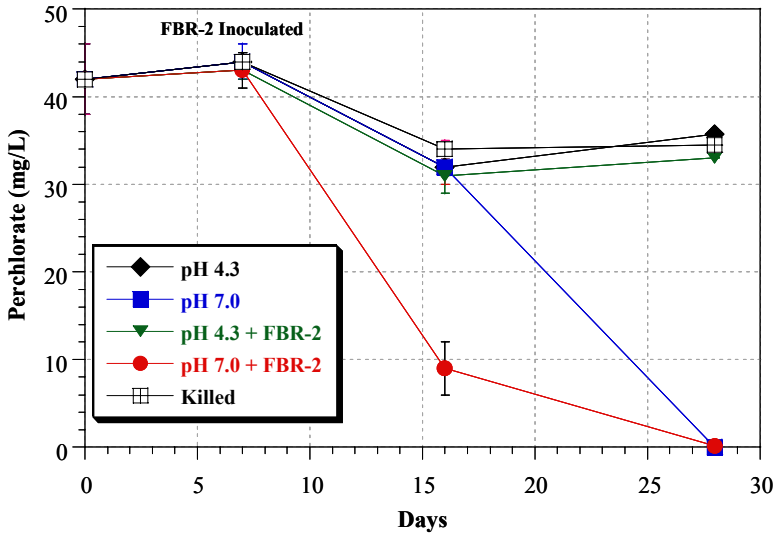

Figure 2. Influence of pH on Perchlorate Degradation in Aquifer Microcosms from the Building 1419 Site

Aquifer solids and groundwater were collected from the test plot area in January 2002 during the initial site assessment (see the "Site Characterization" section). Sediments were obtained from several points behind Building 1419 using a Geoprobe rig. The levels of perchlorate in groundwater samples from each Geoprobe location were determined, and, based on these results as well as the physical conditions at the site (presence of utilities, buildings, etc.), a general test plot area was designated. To conduct laboratory studies, groundwater collected from three different Geoprobe points within the test plot area (GP-1, GP-11, GP-13) was mixed in a large, sterile glass container. Sediments from two of these points (GP-1 and GP-11) were also combined and thoroughly homogenized. The sediments from GP-1 were obtained from 13 to 20 ft below surface, and those from GP-11 were obtained from 11 to 16 ft below surface. Samples from two or three Geoprobe locations were combined to obtain the most representative groundwater and sediment conditions within the test plot area.

Microcosms were prepared in sterile, 160-mL serum bottles. Groundwater and sediment were added to each 160-mL bottle at a ratio of 3:1 (75 mL groundwater and 25 g sediment). One group of bottles was amended with 14 mg of carbonate to bring the slurry pH to approximately 7.3. The other set of bottles received no buffer and remained at a pH of 4.5. Acetate, ethanol, lactate, or hydrogen gas was added to four bottles, two at each pH (i.e., duplicate bottles at site pH and duplicates adjusted to pH 7.3). The liquid electron donors (ethanol, acetate, lactate) were added at a concentration of 250 mg/L, and hydrogen (a gaseous donor) was added to the bottle headspace in a 5-mL volume. In addition, two microcosm bottles at each pH received no electron donor and two adjusted to pH 7.3 received 1% formaldehyde to inhibit all microbial activity (killed controls). The killed samples also received acetate as an electron donor. All samples were prepared in a Coy Environmental Chamber with a nitrogen headspace. The bottles were incubated on a rotary shaker at 15 °C. At various times of incubation, an 8-mL subsample of groundwater was removed from each bottle. The water was then passed through a 0.22-µm syringe filter to remove bacteria and sediment fines and placed at 4 °C until analysis. The

samples were analyzed for perchlorate by EPA Method 314.0 and for nitrate and sulfate by EPA 300.0 series methods.

The initial perchlorate levels in the microcosms at day 0 averaged 116 mg/L, and the starting nitrate concentration was 27.7 mg/L. The level of perchlorate in the microcosms increased from 116 mg/L at day 0 (immediately after slurry preparation) to approximately 170 mg/L at day 14. This increase was consistent among samples and appears not to reflect an analytical error or inconsistency. Therefore, it is likely that this increase reflects perchlorate desorbing from the site sediments into solution. There was no degradation of perchlorate or nitrate in any of the microcosms that remained at pH 4.5, irrespective of the type of electron donor added (data not shown). This finding confirms results from previous studies conducted at Shaw Environmental with samples from IHDIV and the Longhorn Army Ammunition Plant which suggest that low pH (< 5.7) is inhibitory to biological perchlorate reduction. The data also suggest that the low pH is inhibitory to biological nitrate reduction at the hog-out site.

In the samples adjusted to pH 7.3, nitrate was biodegraded to below detection (< 2 mg/L) within 22 days in samples amended with ethanol, acetate, lactate, or hydrogen gas (Figure 3). Nitrate biodegradation was not observed in samples that did not receive an electron donor or in killed control samples. Biodegradation of perchlorate was apparent in pH-adjusted microcosms amended with lactate (Figure 4). Perchlorate concentrations declined from a high of 181 mg/L at day 14 to less than 14 mg/L by day 61 (the last sample collected) in the microcosms receiving lactate. The pH-adjusted microcosms receiving acetate, ethanol, and hydrogen gas did not show appreciable perchlorate reduction during the course of the study. Perchlorate levels also did not decline in microcosms without added electron donor or in killed controls.

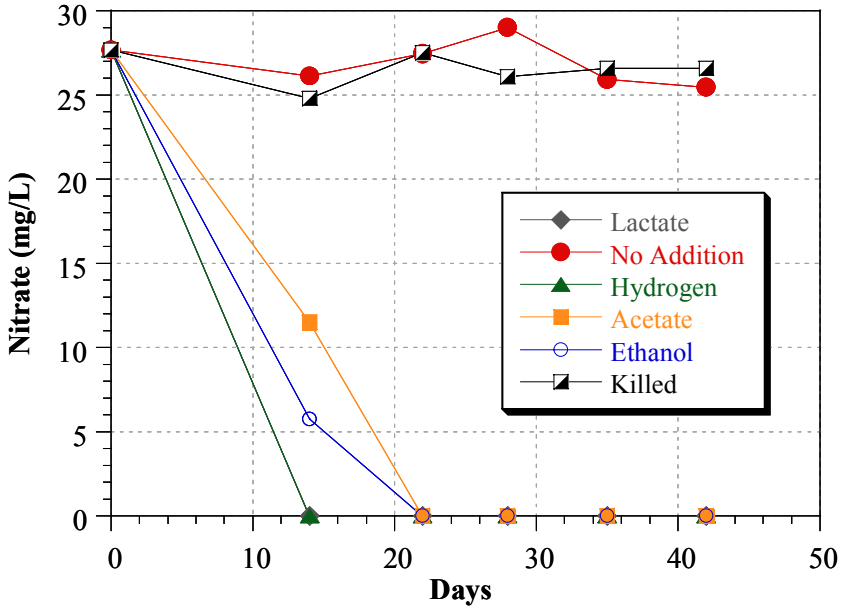

Figure 3. Influence of Different Electron Donors on Nitrate Biodegradation in Buffered Site Samples

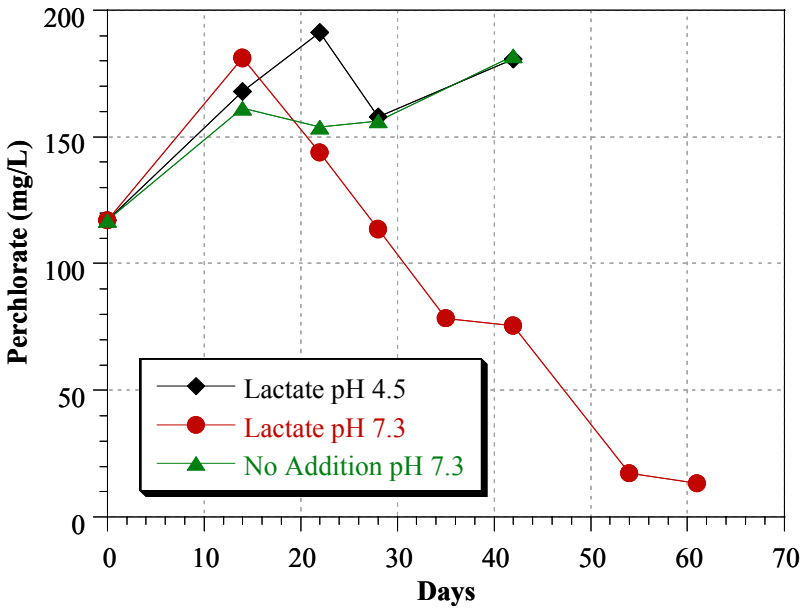

Figure 4. Perchlorate Levels in Aquifer Microcosms Receiving Lactate (pH 4.5 or 7.3) or No Electron Donor

The data from this microcosm experiment generally support previous laboratory studies conducted by Shaw Environmental and IHDIV from several sites across the country. The data show the following:

(1) Naturally occurring bacteria capable of degrading perchlorate are present in the test plot location.

(2) These bacteria can be stimulated to degrade perchlorate using lactate as an electron donor.

(3) Adjustment of pH from 4.5 to neutrality will be required for perchlorate reduction to occur.

However, the laboratory results differed slightly from previous findings in a couple of ways. First, the rate of perchlorate reduction in the pH-adjusted microcosms receiving lactate was somewhat slower than anticipated based on results from previous studies at the Building 1419 location. This may reflect the high perchlorate concentration in the designated test plot area or a low starting density of indigenous perchlorate-reducing bacteria in the aquifer in this area. A limitation in inorganic nutrients (phosphate in particular) could also account for the slow rate of perchlorate reduction. However, such a nutrient limitation was ruled out in an additional microcosm study. The data from this study showed that ammonium and phosphate addition did not appreciably enhance perchlorate reduction in the lactate-amended aquifer samples (pH 7.3) (data not shown). The data from this study also differed from that in the previous SERDP study

in that acetate was observed to be a suitable electron donor for perchlorate reduction in pH-adjusted samples in the study with samples from Building 1419 (see Figure 3). Acetate did not support perchlorate reduction in this study. The samples for the first SERDP study were obtained in August 2000 at a location much closer to Building 1419 than those used for the current study. Therefore, it is possible that the geochemistry and microbiology differ somewhat between the two locations. Based on the most recent laboratory study, lactate was chosen for use in the field pilot study.

In addition to biodegradation studies, experiments were conducted with site samples to evaluate the most effective buffer for the demonstration. The addition of pure sodium carbonate to the IHDIV groundwater was anticipated to raise the pH of that water to more than 10.0, which is inhibitory to bacterial growth. Although the added alkalinity was expected to be quickly consumed by the sediments, it was possible that the initially high pH near the injection wells would inhibit microbial growth and subsequently perchlorate reduction. Because of this possibility, laboratory studies were performed in sediment/groundwater slurries and in groundwater only to evaluate pH adjustment using sodium bicarbonate ($NaHCO_3$) and various carbonate/bicarbonate mixtures.

As described for previous microcosm experiments, sediment and groundwater collected within the demonstration area were combined and homogenized for these studies. Titrations were performed with sediment/groundwater slurries using sodium bicarbonate only, a mixture of 20% sodium carbonate and 80% sodium bicarbonate, and a mixture of 40% sodium carbonate and 60% sodium bicarbonate. To conduct these experiments, 50 g of site sediment and 50 mL of groundwater were mixed, the bicarbonate or bicarbonate/carbonate mixture was added in small increments, and the pH of the slurry was measured after each addition of buffer. In addition, the influence of the bicarbonate solution and carbonate/bicarbonate mixtures on the pH of groundwater only was examined.

The titration curves for bicarbonate and two carbonate/bicarbonate mixtures in the aquifer sediment slurries are provided in Figure 5. The quantity of buffer required to reach a pH of 7.0 was appreciably higher when bicarbonate alone was used (1,600 mg/L) compared to a 80/20 mixture or a 60/40 mixture of bicarbonate/carbonate (800 mg/L and 750 mg/L, respectively). However, the pH of the aquifer sediments increased only gradually beyond 7.0 with continued amendment with bicarbonate only. The pH of the sediment slurry was only 7.12 after addition of 2,000 mg/L of bicarbonate (the highest dose tested). The pH of aquifer samples receiving 20% carbonate and 80% bicarbonate reached 7.0 after addition of 800 mg/L of buffer, and the pH achieved after addition of 2,000 mg/L was 8.3. The 60/40 mixture of bicarbonate/carbonate brought the sediment slurry to a pH of 8.8 after addition of 1,200 mg/L. The pH response of site groundwater amended with the three different buffer solutions is presented in Figure 6. After addition of 2,000 mg/L of each buffer, the pH of the groundwater was 8.95 for bicarbonate only, 9.42 for a 90/10 mixture, and 9.60 for an 80/20 mixture of bicarbonate/carbonate, respectively.

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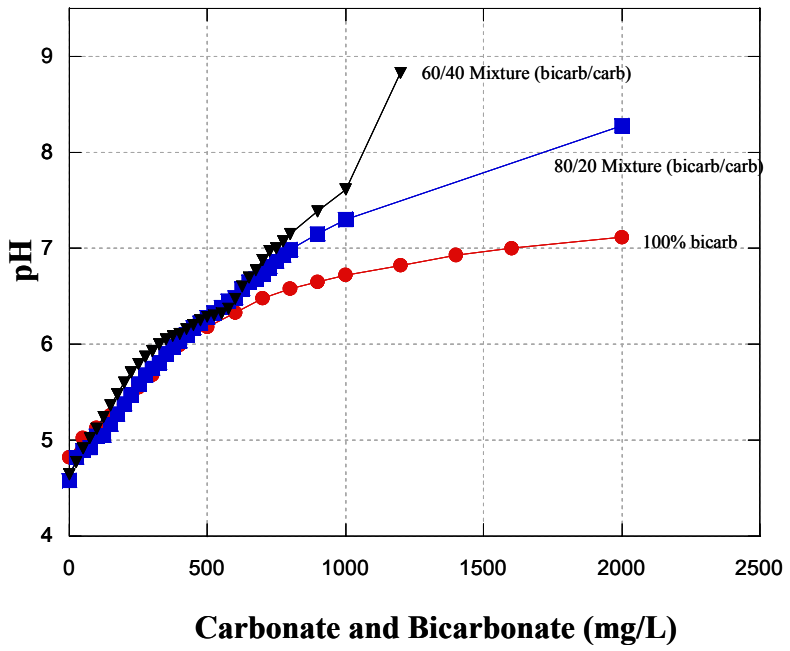

Figure 5. Influence of Bicarbonate/Carbonate Mixtures on pH of Sediment Slurries from the Demonstration Area

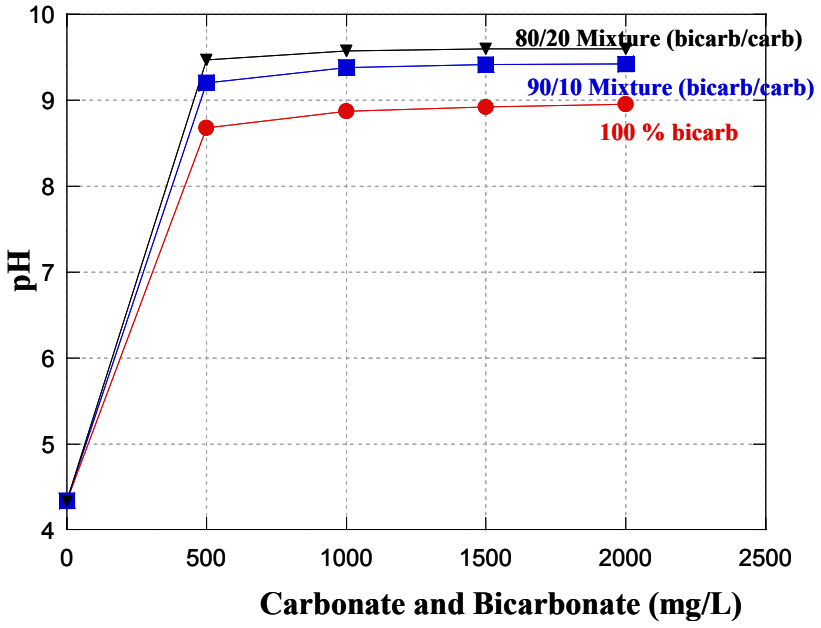

Figure 6. Influence of Bicarbonate and Carbonate/Bicarbonate Mixtures on Groundwater pH

The equilibrium chemistry for carbon dioxide, bicarbonate, and carbonate in natural waters is complicated and is affected by the geology and geochemistry of the system. Based on equilibrium curves published for carbon dioxide/bicarbonate/carbonate, the maximum pH in an aqueous solution containing only bicarbonate should be approximately 8.5 to 9.0 (Wetzel, 1975). The final pH of the site groundwater amended with bicarbonate only was within this range. As the ratio of carbonate/bicarbonate increases, pH will increase accordingly, exceeding 12 when carbonate only is in solution. Thus, while carbonate is more effective than bicarbonate for neutralizing acidity, the potential for increasing aqueous pH to levels beyond those which are optimal for the activity of perchlorate-reducing bacteria (6.0–8.0) is also higher when using a carbonate solution compared to bicarbonate. These factors must be taken into account when attempting to buffer an acidic aquifer. Based on these results and the expected consumption of alkalinity during aquifer buffering, a concentrated solution (6.67%) of 80% bicarbonate and 20% carbonate was initially chosen for the concentrated buffer to be used during the demonstration. The pH of the water in the monitoring wells was closely monitored to determine the effectiveness of buffering, and adjustments were made to the buffer mixture based on these data.

SITE CHARACTERIZATION

Site Background

The Indian Head Division is located near Indian Head, Maryland. Geographically the site is located at 38°35′05″ N latitude, 77°09′50″ W longitude in Charles County, Maryland (United States Geological Survey [USGS] Indian Head, MD-VA 15′ Quadrangle, 1982). Figure 7 shows the site location. The study area is located on the southeast side of IHDIV Building 1419, also known as the Hog-out Facility. Figure 8 shows the site plan view. Building 1419 is used to clean out or "hog out" solid propellant containing ammonium perchlorate from various devices, including rockets and ejection seat motors, that have exceeded their useful life span. The hog-out process and former waste handling methods have impacted the groundwater near Building 1419.

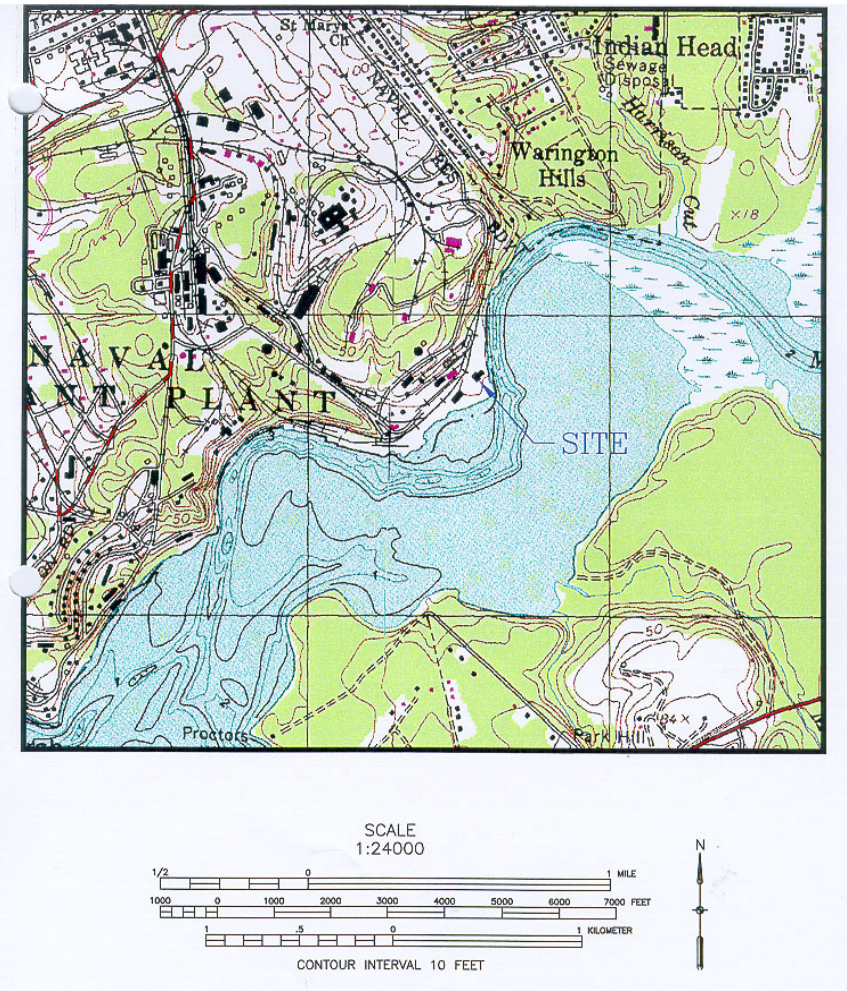

Figure 7. Site Location Map

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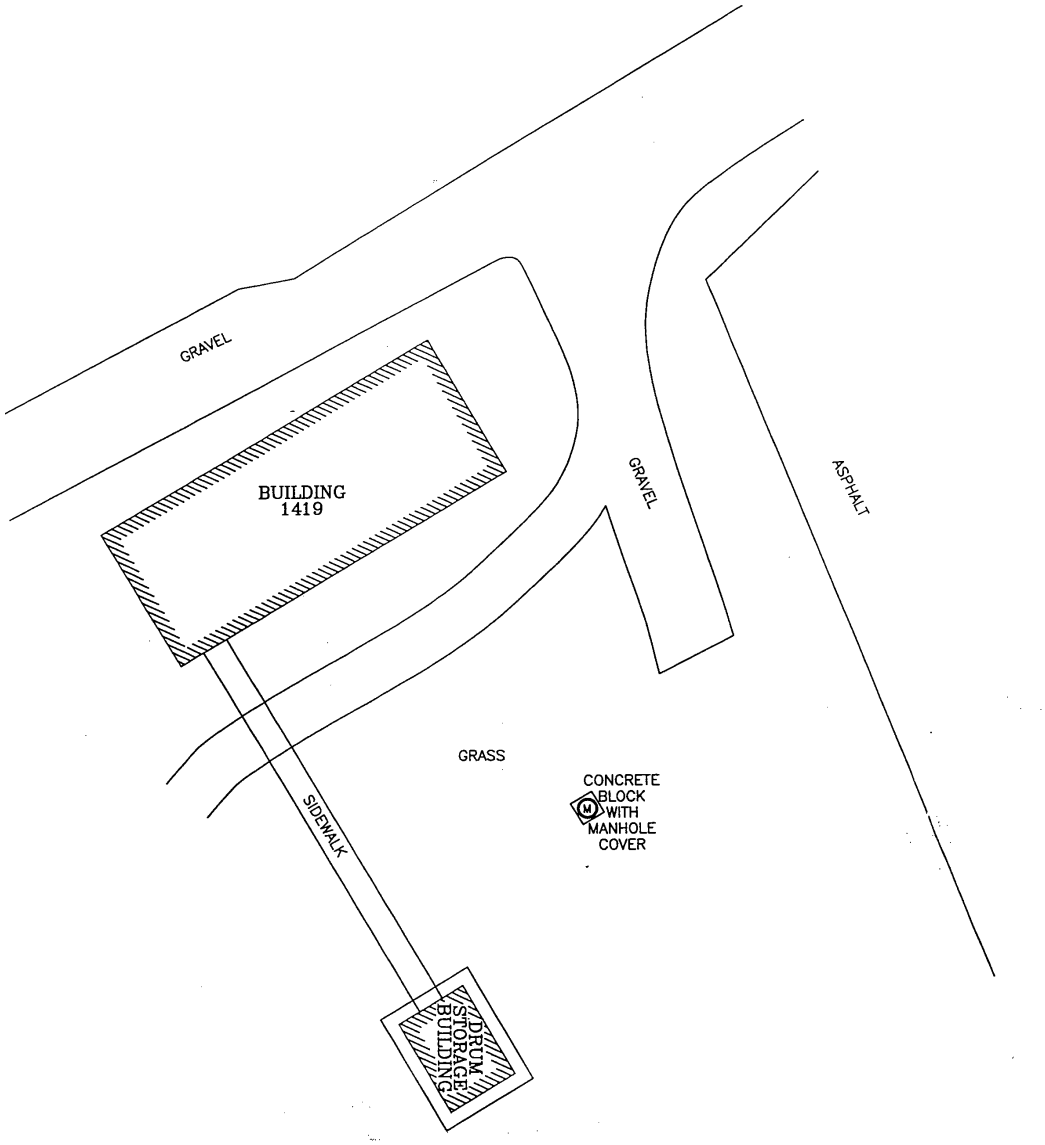

Figure 8. Site Plan View

Procedures

Field characterization of the demonstration area behind Building 1419 was performed in January and February 2002. A direct-push (Geoprobe) rig was used to collect continuous sediment cores for geological analysis. Standard Geoprobe penetrations were conducted with a vehicle-mounted rig. Geoprobe penetration was performed by the pneumatic hammering action of a 1-inch outside diameter steel rod. For the pneumatic advancement of the Geoprobe extensions, a 2- to 4-ft-long, 2-inch-diameter, split-barrel sampler was mounted on the leading end of the penetration probe rod. The sampler and probe rods were then advanced into the

ground, allowing soil to enter the sample barrel. The sample barrel assembly was then removed, and the soil sample was extruded for analysis. A total of 17 Geoprobe borings were installed. Following the completion of each boring, a temporary 1-inch inner diameter (I.D.) polyvinyl chloride (PVC) well casing with a screened (0.010-inch slot) lower section was inserted into the open Geoprobe hole. Groundwater samples were then collected from each borehole for geochemical analysis using a peristaltic pump and plastic tubing.

Based on the groundwater analysis from the 17 Geoprobe points, six permanent groundwater monitoring wells were initially installed in the demonstration area. Drilling activities were conducted in general accordance with ASTM:D1586. Borings were advanced using hollow-stem auger/split-spoon sample drilling methods. Split-spoon soil samples were collected at 2.5-ft intervals from each boring ahead of the hollow-stem auger. The six borings were then completed as groundwater monitoring wells. The monitoring wells were constructed using 2-inch I.D. schedule 40 PVC risers and 10-ft well screens (0.010-inch slot). The bottom of the screened section was set approximately 1 ft into the gray clay layer. A sand pack was placed around each screen section. A bentonite plug was placed above the sand pack to prevent surface water from entering the sand pack. Copies of typical boring logs and well construction forms are given in Appendix A.

The wells were developed using a submersible pump. During development, at least ten well volumes were purged from each well. The purpose of the development process was to remove fine-grained sediment from the sand pack and to provide a proper hydraulic connection between the well and the surrounding aquifer. Groundwater samples were then collected from each of the monitoring wells for geochemical analysis using a peristaltic pump and plastic tubing.

A mark was placed on the top of each monitoring well casing for use as a reference point when measuring water elevations. Water levels are recorded to the nearest 0.01 ft in each monitoring well using an electronic sensing device. The water level indicator was decontaminated after each measurement to prevent cross contamination. The top-of-casing (TOC) elevation of each well was then surveyed to the nearest 0.01 ft and referenced to a site datum. The water level is referenced to the TOC elevation to determine the water table elevation.

SITE GEOLOGY AND HYDROGEOLOGY

Regional Geology

Surficial geology in the general area of the IHDIV site is composed of Pleistocene lowland deposits. These deposits consist of gravel, sand, silt, and clay. Medium- to coarse-grained sand and gravel, cobbles, and boulders are located near the base of the formation. The deposits commonly contain reworked Eocene glauconite, varicolored silts and clays, and brown to dark gray lignitic silty clay. Estuarine to marine fauna are found in some areas. The thickness of the formation varies from 0 to 150 ft.

The Cretaceous Potomac Group is located adjacent to the Potomac River (and covers almost the entire peninsula between the Mattawoman Creek and the Potomac River). This formation consists of interbedded quartzose gravels, protoquartzitic to orthoquartzitic argillaceous sands, and white, dark gray, and multicolored silts and clays. The thickness of the formation varies from 0 to 800 ft. The dark gray clays of this formation likely underlie the site. The surficial geologic map for Charles County is shown in Figure 9.

Local Geology

The field demonstration area is located southeast of Building 1419 and is approximately 300 ft from the Mattawoman Creek. The surficial geology of the test plot area was derived from soil samples collected from 17 Geoprobe borings and six test borings that ranged in depth from 16 to 20 ft below the ground surface (bgs). The top 2 to 4 ft consisted of fill material including organic material, gravel, and silty sand. The underlying 11 to 13 ft consisted of mottled light to olive brown clay to sandy silts. The clay and sand fraction of the silts varied horizontally and vertically. Fine grained sand seams 1 to 2 inches in thickness were seen in many of the boring locations, but these seams were not continuous from boring to boring. At a depth of approximately 15 ft bgs, a 1- to 1-1/2-ft-thick layer of sand and gravel was encountered. This layer was found to be continuous throughout the area near the test plot. The sand and gravel layer is underlain by a gray clay layer, which extends to a depth of at least 20 ft bgs, the deepest extent of the Geoprobe and test borings. This is likely the clays of the Potomac Group. Figures 10, 11, and 12 show the Geoprobe and well locations, cross-section plan view, and geologic cross sections A-A′ and B-B′ for the demonstration area.

Local Hydrogeology

Groundwater elevations measured in the six monitoring wells in the demonstration area indicate a groundwater flow direction to the southeast toward the Mattawoman Creek. The flow direction basically follows the surface topography. Depth to groundwater ranged from approximately 6.5 to 10.25 ft below the ground surface. The average hydraulic gradient, as measured between wells MW-1 and MW-3, was 0.023 ft/ft. The groundwater potentiometric surface in the demonstration area is shown in Figure 13.

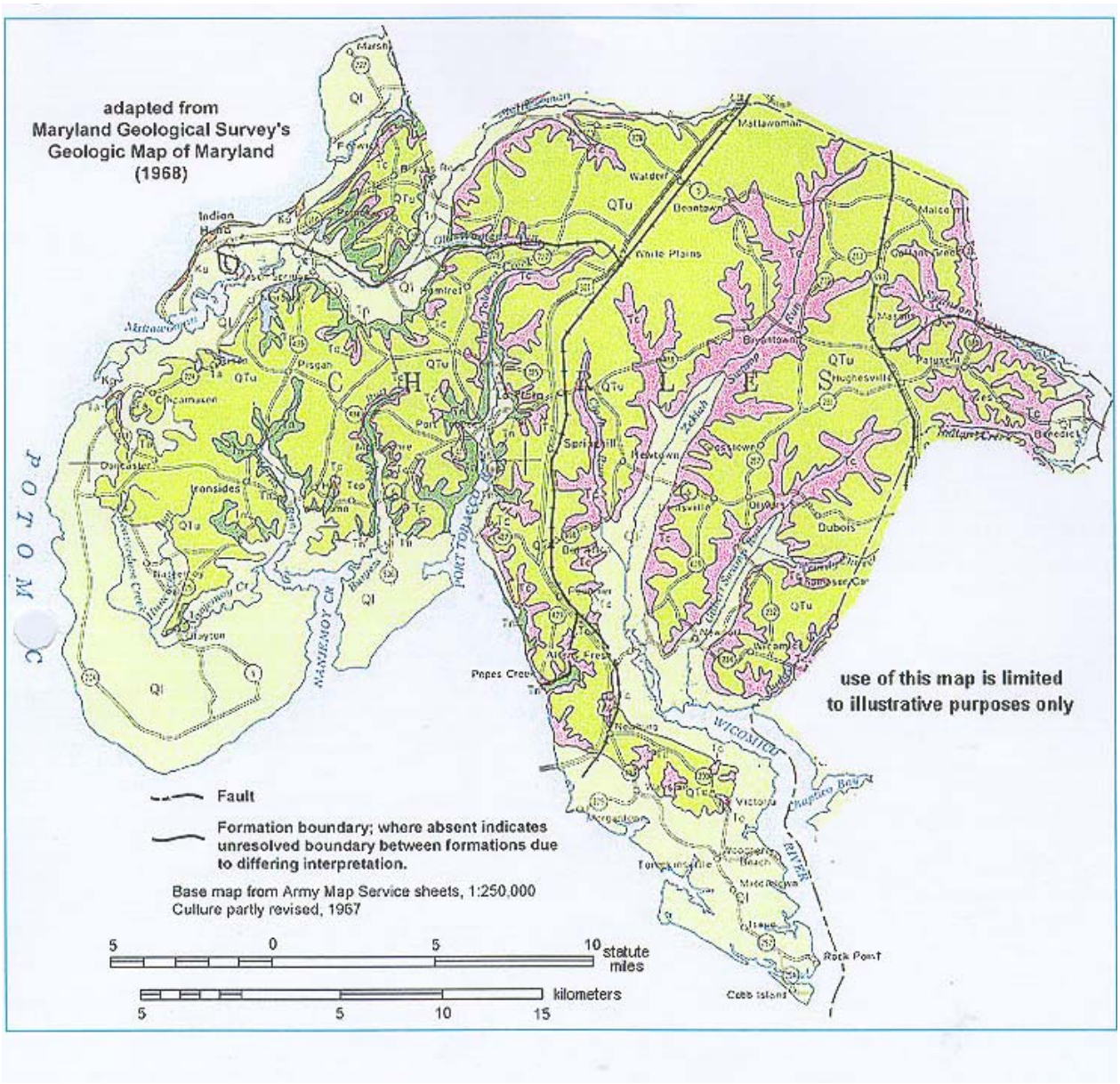

Figure 9. Geologic Map of Charles County

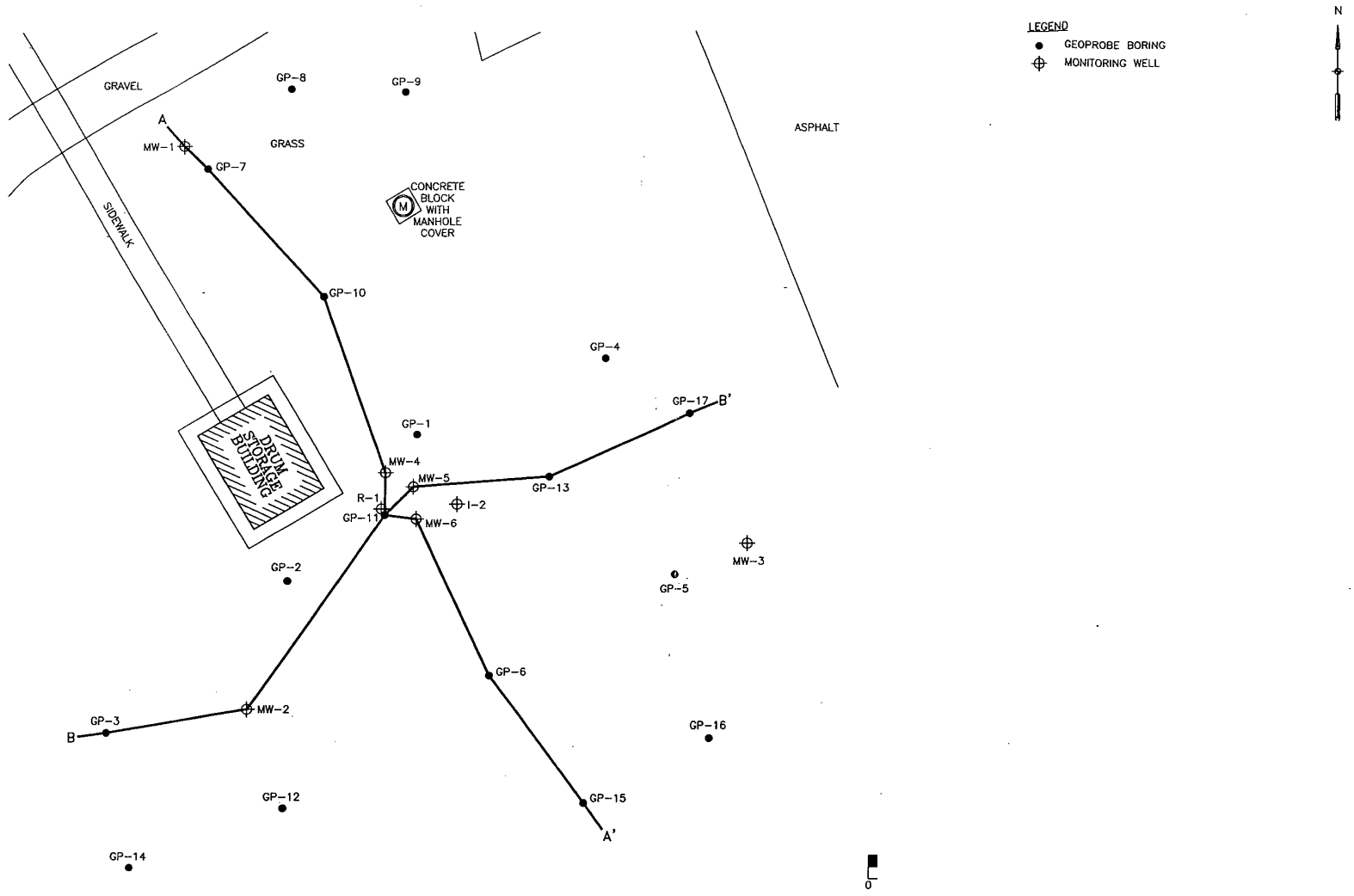

Figure 10. Boring Location and Cross-Section Plan View

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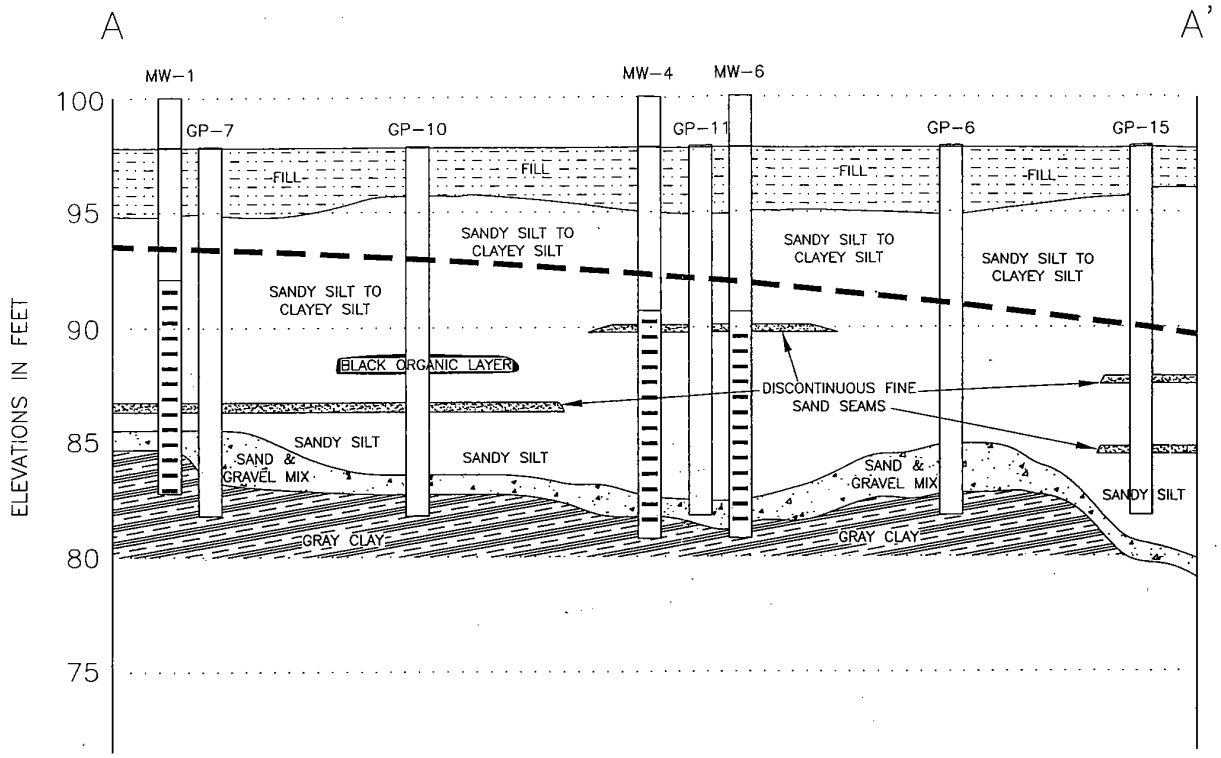

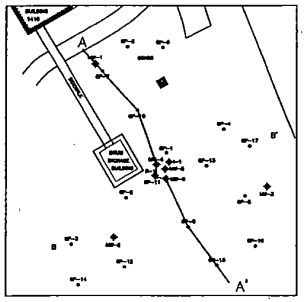

GROUNDWATER TABLE

Figure 11. Geologic Cross-Section A-A'

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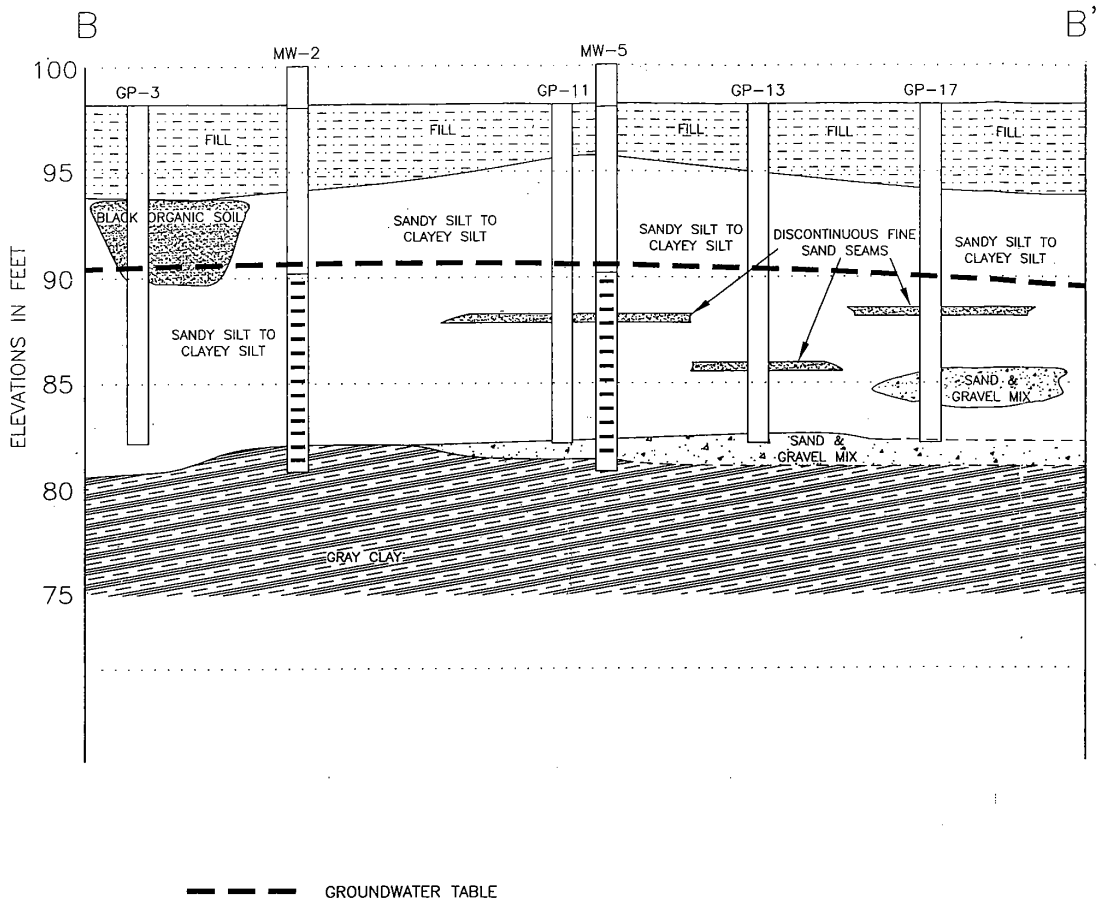

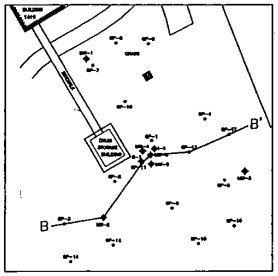

Figure 12. Geologic Cross-Section B-B'

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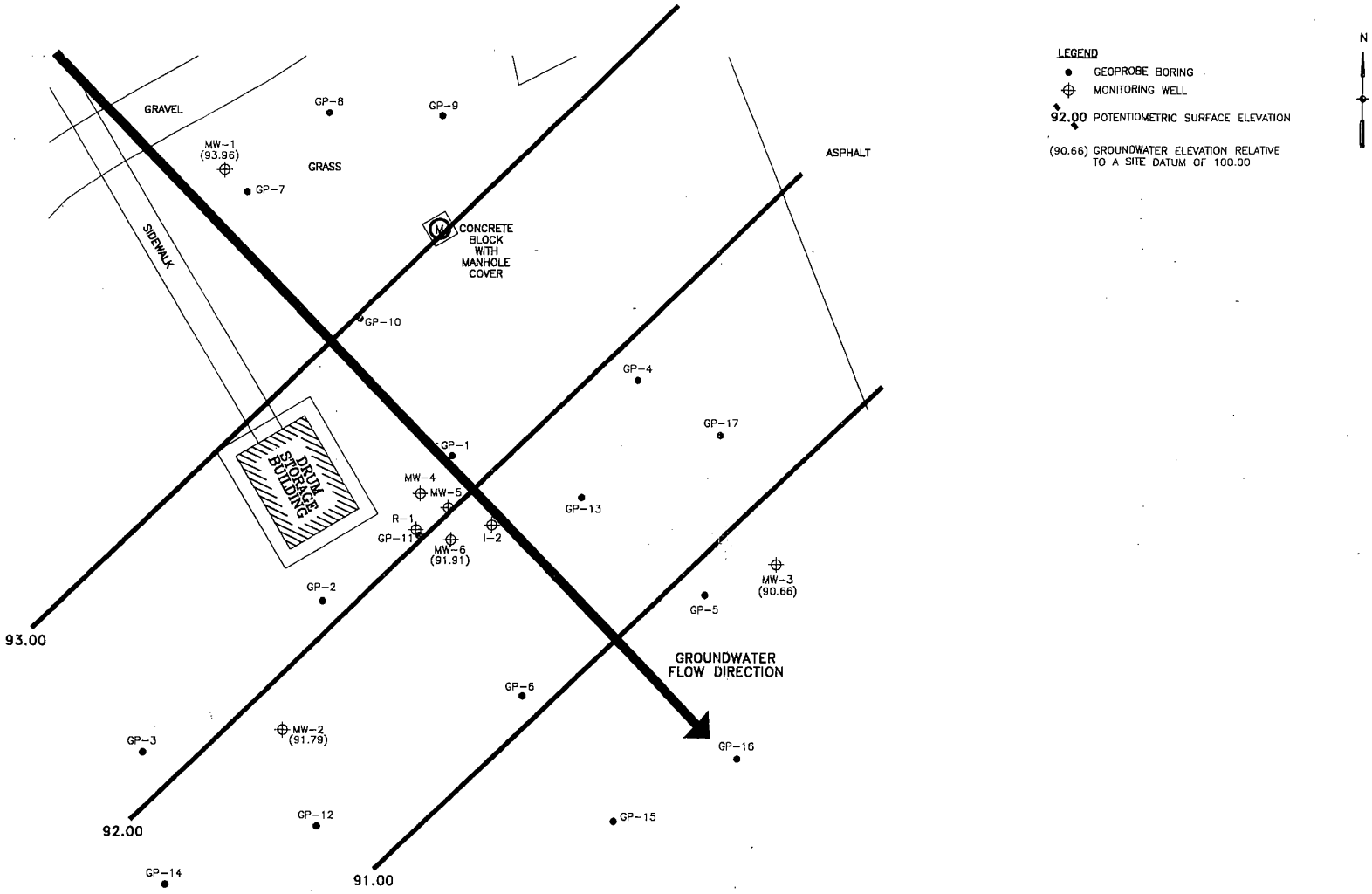

Figure 13. Groundwater Potentiometric Surface

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Geochemical Results

Groundwater samples were collected from the 17 Geoprobe borings on 22 and 24 January 2002, and from the six monitoring wells on 5 and 6 February 2002. The groundwater samples collected from the Geoprobe borings were analyzed for perchlorate, nitrate, sulfate, pH, and dissolved oxygen (DO). Results of the chemical analyses from the Geoprobe borings are provided in Table III. Groundwater samples collected from the six monitoring wells were analyzed for perchlorate, pH, and DO. Results of the chemical analyses are provided in Table IV. The distribution of perchlorate in groundwater based on the Geoprobe and monitoring well sample results are shown in Figure 14. As shown, the field investigation revealed a shallow, narrow plume of perchlorate contamination behind Building 1419 with levels ranging from below detection to approximately 430 mg/L. With a few exceptions, the pH of the site was below 5, and the dissolved oxygen levels were less than 2 mg/L.

Table III. Groundwater Chemistry at the Demonstration Site

Geoprobe boring	Perchlorate (mg/L)	Nitrate as N (mg/L)	Sulfate (mg/L)	pH	Dissolved oxygen (mg/L)[a,b]
GP-1	120	0.6	66	4.67	NA
GP-2	< 2.5	3.0	220	8.08	NA
GP-3	8.2	1.9	280	5.23	NA
GP-4	57	0.3	110	4.54	NA
GP-5	65	0.1	130	4.21	1
GP-6	280	11	69	5.62	1
GP-7	35	1.5	66	4.21	0.1
GP-8	430	14	62	4.57	ND
GP-9	73	0.4	56	4.44	0.8
GP-10	300	12	70	4.31	1
GP-11	230	14	72	4.71	0.8
GP-12	55	2.0	110	6.46	ND
GP-13	230	3.8	64	4.61	1.5
GP-14	14	1.5	250	4.97	ND
GP-15	9.8	< 0.2	160	5.34	0.2
GP-16	270	2.8	74	4.16	1
GP-17	< 5	< 0.2	140	4.83	0.2

[a]Analysis performed by colorimetric field method (Chemets).

[b]NA: Not analyzed; ND: Not determined.

Table IV. Groundwater Chemistry and Perchlorate Concentrations in Monitoring Wells 1 through 6

Monitoring well	Perchlorate (mg/L)	pH	Dissolved oxygen (mg/L)
MW-1	84.7	5.02	1.49
MW-2	1.9	6.75	5.50[a]
MW-3	1.6	4.13	6.60[a]
MW-4	181	5.00	1.64
MW-5	82.8	6.20	1.13
MW-6	142.4	5.03	1.33

[a]DO meter recalibrated — results may not reflect site conditions.

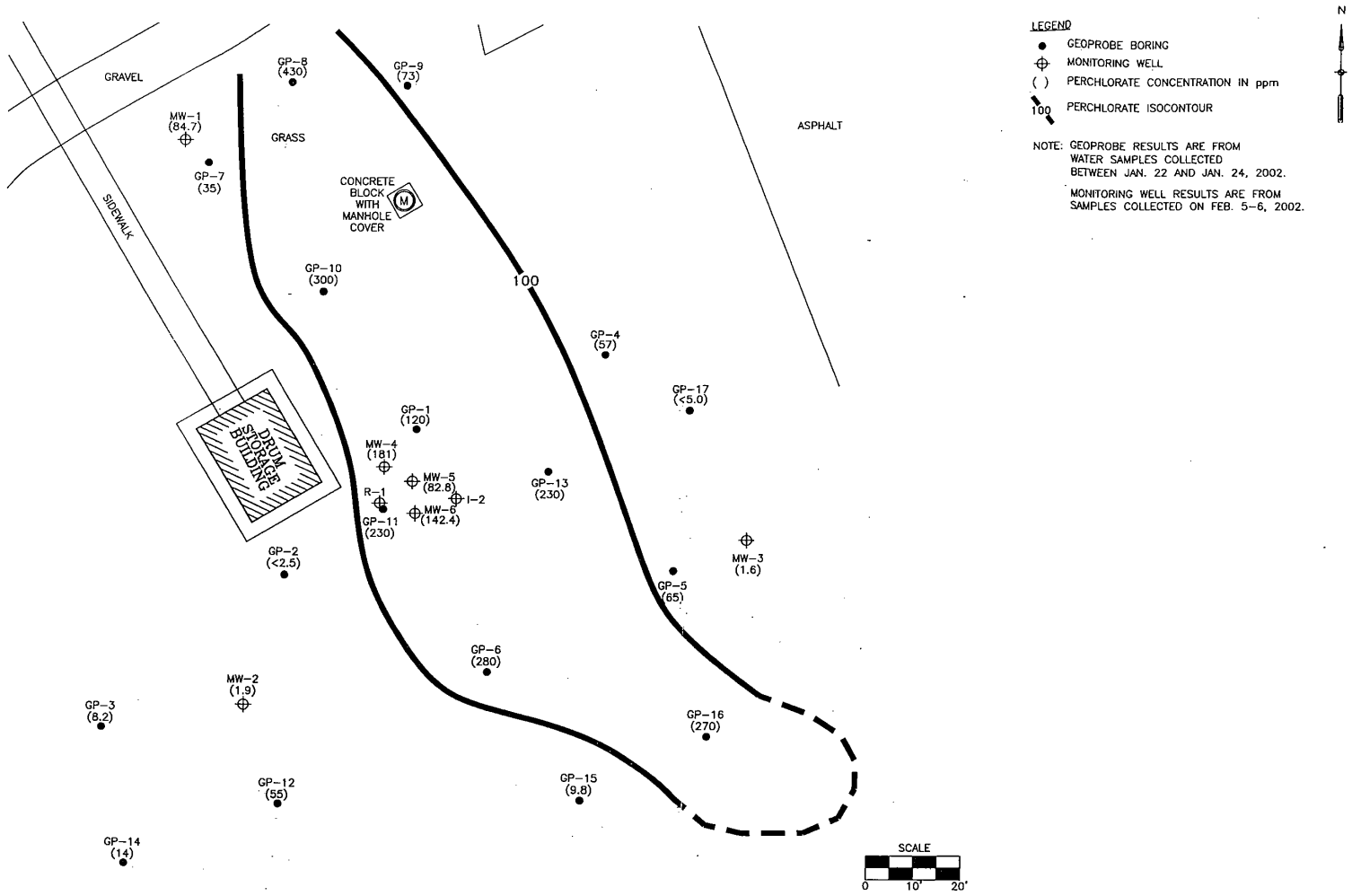

Figure 14. Groundwater Perchlorate Distribution

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SLUG AND PUMP TEST RESULTS

Slug Testing

Slug testing was performed on monitoring wells MW-4, MW-5, and MW-6. These wells were selected due to their proximity to the planned test plot area. All slug test results were reduced using the Bower-Rice unconfined aquifer method. Appendix B contains copies of the slug test graphs and curve fit lines. The slug test results indicated an average hydraulic conductivity (*K*) of approximately 0.012 ft/min within the aquifer.

Pump Testing

An aquifer-pumping test was completed at the site during early March 2002. The goal of the aquifer pumping test was to determine how the aquifer in the area of the pilot study responded to actual groundwater pumping scenarios. Using the results of the slug testing as a starting point, a stepped test was performed to determine the optimum flow rate for the pump test. During the stepped test the flow rate was varied between 0.13 and 0.528 gal/min. Based on the results of the stepped test (data not shown) it was estimated that a flow rate of less then 0.25 gal/min would be required to allow for continuous steady-state pumping throughout the pump test.

Using this information a 12-hour pump test was conducted. An initial flow rate of approximately 0.2 gal/min was used at the start. However, based on the observed rate of drawdown within the extraction well, which indicated the well would be pumped dry, the flow rate was adjusted down to approximately 0.15 gal/min after approximately 4.5 hours of pumping. This reduction in flow rate stabilized the rate of decline in water level within the extraction well, allowing for continuous pumping throughout the test.

Drawdown levels were logged in the extraction well and several nearby monitoring wells throughout the pump test to determine the influence on the aquifer of pumping in the vicinity of the extraction well. The drawdown data were reduced and analyzed using the Theis method for unconfined aquifers. Based on the curve data, *K* value estimates ranged from 0.011 to 0.044 ft/min. Appendix B contains copies of the drawdown curves and curve fit lines for the recovery and observation wells.

Re-injection Testing

Following the completion of the pump test, a brief re-injection test was completed using waters collected during the pump test. The purpose of the re-injection test was to ensure that the planned injection wells would be capable of reintroducing the amended water into the formation at the anticipated flow rates and to obtain design parameters such as flow rates and injection pressures. The injection well was able to sustain an injection rate of slightly over 1.2 gal/min at less than 3.5-psi pressure.

FIELD DEMONSTRATION

Demonstration Objectives

The objectives of this demonstration were as follows:

1. Demonstrate that the IHDIV aquifer can be effectively buffered using a mixture of carbonate and bicarbonate.

2. Show that electron donor (lactate) can be effectively distributed throughout the contaminated aquifer using a groundwater extraction-injection design.

3. Demonstrate that perchlorate and nitrate can be biodegraded in the buffered aquifer using lactate as an electron donor, with minimal reduction of sulfate.

4. Quantify the time required for perchlorate biodegradation and the levels of degradation achievable.

5. Identify key design and operational factors that influence full-scale application of in situ perchlorate bioremediation at this and other sites.

Recirculation Cell Design

A simple single-layer numeric model was developed to represent site conditions. The model was calibrated by simulating the pump test conditions and adjusting the *K* value for the aquifer until the drawdown levels observed in the model at distance were similar to those measured in the field at the 12-hour interval. This information was utilized to assess recirculation well layouts and anticipate operating conditions associated with the final field scale design.

The final recirculation cell layouts comprised two injection wells and two recovery wells installed 12 ft apart. The extraction and injection wells were installed cross-gradient to the natural groundwater flow direction. The relatively close spacing was chosen to allow for faster pore volume turnover rates and to minimize the amount of formation to be buffered during the study. Two sets of well nests were installed between each set of injection/recovery well pairs located at 4-ft intervals. Each of the four well nests included one well screened within the saturated zone of the clayey silt layer and above the gravel layer, and one well with a screened interval intersecting the coarse sand and gravel layer located above the underlying clay soils found at the 13- to 16-ft depth interval. The two screened sections overlapped approximately 6 inches to ensure that no sand lenses were missed. This nested configuration was chosen to allow the spread of buffer agent and electron donor within both the upper clayey silt layer and

the highly conductive sand and gravel layer to be monitored separately. In addition to the four nested wells, one fully screened well was installed in the center of each cell.

The treatment and control cells (test plot and control plot) were located 20 ft apart to ensure that similar perchlorate concentrations were present in both cells. The injection wells were installed to the depth of the gravel/clay interface. The recovery wells were set 4 ft into the clay layer. The control plot was located to the west of the test plot. In the test plot, the injection wells were on the west side of the cell (nearest the control plot) and the recovery wells on the east side of the cell (away from the control plot). This layout was reversed for the control plot. This configuration resulted in cross-gradient flow patterns within each cell (east to west in the control plot and west to east in the test plot) and groundwater flow in each cell that was moving in an opposite direction to that in the adjacent cell. The mounding created by the injection wells in the control plot prevented the amendments from the test plot from being introduced into the control plot cell. The final location, layout, and cross-sectional schematic of the control and test plot cells are shown in Figure 15.

An injection skid was designed to be integrated with the wells. The injection skid had separate transfer tanks, injection pumps, flow meters, and associated valves for the control and test plots. In addition, the test plot had two metering pumps installed to inject a pH solution and an electron donor-reagent to promote optimal aquifer conditions and stimulate biological activity. The injection skid was located between the control and test plots.

Pilot System Installation

The injection and recovery wells were installed using a standard hollow stem auger drilling rig equipped with 10.25-inch outside diameter augers. Both the injection and recovery wells were constructed using 6-inch I.D. schedule 40 PVC. The injection wells were installed with approximately 8 ft of screen (0.010-inch slot) set at the gravel/clay interface. The recovery wells were installed with approximately 15-ft screens (0.010-inch slot) set 4 ft into the clay layer. A sand pack was placed around each screened section, and a bentonite plug (approximately 2 ft thick for the recovery wells and 4 to 5 ft thick for the injection wells) was placed above the sand pack. The extra seal thickness was used for the injection wells to ensure that the injected fluid was not rejected up the annular space of the borehole and was directed into the formation.

The nested and fully penetrating monitoring wells were installed using the same hollow stem auger drilling and installation methods as described previously for monitoring wells MW-1 through MW-6. The wells were constructed using 2-inch I.D. schedule 40 PVC well casing and screen materials. Screen lengths (0.010-inch slot) varied from approximately 7 to 8 ft long for the shallow nested wells, 2.5 to 3 ft long for the deep nested wells, and 10 to 11 ft long for the fully penetrating wells. A sand filter pack was placed around the screened sections and a 2-ft-thick bentonite seal was placed around the upper portion of the well casing to prevent fluid infiltration or loss.

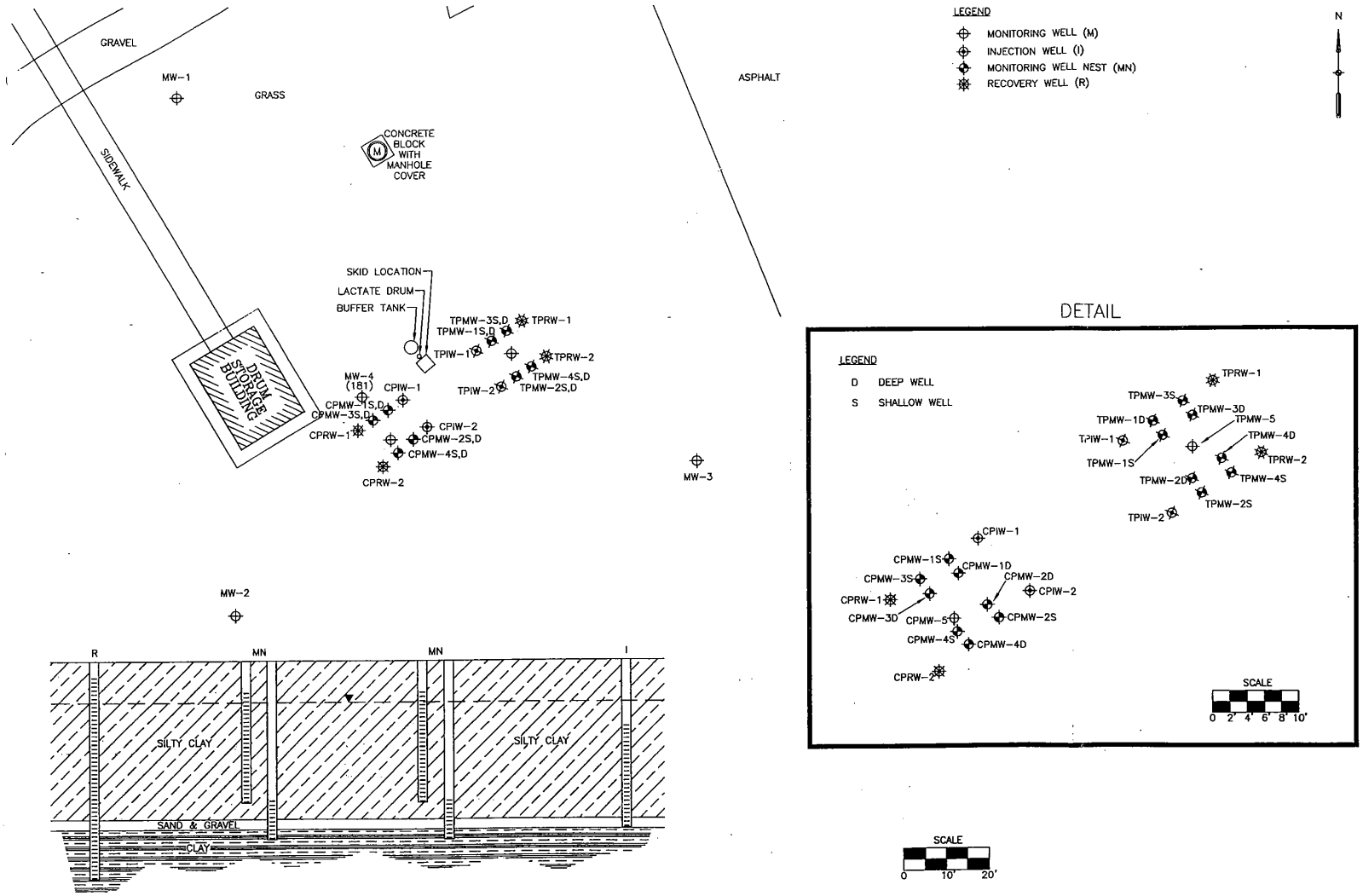

Figure 15. Recirculation Cell Layouts and Schematic Cross-Section View

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The injection skid was fabricated off-site and delivered to the site in early July 2002. One-inch PVC piping was used to connect all the extraction/injection wells to the injection skid. The groundwater extraction pumps were installed and adjusted to pump at approximately 0.25 gal/min each. High-level and low-level floats were installed in each well to turn the pumps on and off if the extraction rate exceeded the recharge rate, causing significant drawdown. The injection pump was set to operate at approximately 1 gal/min per injection well.

The pH buffer tank (1,500-gal polyethylene tank) was filled with groundwater extracted from this site. Site water was used to prepare the buffer to ensure that there was no dilution in perchlorate levels in the test plot during buffer injection. A special line was run from the extraction wells to the buffer tank so that water could be periodically diverted to fill the tank. All piping runs and controls were configured to minimize the potential for aeration of the recirculated groundwater. The buffering agents were food-grade sodium bicarbonate and sodium carbonate (see the "System Operation" section). Once the pH buffer tank was filled, the extracted groundwater was diverted to the injection skid and re-injected in the test and control plot areas. The pH buffer tank was connected to the metering pump by 1/2-inch PVC pipe. IHDIV personnel installed the electrical service at the site. A 60-A, 230-V, single-phase service was provided for use on this project. The injection skid and the recirculation cells are shown in Figures 16 and 17.

Figure 16. Control Panel and Treatment Skid

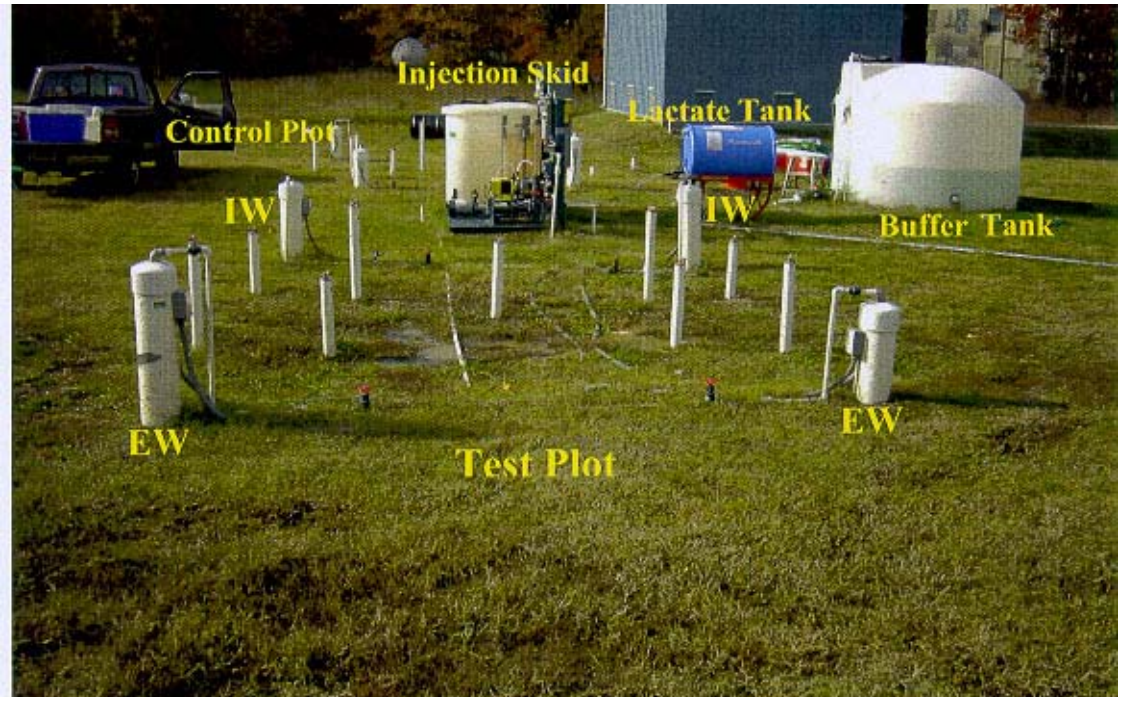


Figure 17. Recirculation Cells and Components

FIELD DEMONSTRATION RESULTS

Tracer Test

A conservative tracer test was performed on 25 July 2002 to determine if each of the monitoring wells installed in the test plot was hydraulically connected with the injection wells where buffer and electron donor were introduced into the formation. To perform this test, approximately 80 gal of groundwater was pumped from the treatment plot into a holding tank and then amended with sodium bromide to achieve a final bromide concentration of 250 mg/L. The bromide solution was then added as a slug to each of the two injection wells at a flow rate of approximately 2 gal/min. Each well received approximately 40 gal of bromide solution. Samples were collected from the bromide tank prior to injection, and then from each of the nine monitoring wells in the test plot (TPMWs) after 1, 5, and 15 days. Samples were also analyzed for bromide during all subsequent groundwater monitoring events. All samples were measured for bromide by ion chromatography (EPA Method 300.0).

The bromide results are presented in Table V. Bromide was detected (> 0.2 mg/L) in four of the nine TPMWs after 1 day and in seven of the nine wells after 5 days of system operation. The remaining two wells showed bromide concentrations above background levels by day 15 and 25 of operation for wells TPMW-4s and TPMW-2d, respectively. Thus, the results of this test suggest that all wells in the test plot are hydraulically connected to the zone where buffer and electron donor are added to the aquifer.

Table V. Bromide Values in the Test Plot with Time

Date	Day	Bromide (mg/L)								
		TPMW-1s	TPMW-1d	TPMW-2s	TPMW-2d	TPMW-3s	TPMW-3d	TPMW-4s	TPMW-4d	TPMW-5
7/18/02	–7	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
7/26/02	1	1.6	3.3	< 0.2	< 0.2	1.5	< 0.2	< 0.2	<0.2	0.77
7/30/02	5	1.1	1.5	2.8	< 0.2	1.5	1.5	< 0.2	0.6	3.9
8/9/02	15	6.8	< 0.2	< 0.2	< 1.0	< 1.0	< 0.2	0.8	< 0.2	1.1
8/19/02	25	0.5	< 0.2	0.3	2.7	7.1	1.8	4.4	33	38
10/3/02	70	< 0.2	< 0.2	2	1.4	< 0.2	< 0.2	1.9	< 0.2	0.7
11/7/02	105	< 0.2	0.64	0.23	< 0.2	0.55	0.6	0.41	0.58	< 0.2
12/12/02	140	0.32	0.54	0.22	< 0.2	0.21	0.28	0.37	0.36	< 0.2

System Operation

A total volume of approximately 20,000 gal of groundwater was recirculated through each plot during the course of the 140-day demonstration (Figure 18). The recirculation system was shut down after 111 days of operation, and one additional sampling event was performed on day 140 to examine the residual effect of buffer and electron donor added to the aquifer. During

the first month of the demonstration, the rate of water recirculation through the test plot was appreciably higher than through the control plot. During this period, approximately 6,500 gal of water were pumped through the test plot compared to 2,100 gal for the control plot. This difference was based on the yield of the aquifer formation in each of these zones. After this time, however, the rate of pumping of the two plots was reasonably similar, as can be seen from the slope of the curves in Figure 18. Increased rainfall in the late summer and early fall, including more than 2.3 inches on 28 August, caused significant aquifer recharge and subsequently increased pumping rates during the demonstration. On 11 November 2002, the groundwater injection rates could no longer be sustained due to the high water table resulting from rainfall in October and early November (nearly 6 inches of rain fell during this period). The system was shut down at this time, which was near the end of the planned period for the demonstration. Rainfall data at IHDIV during the course of the demonstration are provided in Appendix C. Over the course of the entire demonstration, approximately 180 gal of water per day was recirculated through each cell.

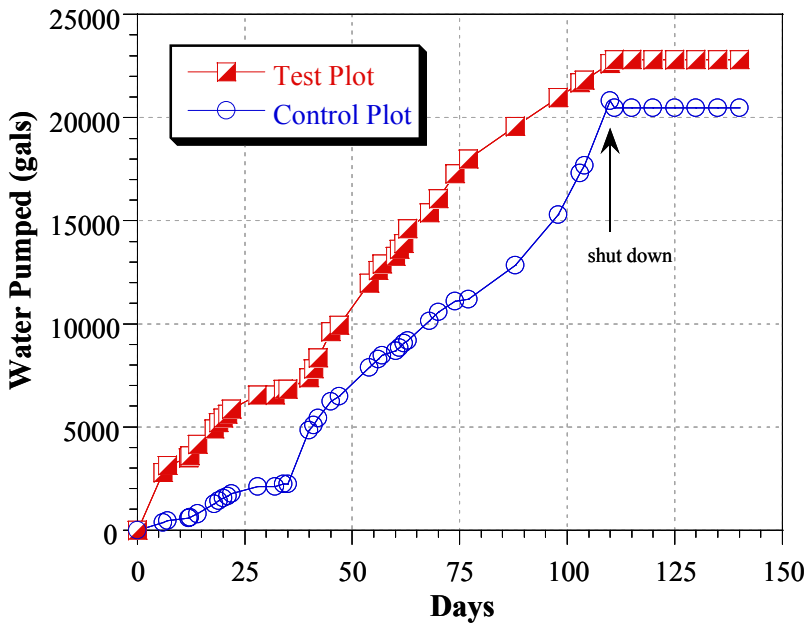


Figure 18. Groundwater Volumes Recirculated through the Test Plot and the Control Plot During the Demonstration

The groundwater pumped from both plots was stored in separate holding tanks until approximately 40 gal was collected, at which time the water was reinjected into the test or control plot at approximately 2 gal/min (~ 1 gal/min per well). The test plot water was amended with electron donor and buffer during the reinjection process. The electron donor was a 60% solution (wt/wt) of food-grade L-(+) lactic acid (sodium salt) supplied by Purac America Inc., Lincolnshire, IL. The sodium lactate syrup, which is neutral in pH, is commonly used as an antimicrobial agent in food products. The concentrated buffer solution consisted of a 6.67% mixture containing either 80% bicarbonate (from $NaHCO_3$) and 20% carbonate (from Na_2CO_3) or 70% bicarbonate and 30% carbonate. The sodium carbonate and sodium bicarbonate were food-grade products purchased from Seidler Chemical Co., Newark, NJ.

The buffer pump was set to amend each 40 gal of groundwater with approximately 2,500 ppm of the carbonate/bicarbonate mixture during re-injection. At two times during the early operation of the system (on days 19 and 35) approximately 250 gal of buffer was added to the aquifer. After each of these additions, the buffer pump was turned off and water was re-circulated for approximately 1 week through the test plot to disperse the buffer amendment throughout the formation. During the course of the demonstration, 1,175 gal of buffer was added to the aquifer. Approximately 875 gal of this buffer was a 6.67% solution containing 80% bicarbonate and 20% carbonate. The other 300 gal was a 6.67% solution containing a mixture of 70% bicarbonate and 30% carbonate. The latter solution, with a slightly higher ratio of carbonate, was added to the aquifer 1 month after the beginning of the demonstration to increase the rate at which the aquifer was buffered. After the 300-gal addition was complete, the mixture was returned to an 80% bicarbonate and 20% carbonate mixture for the remainder of the demonstration.

The lactate pump was set to supply electron donor at a flow rate of approximately 4.5 mL/min during reinjection of groundwater. Based on an injection time of 20 min per 40 gal of groundwater, the concentration of lactate added to the injected water was expected to be approximately 380 mg/L. This concentration of lactate was calculated to provide a reasonable excess of electron donor in the formation based on the average concentrations of oxygen, nitrate, and perchlorate present throughout the test plot. An additional dose of electron donor (~ 3 gal) was added to the aquifer during the early operation of the system on two occasions (on days 19 and 35) in conjunction with the extra buffer addition. The lactate pump was turned off and the groundwater was recirculated for 1 week to mix the electron donor after each of these additions. A total volume of 91 L (24 gal) of the 60% lactate solution was added to the aquifer during the demonstration period (i.e., an average of 0.22 gal/day). A total weight of 58 kg of lactate was added during the 111-day study.

The pH and alkalinity of the water within the test plot were monitored throughout the demonstration to evaluate the effectiveness of the buffer addition to the aquifer. The concentrations of lactate and perchlorate as well as nitrate and sulfate were measured with time to assess the distribution and effectiveness of electron donor amendment to the aquifer for perchlorate remediation. The analytical results are summarized in the “Analytical Methods and Results” section.

Groundwater Sampling

Baseline groundwater samples were collected from the test and control plots 69 days (10 weeks) and 7 days (1 week) prior to the startup of the injection system. During the demonstration, samples were taken from all nine monitoring wells in the test plot on days 14, 25, 49, 70, 105, and 140. The control plot wells were sampled on days 14, 49, 105, and 140. Each well received dedicated sampling tubing at the start of the demonstration. The wells were sampled using a peristaltic pump, and each well was purged for 25 to 30 min prior to sampling. During most of the sampling events, a YSI 600 XL water quality meter with a flow cell was used to determine that key parameters (e.g., pH, conductivity) were stable prior to sample collection.

ANALYTICAL METHODS AND RESULTS

Summary results for each significant parameter measured are provided in subsequent sections.

pH and Alkalinity

The pH of groundwater in the test and control plots was measured using a field probe (YSI 600XL water quality meter) during sample collection and in the laboratory by EPA Method 150.1. Alkalinity was measured by titration according to EPA Method 310.1. The pH of the groundwater in each of the nine TPMWs was observed to increase significantly during the course of the 140-day demonstration (Figures 19 and 20 and Table VI). For example, the pH in TPMW-5 increased from 4.02 seven days before the start of the demonstration to 6.28 at day 105, just before the system was shut down. At day 140, 4 weeks after the injection system was shut off, the pH in this well remained at 6.27. Conversely, there was no appreciable and consistent change in the pH of the control plot monitoring wells (CPMWs) during the active demonstration (Figure 21 and Table VII).

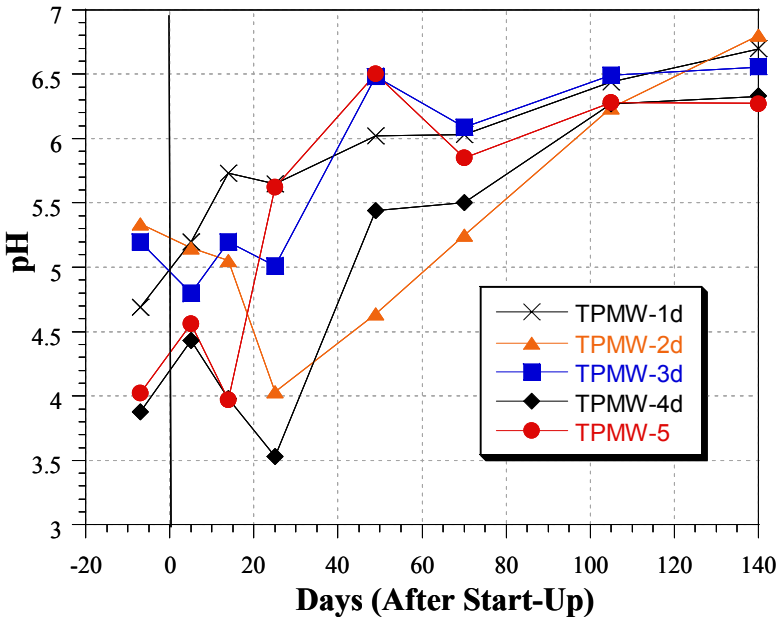


Figure 19. pH Values in Deep TPMWs During the Field Demonstration

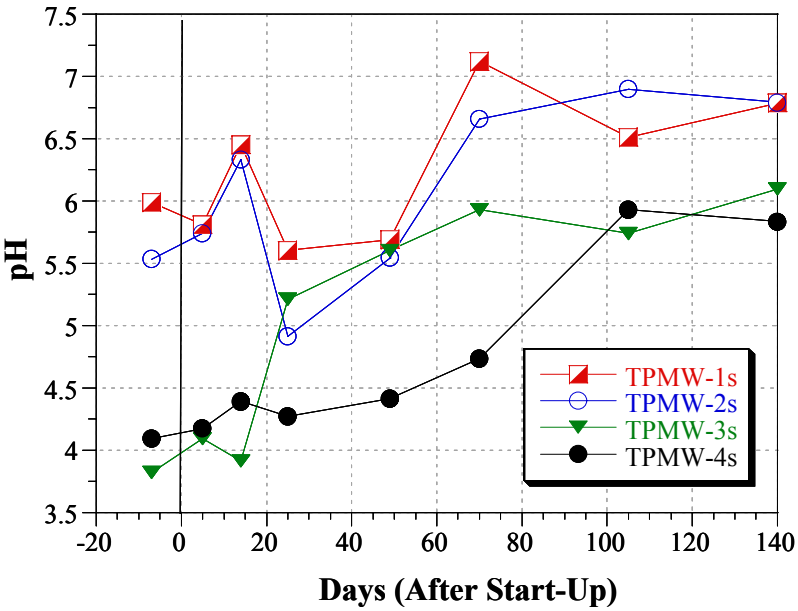


Figure 20. pH Values in Shallow TPMWs During the Field Demonstration

Table VI. pH in the Test Plot with Time

Date	Day	pH[a] at—								
		TPMW-1s	TPMW-1d	TPMW-2s	TPMW-2d	TPMW-3s	TPMW-3d	TPMW-4s	TPMW-4d	TPMW-5
7/18/02	-7	5.99	4.69	5.53	5.34	3.82	5.2	4.09	3.88	4.02
7/30/02	5	**5.81**	**5.2**	**5.74**	**5.15**	**4.09**	**4.8**	**4.17**	**4.43**	**4.56**
8/8/02	14	**6.45**	**5.73**	**6.33**	**5.05**	**3.91**	**5.2**	**4.39**	**3.98**	**3.97**
8/19/02	25	5.6	5.65	4.91	4.03	5.21	5.01	4.27	3.53	5.62
8/19/02	25	**6.32**	**6.14**	**5.3**	**4.46**	**5.54**	**5.29**	**4.55**	**3.85**	**5.97**
9/12/02	49	5.69	6.02	5.54	4.64	5.6	6.48	4.41	5.44	6.5
9/12/02	49	**5.78**	**6.34**	**5.82**	**4.62**	**5.9**	**6.42**	**4.79**	**5.76**	**6.46**
10/3/02	70	7.12	6.03	6.66	5.25	5.93	6.09	4.73	5.5	5.85
11/7/02	105	**6.51**	**6.44**	**6.9**	**6.24**	**5.74**	**6.49**	**5.93**	**6.27**	**6.28**
12/12/02	140	**6.79**	**6.7**	**6.79**	**6.8**	**6.1**	**6.56**	**5.83**	**6.33**	**6.27**

[a]Values in bold are laboratory measurements (EPA 150.1) and those in plain text are field probe values.

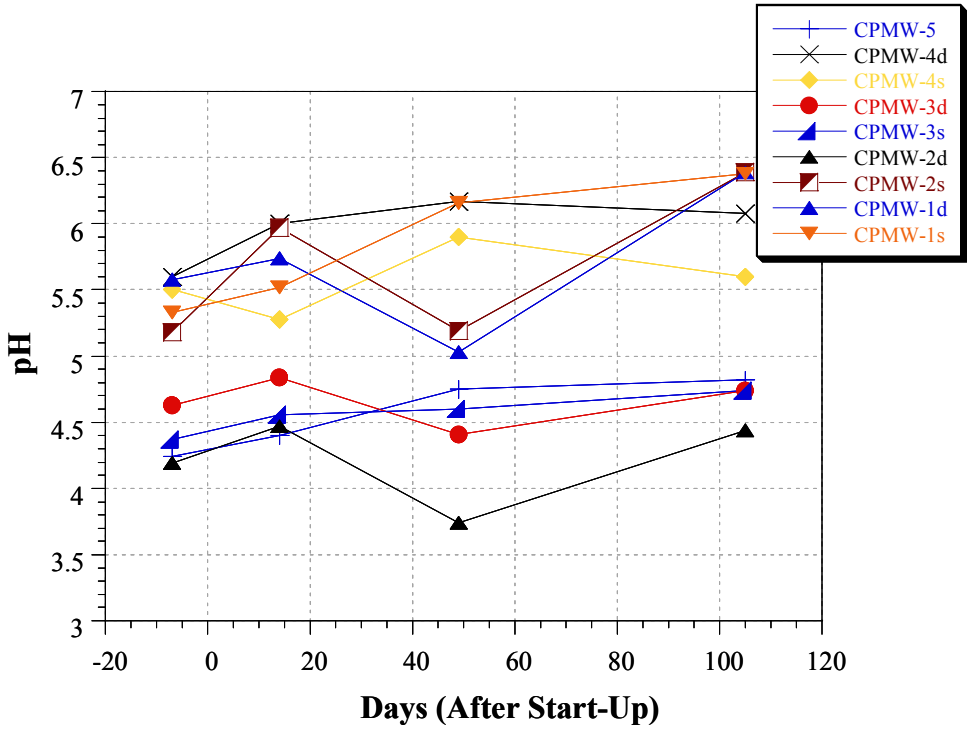


Figure 21. pH Values in the CPMWs During the Field Demonstration

Table VII. pH in the Control Plot with Time

Date	Day	pH[a] at—								
		CPMW-1s	CPMW-1d	CPMW-2s	CPMW-2d	CPMW-3s	CPMW-3d	CPMW-4s	CPMW-4d	CPMW-5
7/18/02	-7	5.33	5.58	5.18	4.19	4.37	4.63	5.5	5.6	4.24
8/8/02	14	**5.52**	**5.74**	**5.97**	**4.47**	**4.56**	**4.84**	**5.28**	**6**	**4.4**
9/12/02	49	6.16	5.03	5.19	3.74	4.6	4.41	5.9	6.17	4.75
9/12/02	49	**6.4**	**5.75**	**6.08**	**4.43**	**5.05**	**4.6**	**5.48**	**5.93**	**4.6**
11/7/02	105	**6.38**	**6.39**	**6.39**	**4.44**	**4.74**	**4.74**	**5.6**	**6.08**	**4.82**
12/12/02	140	**6.2**	**6.43**	**6.33**	**5.02**	**6.28**	**5.66**	**5.93**	**5.8**	**4.8**

[a]Values in bold are laboratory measurements (EPA 150.1) and those in plain text are field probe values.

The alkalinity in each of the wells also showed a marked increase as buffer was added (Tables VIII and IX). The alkalinity in each of the TPMWs reached in excess of 480 mg/L during the course of the study. For example, the alkalinity in TPMW-5 increased from less than 2 mg/L (as $CaCO_3$) prior to the demonstration to 1,600 mg/L on day 105. The data show that the addition of the carbonate/bicarbonate buffer caused an appreciable increase in the alkalinity and the pH of the aquifer underlying the test plot.

Table VIII. Alkalinity Values in the Test Plot with Time

Date	Day	Alkalinity (mg/L) at—								
		TPMW-1s	TPMW-1d	TPMW-2s	TPMW-2d	TPMW-3s	TPMW-3d	TPMW-4s	TPMW-4d	TPMW-5
7/18/02	-7	92	5.4	60	15	< 2.0	16	< 2.0	< 2.0	< 2.0
8/19/02	25	508	200	91	3.9	130	95	14	< 4.0	640
9/12/02	49	160	530	220	69	240	600	49	470	162
10/3/02	70	3200	370	1670	270	710	690	64	320	410
11/7/02	105	680	390	390	740	250	720	480	1040	1600
12/12/02	140	1240	340	1420	150	590	490	340	510	600

Table IX. Alkalinity Values in the Control Plot with Time

Date	Day	Alkalinity (mg/L) at—								
		CPMW-1s	CPMW-1d	CPMW-2s	CPMW-2d	CPMW-3s	CPMW-3d	CPMW-4s	CPMW-4d	CPMW-5
9/12/02	49	150	59	84	20	20	25	34	120	20
11/7/02	105	120	110	89	2	5.9	5.9	26	29	3.9
12/12/02	140	110	110	110	7.9	20	7.9	28	31	7.9

Lactate

Lactate was measured in groundwater samples collected from the test plot using ion chromatography. The samples were analyzed on a Dionex DX-600 ion chromatograph equipped with a Dionex IonPac AS11-HC column. The sample method utilizes a gradient of sodium hydroxide increasing from 1 to 60 mM over a 40-min run time. Complete method details are described in Dionex Application Note 123 "The Determination of Inorganic Anions and Organic Acids in Fermentation Broths." To ensure that lactate was not biodegraded prior to analysis, groundwater samples (20-mL volume) were passed through sterile 0.22-µm-pore-size cellulose acetate filters in the field. The water was collected in sterile 50-mL conical tubes and stored at 4 °C until analysis.

Lactate was detected in groundwater from seven of nine TPMWs by day 14, and all wells had measurable concentrations of lactate by day 25 (Table X). The lactate levels varied somewhat by well and with time; however, the electron donor was detected consistently above 10 ppm in eight of the nine wells during the course of the demonstration, and each of the eight wells had levels exceeding 100 ppm at one or more sample points. At the end of the demonstration period on day 140, 29 days after system shut-down on Day 111, lactate was below detection in seven of nine TPMWs. Among the test plot wells tested during the demonstration, TPMW-1d generally had the lowest concentration of lactate (< 7 ppm on five of six samplings), and the groundwater collected from this well never exceeded 21 ppm lactate. This was also the one well in which perchlorate levels declined only marginally (43%) during the demonstration (see below) and in which nitrate never declined below 1 ppm. Thus, the data suggest that either

the electron donor did not reach the area surrounding this well at high enough concentrations to support complete reduction of perchlorate, or the electron donor was rapidly consumed by biological processes other than perchlorate reduction (i.e., denitrification and aerobic respiration). The latter process could have occurred if "new" water (containing oxygen and nitrate) was entering the treatment zone preferentially near this well. The presence of oxygen and nitrate would inhibit perchlorate reduction and cause excess consumption of lactate. The close proximity of this well to one of the treatment plot injection wells could have impacted water flow in this region, causing water from outside the treatment area to enter the region surrounding the well preferentially.

Table X. Lactate Values in the Test Plot with Time

Date	Day	Lactate (mg/L) at—								
		TPMW-1s	TPMW-1d	TPMW-2s	TPMW-2d	TPMW-3s	TPMW-3d	TPMW-4s	TPMW-4d	TPMW-5
8/8/02	14	139	6	34	37	249	249	< 0.5	< 0.5	376
8/19/02	25	15	21	96	35	85	463	652	562	390
9/12/02	49	38	3.8	68	248	97	159	44	297	114
10/3/02	70	410	2.2	170	21	15	130	12	40	11
11/7/02	105	83	0.18	56	16	2.9	35	21	7.1	15
12/12/02	140	110	< 0.5	230	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5

Perchlorate

Perchlorate in groundwater was analyzed according to EPA Method 314.0. Perchlorate levels throughout the test plot showed a steady decline during the 5-month field demonstration (Figures 22 and 23 and Table XI). During the two baseline sampling events (69 and 7 days before system startup), perchlorate levels ranged from a low of 72 mg/L in well TPMW-3s to a high of 276 mg/L in TPMW-2d. The average perchlorate level in the test plot was 171 mg/L on 10 May (69 days prior to startup) and 174 mg/L on 18 July (7 days prior to startup). By the end of the 20-week demonstration, perchlorate levels in two test wells (TPMW-1s and TPMW-2s) were below the practical quantitation limit (PQL) of 5 µg/L, one well was less than 20 µg/L (TPMW-5), and two additional wells were less than 1 mg/L. The reduction in aqueous perchlorate from the start of the demonstration was in excess of 99% for each of these wells. Of the remaining four wells in the test plot, two displayed perchlorate concentrations of less than 3.7 mg/L (TPMW-3s and TPMW-3d) at the end of the demonstration, and one (TPMW-4d) was less than 10 mg/L. However, perchlorate in groundwater from TPMW-4d had reached levels as low as 2 mg/L during system operation. The percent reduction in perchlorate in each of these wells exceeded 95% from the start to the end of the demonstration. The only well in which perchlorate levels did not decline precipitously during the demonstration was TPMW-1d. Perchlorate levels fell by only 43% in this well, ending at approximately 90 mg/L after 140 days. As previously noted, this well consistently had the lowest concentration of electron donor, and the highest residual nitrate levels during the demonstration. It is likely that the flow pattern in the vicinity of this well continually introduced water from outside of the treatment area.

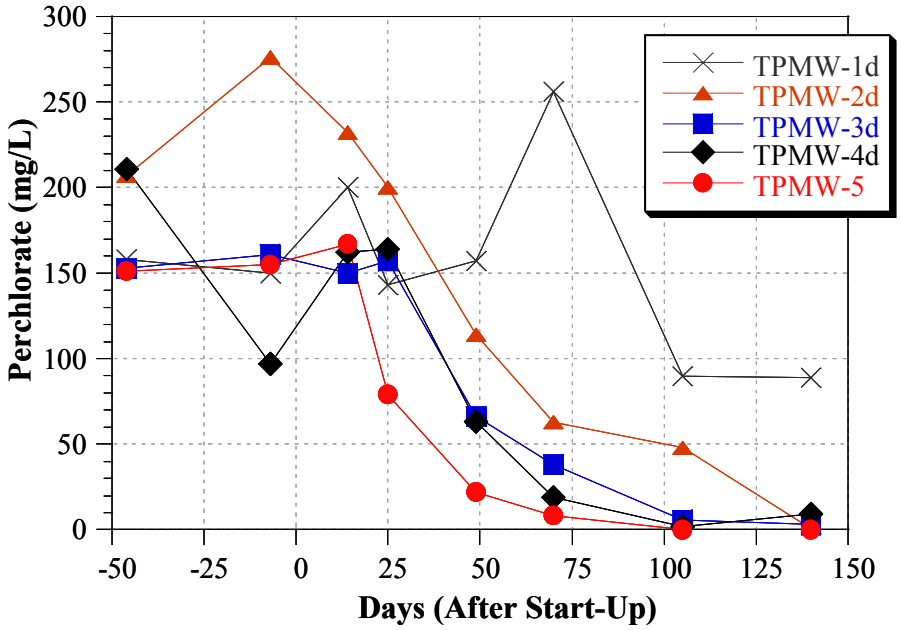


Figure 22. Perchlorate Levels in Deep TPMWs During the Field Demonstration

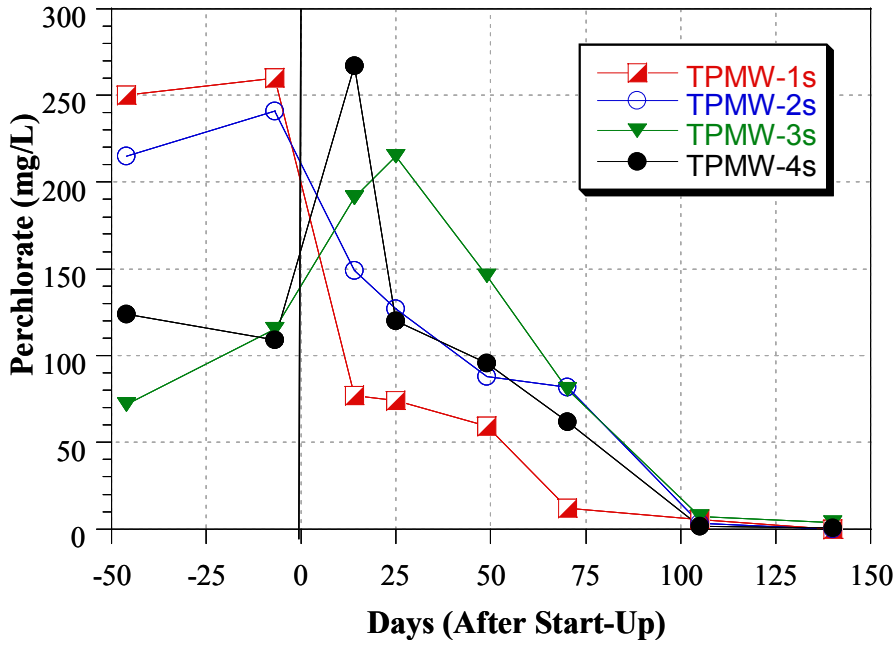


Figure 23. Perchlorate Levels in Shallow TPMWs During the Field Demonstration

Table XI. Perchlorate Concentrations in the Test Plot with Time

Date	Day	Perchlorate (mg/L) at—								
		TPMW-1s	TPMW-1d	TPMW-2s	TPMW-2d	TPMW-3s	TPMW-3d	TPMW-4s	TPMW-4d	TPMW-5
5/10/02	-69	250	158	215	207	72	153	124	211	151
7/18/02	-7	260	150	241	276	115	161	109	97	155
8/8/02	14	77	200	149	232	191	150	267	161	167
8/19/02	25	74	143	127	190	234	160	125	154	93
9/12/02	49	59.2	157	87.7	114	149	66.3	95.9	63.5	22.2
10/3/02	70	12.1	256	81.6	62.9	80.5	32.7	61.9	19	8.3
11/7/02	105	5.5	89	3.3	64	7.2	10.6	1.7	2	0.2
12/12/02	140	< 0.005	89.9	< 0.005	0.89	3.65	3.3	0.815	9.19	0.0196

Unlike the test plot, there was no consistent reduction in perchlorate levels in any of the wells in the control plot during the demonstration period (Figure 24 and Table XII). The average perchlorate concentration in the nine CPMWs 69 days prior to system startup was 127 mg/L, and after 140 days of system operation, the concentration was 118 mg/L. A similar amount of water was re-circulated through both plots during the demonstration, but the water in the control plot received no amendments.

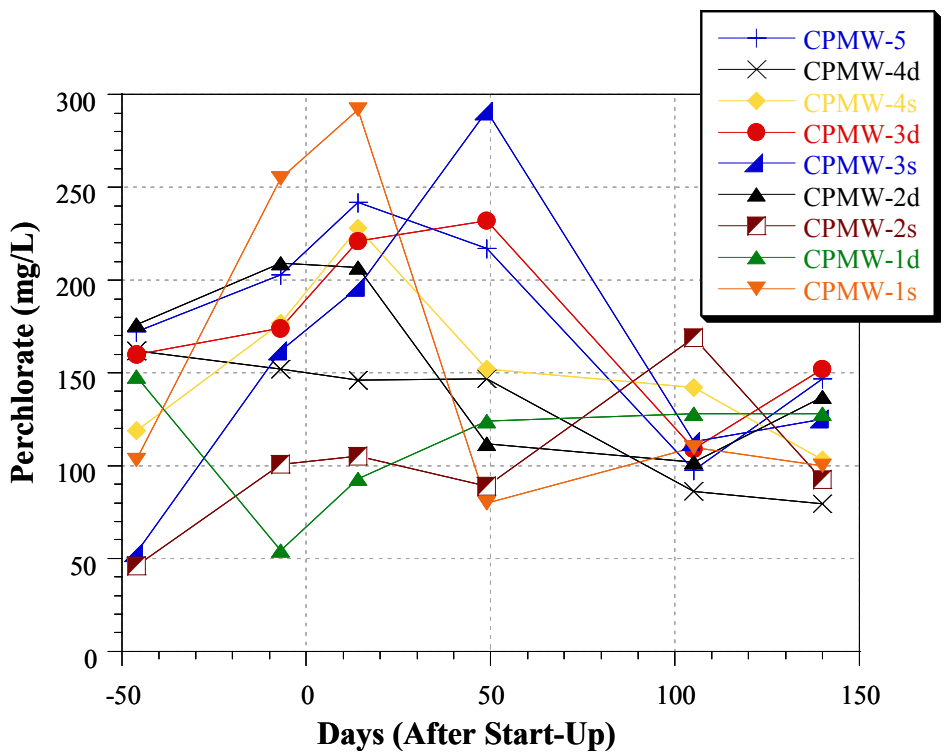


Figure 24. Perchlorate Levels in CPMWs During the Field Demonstration

Table XII. Perchlorate Concentrations in the Control Plot with Time

Date	Day	Perchlorate (mg/L) at—								
		CPMW-1s	CPMW-1d	CPMW-2s	CPMW-2d	CPMW-3s	CPMW-3d	CPMW-4s	CPMW-4d	CPMW-5
5/10/02	-69	103	148	46	176	53	160	119	162	172
7/18/02	-7	255	54.5	101	209	162	174	177	152	203
8/8/02	14	292	93.2	105	207	196	221	228	146	242
9/12/02	49	79.9	124	89	112	291	232	152	147	217
11/7/02	105	110	128	169	102	113	109	142	86.3	97.5
12/12/02	140	100	128	92.3	137	125	152	103	79.5	147

The data from the demonstration clearly show that the addition of buffer and electron donor to the test plot stimulated the microbial reduction of perchlorate in the aquifer. Losses of perchlorate to dilution or any other abiotic process would have been observed in both plots. The data also show that even in an acidic aquifer with extremely high perchlorate levels, in situ biological reduction can effectively reduce perchlorate concentrations to less than 5 µg/L in a reasonably short period. Although a treatment level of 5 µg/L for perchlorate was not achieved in every well, a reduction in perchlorate levels exceeding 95% was observed in eight of the nine TPMWs, including those screened in the shallow, less conductive zone in the aquifer. Based on the trends of perchlorate removal observed during the demonstration, it is likely that many of the other TPMWs would have reached non-detect levels of perchlorate with additional time of system operation.

Nitrate and Sulfate

Although the focus of this demonstration was the biological reduction of perchlorate, levels of other common electron acceptors, including nitrate and sulfate, were monitored. Nitrate reduction (i.e., denitrification) occurs by a biological process similar to perchlorate reduction and generally occurs prior to perchlorate degradation. Nitrate is a regulated pollutant in the U.S., although the Federal Regulatory Level is 10 ppm, much higher than that anticipated for perchlorate (i.e., 1 to 6 µg/L). The biological reduction of sulfate occurs after perchlorate reduction and produces hydrogen sulfide, which has a “rotten egg” odor that is undesirable in groundwater. Thus, one goal of in situ treatment systems for perchlorate and/or nitrate is to mix and distribute electron donor effectively so that sulfate reduction is minimized after reduction of the previous two electron acceptors is complete. This is readily accomplished in ex situ treatment systems (such as biological reactors), but more difficult in in situ applications.

Nitrate and sulfate were measured in groundwater samples by EPA Method 300. The levels of nitrate in the test plot declined rapidly in several wells (Figure 25 and Table XIII). The levels of this contaminant average slightly above 2 mg/L as nitrate-N prior to the investigation in the test plot. Nitrate was below detection (< 0.2 mg/L nitrate-N) in seven of nine TPMWs by day 49 of the study. As noted for perchlorate, TPMW-1d showed the slowest decline in nitrate concentrations. The starting levels of nitrate in the control plot wells were somewhat higher than in the test plot, averaging above 7 mg/L as nitrate-N at the commencement of the study. However, although there was some variability in nitrate levels from point to point in each well,

there was no consistent reduction in nitrate levels across the control plot during the demonstration (Figure 26 and Table XIV). After 140 days, the average concentration among the nine wells remained above 7 mg/L as nitrate-N.

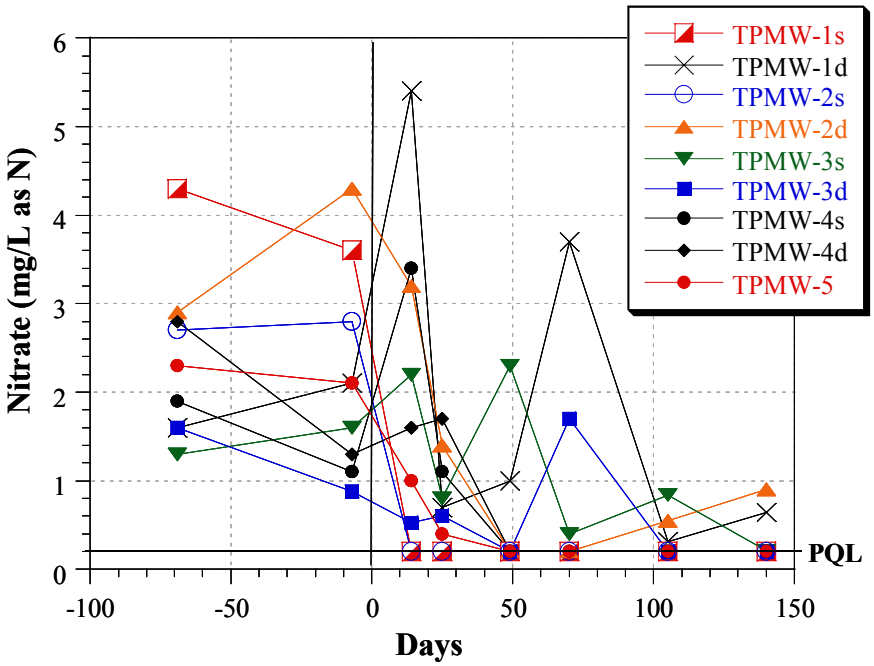


Figure 25. Nitrate Levels in the Test Plot During the Field Demonstration

Table XIII. Nitrate-N Concentrations in the Test Plot with Time

Date	Day	Nitrate-N (mg/L) at—								
		TPMW-1s	TPMW-1d	TPMW-2s	TPMW-2d	TPMW-3s	TPMW-3d	TPMW-4s	TPMW-4d	TPMW-5
5/10/02	-69	4.3	1.6	2.7	2.9	1.3	1.6	1.9	2.8	2.3
7/18/02	-7	3.6	2.1	2.8	4.3	1.6	0.88	1.1	1.3	2.1
8/8/02	14	< 0.2	5.4	< 0.2	3.2	2.2	0.52	3.4	1.6	1
8/19/02	25	< 0.2	0.7	< 0.2	1.4	0.8	0.6	1.1	1.7	0.4
9/12/02	49	< 0.2	1.0	< 0.2	< 0.2	2.3	< 0.2	< 0.2	< 0.2	< 0.2
10/3/02	70	< 0.2	3.7	< 0.2	< 0.2	0.4	1.7	< 0.2	< 0.2	< 0.2
11/7/02	105	< 0.2	0.31	< 0.2	0.55	0.84	< 0.2	< 0.2	< 0.2	< 0.2
12/12/02	140	< 0.2	0.64	< 0.2	0.9	0.21	< 0.2	< 0.2	< 0.2	< 0.2

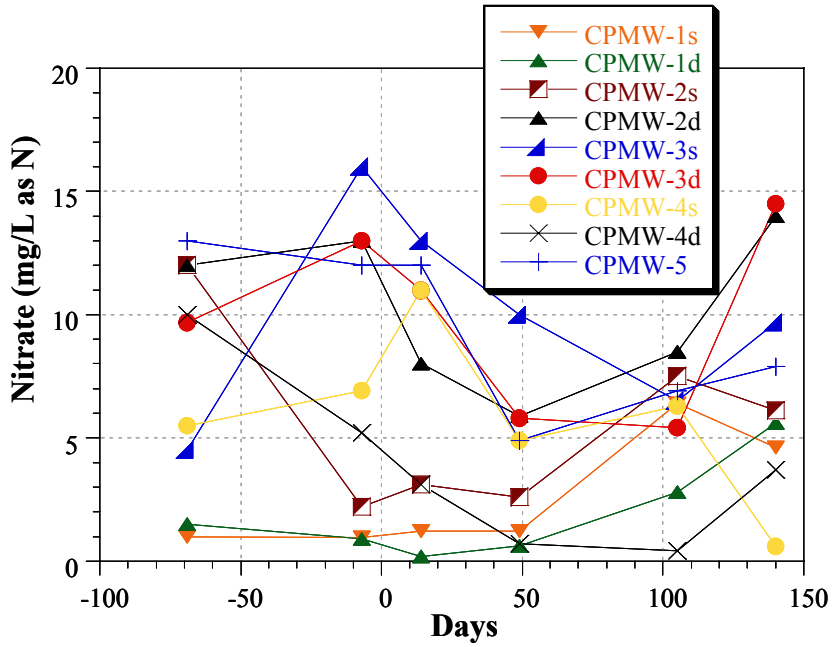


Figure 26. Nitrate Levels in the Control Plot During the Field Demonstration

Table XIV. Nitrate-N Concentrations in the Control Plot with Time

Date	Day	Nitrate-N (mg/L) at—								
		CPMW-1s	CPMW-1d	CPMW-2s	CPMW-2d	CPMW-3s	CPMW-3d	CPMW-4s	CPMW-4d	CPMW-5
5/10/02	-69	1	1.5	12	12	4.5	9.7	5.5	10	13
7/18/02	-7	0.96	0.9	2.2	13	16	13	6.9	5.2	12
8/8/02	14	1.2	< 0.2	3.1	8	13	11	11	3.1	12
9/12/02	49	1.2	0.61	2.6	5.9	10	5.8	4.9	0.7	4.9
11/7/02	105	6.4	2.8	7.5	8.5	6.5	5.4	6.3	0.42	6.9
12/12/02	140	4.6	5.6	6.1	14	9.7	14.5	0.58	3.7	7.9

There was a slight odor of hydrogen sulfide detected in some of the test plot wells during the demonstration, and the presence of a black precipitate was observed in a few wells on these occasions (presumably iron sulfide). During the short demonstration time, the goal was to supply adequate electron donor to achieve nitrate and perchlorate reduction, rather than to tightly control the process. If the demonstration were conducted for a longer period, the level of excess electron donor could have been minimized further. However, overall, the level of sulfate reduction in the test plot was not significant based on sulfate measurements (Figure 27 and Tables XV and XVI). The average concentration at the start of the demonstration in the nine TPMWs was 174 mg/L, and at the end of the demonstration the average was 240 mg/L. The only well that showed a significant decrease in sulfate concentration was TPMW-2s, but this was based on one point collected at day 140. Levels were normal at the previous sampling time on day 105.

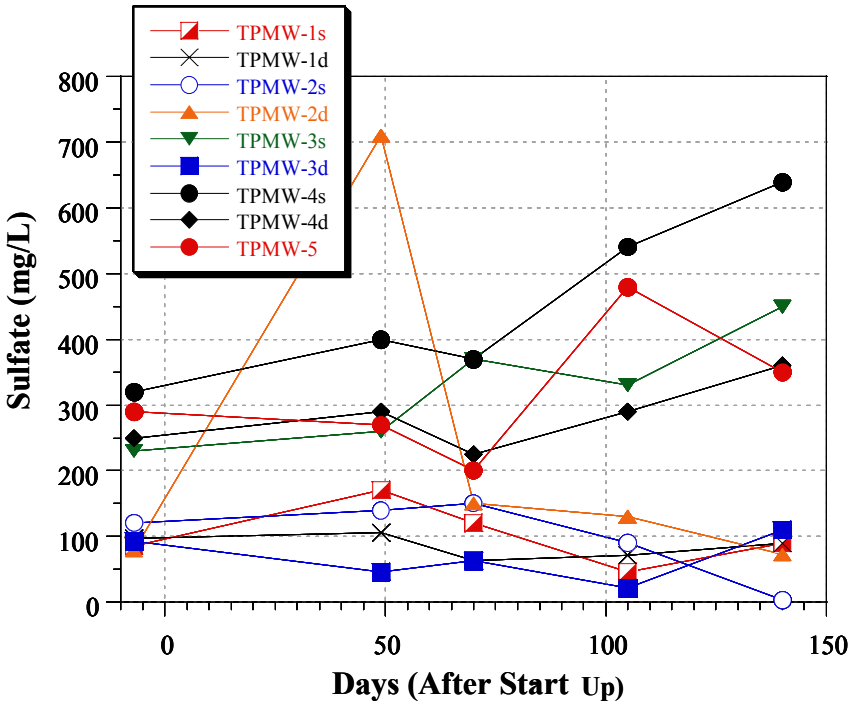


Figure 27. Sulfate Levels in the Test Plot During the Field Demonstration

Table XV. Sulfate Concentrations in the Test Plot with Time

Date	Day	Sulfate (mg/L) at—								
		TPMW-1s	TPMW-1d	TPMW-2s	TPMW-2d	TPMW-3s	TPMW-3d	TPMW-4s	TPMW-4d	TPMW-5
7/18/02	-7	85	97	120	79	230	93	320	250	290
9/12/02	49	170	106	140	710	260	46	400	290	270
10/3/02	70	120	63	150	150	370	63	370	225	200
11/7/02	105	46	71	91	130	330	21	540	290	480
12/12/02	140	89	89	3.7	72	450	110	640	360	350

Table XVI. Sulfate Concentrations in the Control Plot with Time

Date	Day	Sulfate (mg/L) at—								
		CPMW-1s	CPMW-1d	CPMW-2s	CPMW-2d	CPMW-3s	CPMW-3d	CPMW-4s	CPMW-4d	CPMW-5
9/12/02	49	67	89	150	99	60	68	105	77	110
11/7/02	105	99	120	110	99	120	95	130	82	110
12/12/02	140	120	110	150	86	109	74	79	150	120

CONCLUSIONS

This study represents one of the first successful field demonstrations of in situ perchlorate bioremediation in a groundwater aquifer. To our knowledge, this is the first field trial conducted on the East Coast of the United States, the first trial performed in an acidic aquifer, and the first demonstration that perchlorate levels in excess of 200 mg/L can be treated in situ. Thus, we believe that this project provides new and valuable information concerning the application of bioremediation for in situ perchlorate treatment.

The general conclusions from this field demonstration are as follows:

1. The acidic aquifer in the vicinity of Building 1419 was effectively buffered using an aqueous mixture of carbonate and bicarbonate. The buffer increased local groundwater pH from values as low as 3.8 to values exceeding 5.9 for all test plot wells. The alkalinity in each of the wells reached in excess of 480 mg/L during the study.

2. The system design, which generated a recirculation cell within the aquifer, provided an effective distribution of buffer and electron donor throughout the saturated zone, even though the aquifer was characterized by regions with widely differing geology and conductivity.

3. In situ perchlorate biodegradation was rapidly observed using lactate as an electron donor. Perchlorate levels were reduced by more than 95% in eight of the nine monitoring wells within the test plot during the demonstration. In two wells, with starting perchlorate concentrations in excess of 210 mg/L, final perchlorate levels after 20 weeks of treatment were less than the PQL of 5 µg/L. Conversely, there was no significant reduction in perchlorate levels in the control plot.

4. Nitrate-N levels in the test plot were reduced to below detection in seven of the nine monitoring wells within 7 weeks. The other two wells had nitrate-N concentrations less than 1 mg/L at the end of the 20-week study. There was no significant reduction in nitrate-N in the control plot during the demonstration.

5. Sulfide was detected by odor in some of the test plot monitoring wells during the demonstration. However, analytical data revealed no appreciable reduction in sulfate levels throughout the test plot during the demonstration period. In future work at the site, tests should be performed to optimize electron donor delivery such that sulfate reduction is completely inhibited.

6. The field pilot results suggest that the addition of buffer and electron donor to the shallow aquifer behind Building 1419 using a recirculation cell for mixing and distribution of the amendments is a viable approach for perchlorate remediation at this location. However, groundwater recirculation may have to be interrupted periodically during times of high rainfall due to flooding and a high water table in the area.

7. Data from the demonstration suggest that in situ bioremediation will be a viable option for perchlorate treatment in aquifers containing localized, high concentrations of the oxidant. These include source areas from hog-out operations, demolition and open burn areas, and other regions where perchlorate or perchlorate-laden fuels are discharged.

REFERENCES

Achenbach, L.A., Michaelidou, U., Bruce, R.A., Fryman, J., and Coates, J.D. (2001). *Dechloromonas agitata* gen. nov., sp. nov. and *Dechlorosoma suillum* gen. nov., sp. nov., two novel environmentally dominant (per)chlorate-reducing bacteria and their phylogenetic position. International Journal of Systematic and Evolutionary Microbiology, 51, 527-533.

Betts, K.S. (2000). Accelerating perchlorate detection. Environmental Science and Technology, 34, 245A-246A.

CDHS; California Department of Health Services. (1997). Determination of perchlorate by ion chromatography. Website: http://www.dhs.ca.gov/ps /ddwem/chemicals /perchl/ clo4meth.pdf.

CDHS; California Department of Health Services. (2003). Perchlorate in California Drinking Water: Monitoring Update. Website: http://www.dhs.ca.gov/ps/ddwem/chemicals/perchl/ monitoringupdate.htm.

Coates, J.D., Michaelidou, U., Bruce, R.A., O'Conner, S.M., Crespi, J.N., and Achenbach, L.A. (1999). The ubiquity and diversity of dissimilatory (per)chlorate-reducing bacteria. Applied and Environmental Microbiology, 65, 5234-5241.

Damian, P., and Pontius, F.W. (1999). From rockets to remediation: the perchlorate problem. Environmental Protection, June, 24-31.

Greene, M.R., and Pitre, M.P. (2000). Treatment of groundwater containing perchlorate using biological fluidized bed reactors with GAC or sand media. pp. 241-256, In E.T. Urbansky (Ed), Perchlorate in the environment. Kluwer Academic/Plenum Publishers, New York.

Hatzinger, P.B. (2002). In situ bioremediation of perchlorate. Final Report for SERDP Project CU-1163. Strategic Environmental Research and Development Program, Arlington, VA. 131 pp.

Hatzinger, P.B., Greene, M.R. Frisch, S., Togna, A.P. Manning, J., and Guarini, W.J. (2000). Biological treatment of perchlorate-contaminated groundwater using fluidized bed reactors. pp. 115-122. In G.B. Wickramanayake et al. (Eds). Case studies in the remediation of chlorinated and recalcitrant compounds, Battelle Press, Columbus, OH.

Hatzinger, P.B., Whittier, M.C., Arkins, M.D., Bryan, C.W., and Guarini, W.J. (2002). In-situ and ex-situ bioremediation options for treating perchlorate in groundwater. Remediation, 12, 69-86.

Kengen, S.W.M., Rikken, G.B., Hagen, W.R., van Ginkel, C.G., and Stams, A.J.M. (1999). Purification and characterization of (per)chlorate reductase from chlorate-respiring strain GR-1. Journal of Bacteriology, 181, 6706-6711.

Logan, B.E. (1998). A review of chlorate- and perchlorate-respiring microorganisms. Bioremediation Journal, 2, 69-79.

Logan, B.E. (2001). Assessing the outlook for perchlorate remediation, Environmental Science and Technology, 35, 483A-487A.

Miller, J.P. and Logan, B.E. (2000). Sustained perchlorate degradation in an autotrophic, gas-phase, packed-bed bioreactor. Environmental Science and Technology, 34, 3018-3022.

Rikken, G.B., Kroon, A.G.M., and van Ginkel, C.G. (1996). Transformation of (per)chlorate into chloride by a newly isolated bacterium: reduction and dismutation. Applied Microbiology and Biotechnology, 45, 420-426.

Urbansky, E.T. (1998). Perchlorate chemistry: implications for analysis and remediation. Bioremediation Journal, 2, 81-95.

USEPA; U.S. Environmental Protection Agency. (2001). Perchlorate. Office of Water. Website: http://www.epa.gov/safewater/ccl/perchlor/ perchlo.html.

van Ginkel, C.G., Rikken, G.B., Kroon, A.G.M., Kengen, S.W.M. (1996). Purification and characterization of a chlorite dismutase: a novel oxygen-generating enzyme. Archives of Microbiology, 166, 321-326.

Wetzel, R.G. (1975). Limnology. W. B. Saunders Co., Philadelphia, PA.

Wu, J., Unz, R.F., Zhang, H., and Logan, B.E. (2001). Persistence of perchlorate and the relative numbers of perchlorate- and chlorate-respiring microorganisms in natural waters, soils, and wastewater. Bioremediation Journal, 5, 119-130.

Appendix A

TYPICAL WELL CONSTRUCTION AND SOIL BORING LOGS

ENVIROGEN

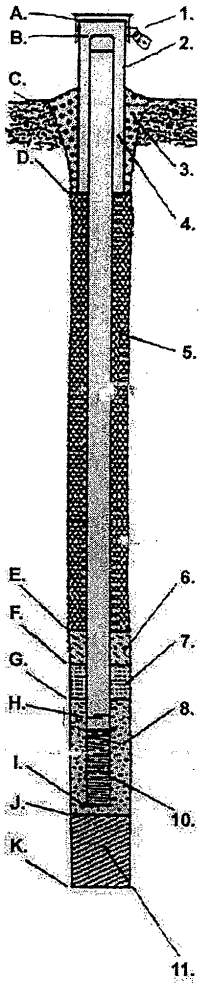
Monitoring Well Construction

Facility/Project Name INDIAN HEAD BUILDING 1419	Well Name TPRW-1
Facility License, Permit or Monitoring No.	Date of Well Installation 05/08/02 M/D/Y
Facility ID 010206	Well Installed By: Name (first, last) & Firm CARL HUGO C.R. HUGO DRILLERS
Type of Well MONITORING WELL	
Distance from Waste/Source _____ ft.	Enf. Stds. Apply □

A. Protective pipe, top elevation.	N/A
B. Well casing, top elevation.	N/A
C. Land surface elevation.	N/A
D. Surfaces seal, bottom.	1.5 ft

12. USCS classification of soil near screen:
GP □ GM □ GC □ GW □ SW □ SP □
SM □ SC □ ML □ MH □ CL ■ CH □
Bedrock □
13. Sieve analysis performed? Yes □ No ■
14. Drilling method used:
Rotary □ _ _
Hollow Stem Auger ■ _ _
_____ Other □ _ _
15. Drilling fluid used:
Water □ _ _ Air □ _ _
Drilling Mud □ _ _ None ■ _ _
16. Drilling additives used? Yes □ No ■
Describe _____
17. Source of water (attach analysis if required)

E. Bentonite seal, top	1.5 ft.
F. Fine sand, top	3.5 ft.
G. Filter pack, top	3.5 ft
H. Screen joint, top	5 ft
I. Well bottom	17 ft
J. Filter pack, bottom	17 ft
K. Borehole, bottom	17 ft
L. Borehole, diameter	12.25 in.
M. O.D. Well casing	6.33.in.
N. I.D. Well casing	6 in



1. Cap and lock? NO
2. Protective cover pipe:
a. Inside diameter: 10 in.
b. Length: 1 ft.
c. Material: Steel □ _ _
ALUMINUM Other ■ _ _
d. Additional protection? Yes □ No ■
If yes, describe _____
3. Surface seal: Bentonite □ _ _
Concrete ■ _ _
Other □ _ _
4. Material between well casing and protective pipe:
Bentonite ■ _ _
_____ Other □ _ _
5. Annular space seal:
a. Granular/Chipped Bentonite ■ _ _
b. ___Lbs/gal mud weight Bentonite-sand slurry □ _ _
c. ___Lbs/gal mud weight... Bentonite slurry □ _ _
d. ___% Bentonite... Bentonite-cement grout □ _ _
e. 0.68 ft^3 volume added for any of the above
f. How installed: Tremie □ _ _
Tremie pumped □ _ _
Gravity ■ _ _
6. Bentonite seal: a. Bentonite granules □ _ _
b. □ ¼ in. □ 3/8 in. □ ½ in. Bentonite chips ■ _ _
c. _____ Other □ _ _
7. Fine sand material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
8. Filter pack material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
b. Volume added 4.59 ft^3
9. Well casing:
Flush threaded PVC schedule 40 ■ _ _
Flush threaded PVC 80 □ _ _
_____ Other □ _ _
10. Screen material: PVC
a. Screen type: Factory cut ■ _ _
Continuous slot □ _ _
_____ Other □ _ _
b. Manufacturer _____
c. Slot size: 0.01 in.
d. Slotted length: 12 ft.
11. Backfill material (below filter pack) None ■ _ _
_____ Other □ _ _

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature RIE BILES	Firm ENVIROGEN, INC

For Official Use Only

ENVIROGEN

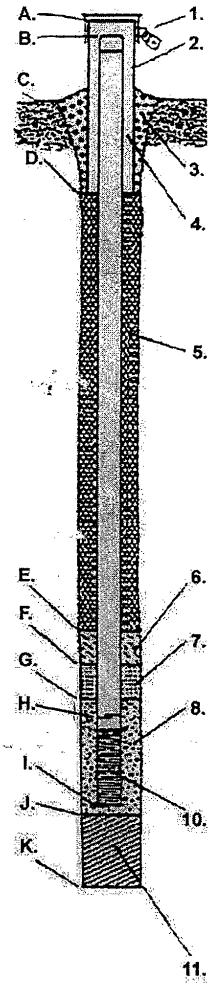
Monitoring Well Construction

Facility/Project Name DIAN HEAD BUILDING 1419	Well Name TPIW-1
ility License, Permit or Monitoring No.	Date of Well Installation 05/08/02 M/D/Y
Facility ID 010206	Well Installed By: Name (first, last) & Firm CARL HUGO C.R. HUGO DRILLERS
Type of Well MONITORING WELL	
Distance from Waste/Source _____ ft.	Enf. Stds. Apply □

A. Protective pipe, top elevation.	N/A
B. Well casing, top elevation.	NA
C. Land surface elevation.	N/A
D. Surfaces seal, bottom.	2 ft

12. USCS classification of soil near screen:
GP □ GM □ GC □ GW □ SW □ SP □
SM □ SC □ ML □ MH □ CL ■ CH □
Bedrock □
13. Sieve analysis performed? Yes □ No ■
14. Drilling method used:
Rotary □ _ _
Hollow Stem Auger ■ _ _
_____ Other □ _ _
15. Drilling fluid used:
Water □ _ _ Air □ _ _
Drilling Mud □ _ _ None ■ _ _
16. Drilling additives used? Yes □ No ■
Describe _____
17. Source of water (attach analysis if required)

E. Bentonite seal, top	2 ft.
F. Fine sand, top	6 ft.
G. Filter pack, top	5 ft
H. Screen joint, top	6 ft
I. Well bottom	13 ft
J. Filter pack, bottom	13 ft
K. Borehole, bottom	13 ft
L. Borehole, diameter	12.25 in.
M. O.D. Well casing	6.33.in.
N. I.D. Well casing	6 in



1. Cap and lock? NO
2. Protective cover pipe:
a. Inside diameter: 12 in.
b. Length: 2 ft.
c. Material: Steel □ _ _
ALUMINUM Other ■ _ _
d. Additional protection? Yes □ No ■
If yes, describe _____
3. Surface seal: Bentonite □ _ _
Concrete ■ _ _
Other □ _ _
4. Material between well casing and protective pipe:
Bentonite ■ _ _
_____ Other □ _ _
5. Annular space seal:
a. Granular/Chipped Bentonite ■ _ _
b. ___Lbs/gal mud weight Bentonite-sand slurry □ _ _
c. ___Lbs/gal mud weight... Bentonite slurry □ _ _
d. ___% Bentonite... Bentonite-cement grout □ _ _
e. 0.68 ft^3 volume added for any of the above
f. How installed: Tremie □ _ _
Tremie pumped □ _ _
Gravity ■ _ _
6. Bentonite seal: a. Bentonite granules □ _ _
b. □ ¼ in. □ 3/8 in. □ ½ in. Bentonite chips ■ _ _
c. _____ Other □ _ _
7. Fine sand material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
8. Filter pack material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
b. Volume added 2.72 ft^3
9. Well casing:
Flush threaded PVC schedule 40 ■ _ _
Flush threaded PVC 80 □ _ _
_____ Other □ _ _
10. Screen material: PVC
a. Screen type: Factory cut ■ _ _
Continuous slot □ _ _
_____ Other □ _ _
b. Manufacturer _____
c. Slot size: 0.01 in.
d. Slotted length: 7 ft.
11. Backfill material (below filter pack) None ■ _ _
_____ Other □ _ _

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature RIE BILES	Firm ENVIROGEN, INC

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ENVIROGEN

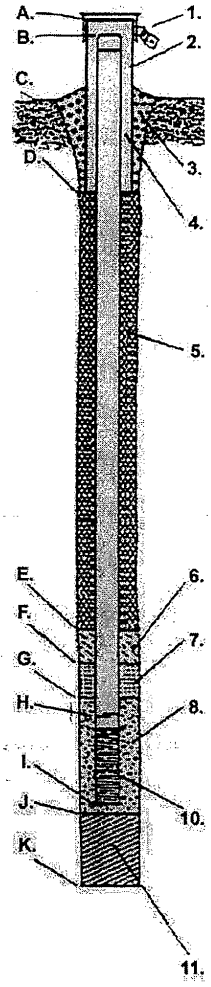
Monitoring Well Construction

Facility/Project Name DIAN HEAD BUILDING 1419	Well Name MW-3
ility License, Permit or Monitoring No.	Date of Well Installation 01/24/01 M/D/Y
Facility ID 010206	Well Installed By: Name (first, last) & Firm STEFAN SMITH TIDE WATER
Type of Well MONITORING WELL	
Distance from Waste/Source _____ ft.	Enf. Stds. Apply □

A. Protective pipe, top elevation.	N/A
B. Well casing, top elevation.	100.91
C. Land surface elevation.	N/A
D. Surfaces seal, bottom.	3 ft

12. USCS classification of soil near screen:
GP □ GM □ GC □ GW □ SW □ SP □
SM □ SC □ ML □ MH □ CL ■ CH □
Bedrock □
13. Sieve analysis performed? Yes □ No ■
14. Drilling method used:
Rotary □ _ _
Hollow Stem Auger ■ _ _
_____ Other □ _ _
15. Drilling fluid used:
Water □ _ _ Air □ _ _
Drilling Mud □ _ _ None ■ _ _
16. Drilling additives used? Yes □ No ■
Describe _____
17. Source of water (attach analysis if required)

E. Bentonite seal, top	3 ft.
F. Fine sand, top	5 ft.
G. Filter pack, top	5 ft
H. Screen joint, top	7 ft
I. Well bottom	17 ft
J. Filter pack, bottom	17 ft
K. Borehole, bottom	17 ft
L. Borehole, diameter	8.25 in.
M. O.D. Well casing	2.33.in.
N. I.D. Well casing	2 in



1. Cap and lock? NO
2. Protective cover pipe:
a. Inside diameter: 6 in.
b. Length: 1 ft.
c. Material: Steel □ _ _
ALUMINUM Other ■ _ _
d. Additional protection? Yes □ No ■
If yes, describe _____
3. Surface seal: Bentonite □ _ _
Concrete □ _ _
SAND Other ■ _ _
4. Material between well casing and protective pipe:
Bentonite ■ _ _
_____ Other □ _ _
5. Annular space seal:
a. Granular/Chipped Bentonite ■ _ _
b. ___Lbs/gal mud weight Bentonite-sand slurry □ _ _
c. ___Lbs/gal mud weight... Bentonite slurry □ _ _
d. ___% Bentonite... Bentonite-cement grout □ _ _
e. 0.68 ft^3 volume added for any of the above
f. How installed: Tremie □ _ _
Tremie pumped □ _ _
Gravity ■ _ _
6. Bentonite seal: a. Bentonite granules □ _ _
b. □ ¼ in. □ 3/8 in. □ ½ in. Bentonite chips ■ _ _
c. _____ Other □ _ _
7. Fine sand material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
8. Filter pack material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
b. Volume added 4.08 ft^3
9. Well casing:
Flush threaded PVC schedule 40 ■ _ _
Flush threaded PVC 80 □ _ _
_____ Other □ _ _
10. Screen material: PVC
a. Screen type: Factory cut ■ _ _
Continuous slot □ _ _
_____ Other □ _ _
b. Manufacturer _____
c. Slot size: 0.01 in.
d. Slotted length: 10 ft.
11. Backfill material (below filter pack) None ■ _ _
_____ Other □ _ _

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature RIE BILES	Firm ENVIROGEN, INC

For Official Use Only

ENVIROGEN

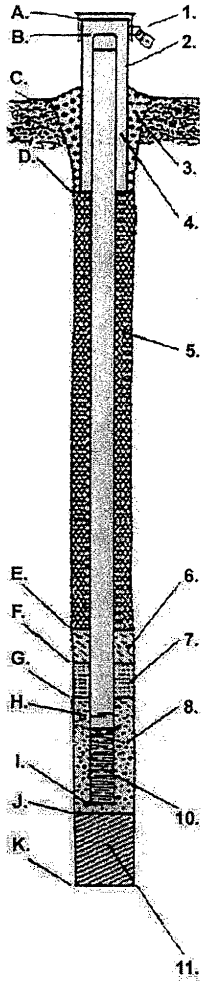
Monitoring Well Construction

Facility/Project Name IAN HEAD BUILDING 1419	Well Name TPMW-3S
..ity License, Permit or Monitoring No.	Date of Well Installation 05/08/02 M/D/Y
Facility ID 010206	Well Installed By: Name (first, last) & Firm CARL HUGO C.R. HUGO DRILLERS
Type of Well MONITORING WELL	
Distance from Waste/Source _____ ft.	Enf. Stds. Apply □

A. Protective pipe, top elevation.	N/A
B. Well casing, top elevation.	N/A
C. Land surface elevation.	N/A
D. Surfaces seal, bottom.	3.5 ft

12. USCS classification of soil near screen:
GP □ GM □ GC □ GW □ SW □ SP □
SM □ SC □ ML □ MH □ CL ■ CH □
Bedrock □
13. Sieve analysis performed? Yes □ No ■
14. Drilling method used:
Rotary □ _ _
Hollow Stem Auger ■ _ _
_____ Other □ _ _
15. Drilling fluid used:
Water □ _ _ Air □ _ _
Drilling Mud □ _ _ None ■ _ _
16. Drilling additives used? Yes □ No ■
Describe _____
17. Source of water (attach analysis if required)

E. Bentonite seal, top	1.5 ft.
F. Fine sand, top	3.5 ft.
G. Filter pack, top	3.5 ft
H. Screen joint, top	4 ft
I. Well bottom	11 ft
J. Filter pack, bottom	11 ft
K. Borehole, bottom	11 ft
L. Borehole, diameter	8.25 in.
M. O.D. Well casing	2.33.in.
N. I.D. Well casing	2 in



1. Cap and lock? NO
2. Protective cover pipe:
a. Inside diameter: 6 in.
b. Length: 1 ft.
c. Material: Steel □ _ _
ALUMINUM Other ■ _ _
d. Additional protection? Yes □ No ■
If yes, describe _____
3. Surface seal: Bentonite □ _ _
Concrete ■ _ _
Other □ _ _
4. Material between well casing and protective pipe:
Bentonite ■ _ _
_____ Other □ _ _
5. Annular space seal:
a. Granular/Chipped Bentonite ■ _ _
b. ___Lbs/gal mud weight Bentonite-sand slurry □ _ _
c. ___Lbs/gal mud weight... Bentonite slurry □ _ _
d. ___% Bentonite... Bentonite-cement grout □ _ _
e. 3.91 ft^3 volume added for any of the above
f. How installed: Tremie □ _ _
Tremie pumped □ _ _
Gravity ■ _ _
6. Bentonite seal: a. Bentonite granules □ _ _
b. □ ¼ in. □ 3/8 in. □ ½ in. Bentonite chips ■ _ _
c. _____ Other □ _ _
7. Fine sand material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
8. Filter pack material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
b. Volume added 1.7 ft^3
9. Well casing:
Flush threaded PVC schedule 40 ■ _ _
Flush threaded PVC 80 □ _ _
_____ Other □ _ _
10. Screen material: PVC
a. Screen type: Factory cut ■ _ _
Continuous slot □ _ _
_____ Other □ _ _
b. Manufacturer _____
c. Slot size: 0.01 in.
d. Slotted length: 7 ft.
11. Backfill material (below filter pack) None ■ _ _
_____ Other □ _ _

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature ..IE BILES	Firm ENVIROGEN, INC

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ENVIROGEN

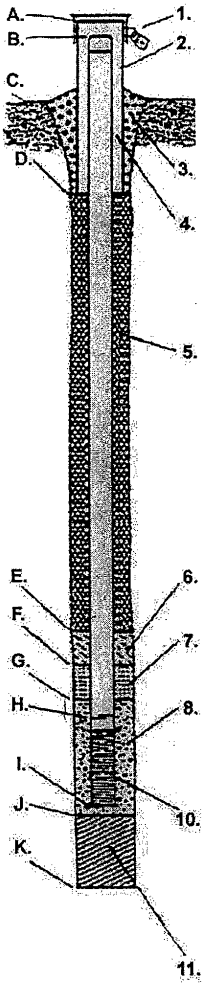
Monitoring Well Construction

Facility/Project Name)IAN HEAD BUILDING 1419	Well Name TPMW-3D
..ility License, Permit or Monitoring No.	Date of Well Installation 05/08/02 M/D/Y
Facility ID 010206	Well Installed By: Name (first, last) & Firm CARL HUGO C.R. HUGO DRILLERS
Type of Well MONITORING WELL	
Distance from Waste/Source _____ ft.	Enf. Stds. Apply □

A. Protective pipe, top elevation.	N/A
B. Well casing, top elevation.	N/A
C. Land surface elevation.	N/A
D. Surfaces seal, bottom.	1.5 ft

12. USCS classification of soil near screen:
GP □ GM □ GC □ GW □ SW □ SP □
SM □ SC □ ML □ MH □ CL ■ CH □
Bedrock □
13. Sieve analysis performed? Yes □ No ■
14. Drilling method used:
Rotary □ _ _
Hollow Stem Auger ■ _ _
_____ Other □ _ _
15. Drilling fluid used:
Water □ _ _ Air □ _ _
Drilling Mud □ _ _ None ■ _ _
16. Drilling additives used? Yes □ No ■
Describe _____
17. Source of water (attach analysis if required)

E. Bentonite seal, top	1.5 ft.
F. Fine sand, top	3.5 ft.
G. Filter pack, top	3.5 ft
H. Screen joint, top	10.5 ft
I. Well bottom	13.5 ft
J. Filter pack, bottom	13.5 ft
K. Borehole, bottom	13.5 ft
L. Borehole, diameter	8.25 in.
M. O.D. Well casing	2.33.in.
N. I.D. Well casing	2 in



1. Cap and lock? NO
2. Protective cover pipe:
a. Inside diameter: 6 in.
b. Length: 1 ft.
c. Material: Steel □ _ _
ALUMINUM Other ■ _ _
d. Additional protection? Yes □ No ■
If yes, describe _____
3. Surface seal: Bentonite □ _ _
Concrete ■ _ _
Other □ _ _
4. Material between well casing and protective pipe:
Bentonite ■ _ _
_____ Other □ _ _
5. Annular space seal:
a. Granular/Chipped Bentonite ■ _ _
b. ___Lbs/gal mud weight Bentonite-sand slurry □_ _
c. ___Lbs/gal mud weight... Bentonite slurry □ _ _
d. ___% Bentonite... Bentonite-cement grout □ _ _
e. 2.21 ft^3 volume added for any of the above
f. How installed: Tremie □ _ _
Tremie pumped □ _ _
Gravity ■ _ _
6. Bentonite seal: a. Bentonite granules □ _ _
b. □ ¼ in. □ 3/8 in. □ ½ in. Bentonite chips ■ _ _
c. _____ Other □ _ _
7. Fine sand material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
8. Filter pack material: Manufacturer, product name & mesh size:
a. FILPRO #2 WG
b. Volume added 1.7 ft^3
9. Well casing:
Flush threaded PVC schedule 40 ■ _ _
Flush threaded PVC 80 □ _ _
_____ Other □ _ _
10. Screen material: PVC
a. Screen type: Factory cut ■ _ _
Continuous slot □ _ _
_____ Other □ _ _
b. Manufacturer _____
c. Slot size: 0.01 in.
d. Slotted length: 3 ft.
11. Backfill material (below filter pack) None ■ _ _
_____ Other □ _ _

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm
..RRIE BILES	ENVIROGEN, INC

For Official Use Only

ENVIROGEN

PROJECT NUMBER	Building 1419 Boring Number: GP07

SOIL BORING LOG

PROJECT : Indian Head — LOCATION : Indian Head, Maryland

ELEVATION : — DRILLING CONTRACTOR : Stefen Smith

DRILLING METHOD AND EQUIPMENT USED : Drill Rig 2" split spoon

START : 1/23/02 — END : 1/23/2002 — LOGGER : Mike Cushman

DEPTH BELOW SURFACE (FT) INTERVAL (FT)	RECOVERY (FT)	USCS CODE	Moisture Content	Munsell Code	CORE DESCRIPTION: SOIL NAME, COLOR RELATIVE DENSITY OR CONSISTENCY, SOIL STRUCTURE, MINERALOGY.	COMMENTS: DEPTH OF CASING, DRILLING RATE, DRILLING FLUID LOSS, TESTS, AND INSTRUMENTATION
0-4'	2.5'		Damp		**FILL:** Black gravel material with mixed organics Olive clayey silt at 3.5'	
4-8'	4'		Moist		**CLAYEY SILT/SANDY SILT**: alternating layers of clayey silt and sandy silt. Colors ranging ranging from olive to light olive brown and mottled.	
8-12'	4'		Saturated		Sand seam at 12'	
12-16'	4'		Saturated		**SAND/GRAVEL:** 13.5 - 15 feet sand and gravel mix **CLAY:** gray clay at 15' to end of boring	

END OF BORING AT 16'

For Official Use Only

ENVIROGEN

PROJECT NUMBER	Building 1419 Boring Number: GP13

SOIL BORING LOG

PROJECT : Indian Head — LOCATION : Indian Head, Maryland

ELEVATION : — DRILLING CONTRACTOR : Stefen Smith

DRILLING METHOD AND EQUIPMENT USED : Drill Rig 2" split spoon

START : 1/23/02 — END : 1/23/2002 — LOGGER : Mike Cushman

DEPTH BELOW SURFACE (FT) INTERVAL (FT)	RECOVERY (FT)	USCS CODE	Moisture Content	Munsell Code	CORE DESCRIPTION: SOIL NAME, COLOR RELATIVE DENSITY OR CONSISTENCY, SOIL STRUCTURE, MINERALOGY.	COMMENTS: DEPTH OF CASING, DRILLING RATE, DRILLING FLUID LOSS, TESTS, AND INSTRUMENTATION
0-4'	4'		Damp		**FILL**: Black gravel material with mixed organics **SILTY SAND**: mottled olive yellow to olive	
4-8'	4'		Moist			
8-12'	4'		Saturated		**CLAYEY SILT**: colors ranging from olive to pale olive with some red, mottled	
12-16'	4'		Saturated		**SAND/SILT/CLAY**: mixture to 15.5 feet, grading into sand with gravel to end of the boring	

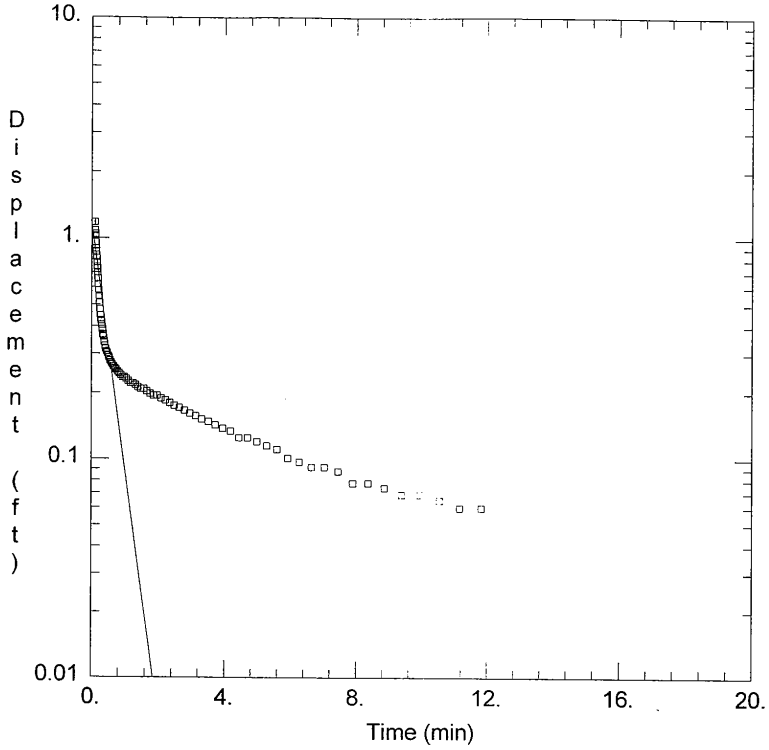
END OF BORING AT 16'

For Official Use Only

Appendix B

SLUG TEST AND PUMP TEST CURVES

For Official Use Only



MW-4 RISING HEAD

Data Set: Q:\APPS\AQTW\MW4OUT.AQT
Date: 03/07/03 Time: 16:25:03

PROJECT INFORMATION

Test Location: Indian Head, MD
Test Well: MW-4
Test Date: 2/14/02

AQUIFER DATA

Saturated Thickness: 11.76 ft
Anisotropy Ratio (Kz/Kr): 1.

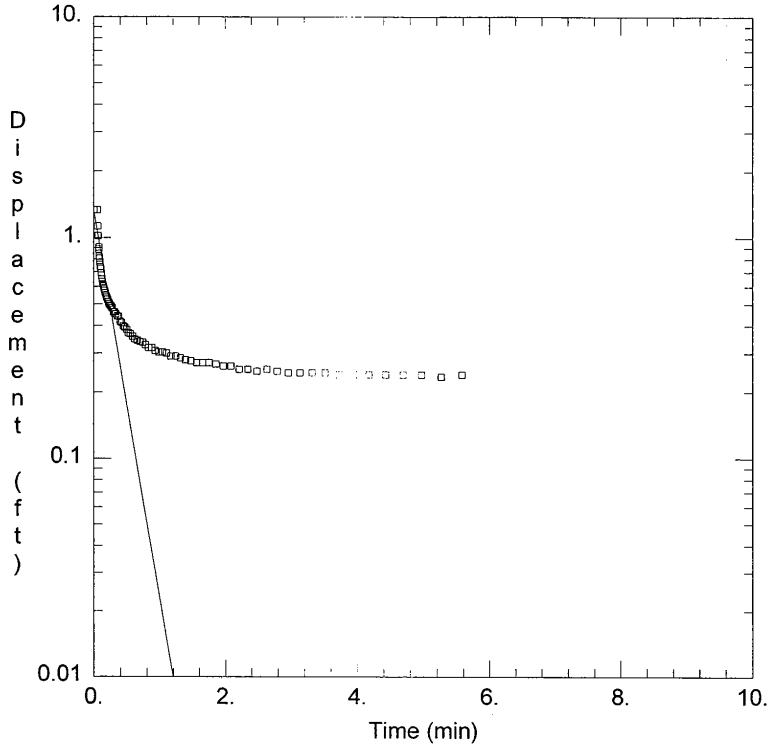
WELL DATA

Initial Displacement: 1.179 ft
Casing Radius: 0.086 ft
Screen Length: 10. ft
Water Column Height: 11.76 ft
Wellbore Radius: 0.344 ft
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 0.01385 ft/min
y0 = 1.168 ft

For Official Use Only



MW-5 RISING HEAD

Data Set: Q:\APPS\AQTW\MW5OUT.AQT
Date: 03/07/03 Time: 16:24:32

PROJECT INFORMATION

Test Location: Indian Head, MD
Test Well: MW-5
Test Date: 2/14/02

AQUIFER DATA

Saturated Thickness: 11. ft
Anisotropy Ratio (Kz/Kr): 1.

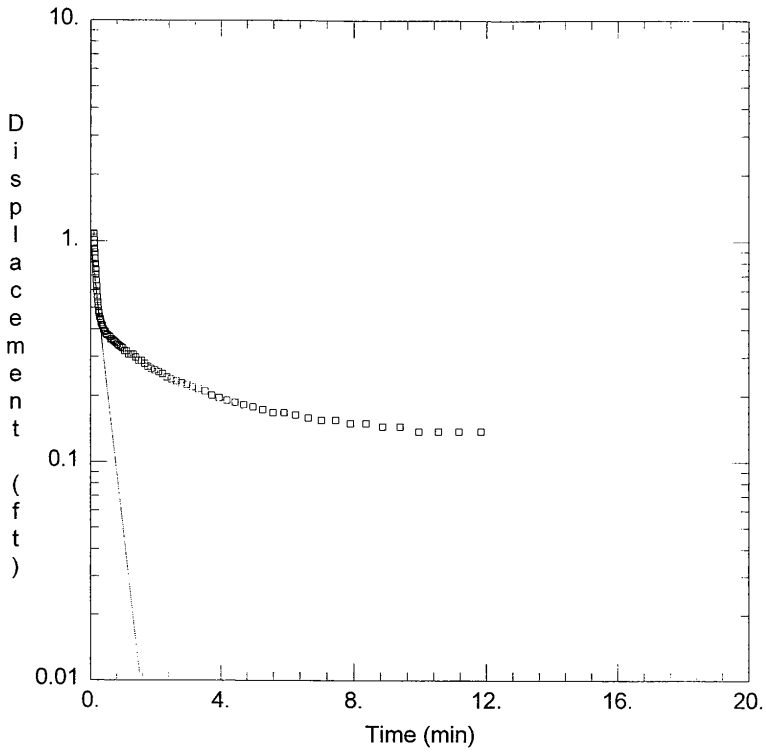
WELL DATA

Initial Displacement: 1.333 ft
Casing Radius: 0.086 ft
Screen Length: 10. ft
Water Column Height: 11. ft
Wellbore Radius: 0.344 ft
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 0.02161 ft/min
y0 = 1.335 ft

For Official Use Only



MW-6 RISING HEAD

Data Set: Q:\APPS\AQTW\MW6OUT.AQT
Date: 03/07/03 Time: 16:19:27

PROJECT INFORMATION

Test Location: Indian Head, MD
Test Well: MW-6
Test Date: 2/14/02

AQUIFER DATA

Saturated Thickness: 11.3 ft
Anisotropy Ratio (Kz/Kr): 1.

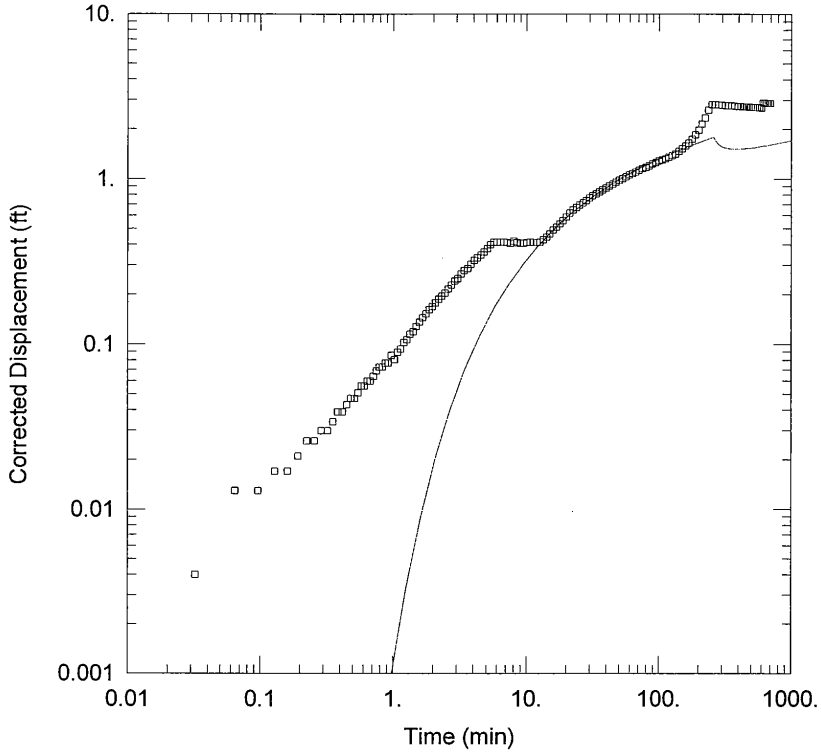
WELL DATA

Initial Displacement: 1.082 ft
Casing Radius: 0.086 ft
Screen Length: 10. ft
Water Column Height: 11.3 ft
Wellbore Radius: 0.344 ft
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 0.01613 ft/min
y0 = 1.017 ft

For Official Use Only



WELL TEST ANALYSIS

Data Set: Q:\APPS\AQTW\PTTLR1.AQT
Date: 02/26/03 Time: 12:09:43

AQUIFER DATA

Saturated Thickness: 11. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
R-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ RW-1	0.1	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 0.1163 ft^2/min
S = 207.6

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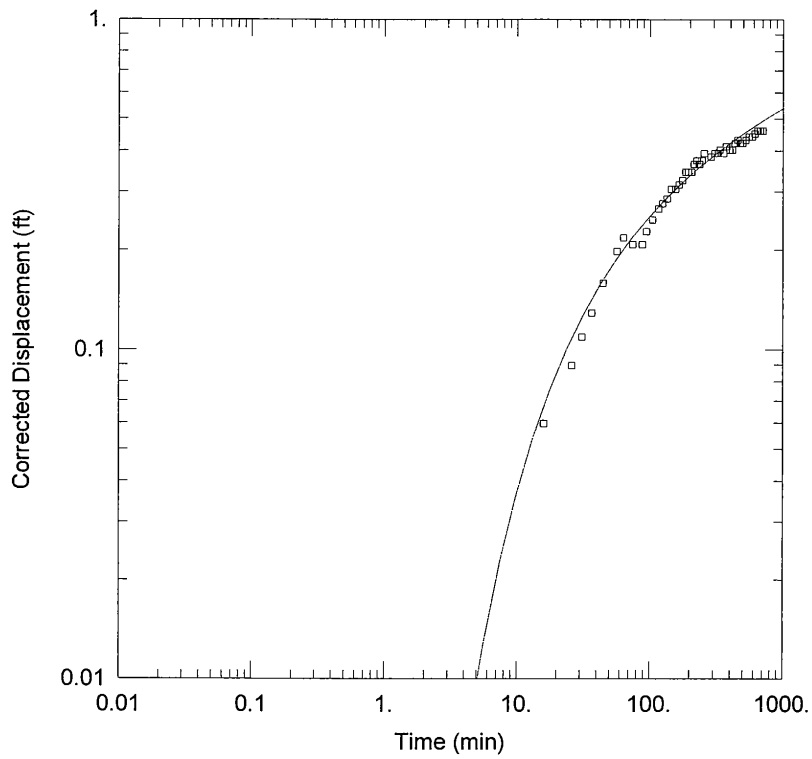

WELL TEST ANALYSIS

Data Set: Q:\APPS\AQTW\PMW4.AQT
Date: 02/26/03 Time: 15:10:18

AQUIFER DATA

Saturated Thickness: 11. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
R-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ mw-4	0	5

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 0.4673 ft^2/min
S = 0.63

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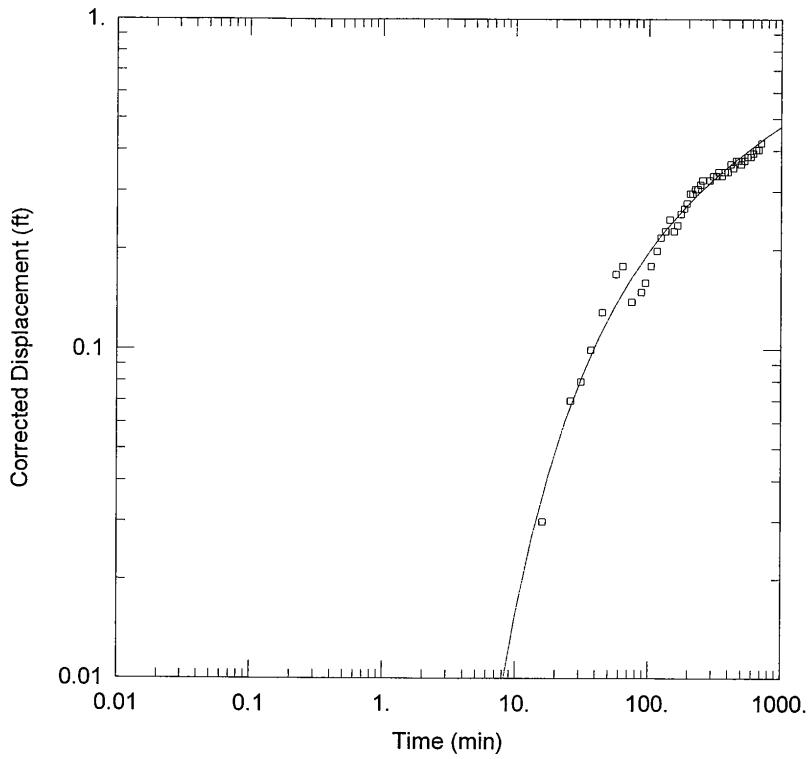


WELL TEST ANALYSIS

Data Set: Q:\APPS\AQTW\PMW5.AQT
Date: 02/26/03 Time: 15:13:25

AQUIFER DATA

Saturated Thickness: 11. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
R-1	0	0

Observation Wells

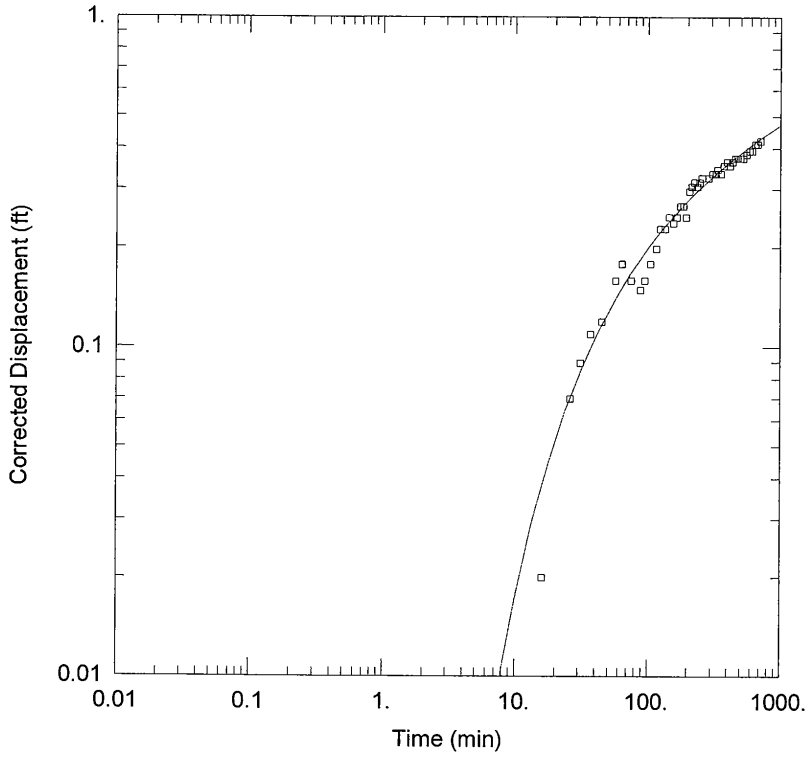
Well Name	X (ft)	Y (ft)
▫ MW-5	5	5

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 0.4719 ft^2/min
S = 0.5136

For Official Use Only



WELL TEST ANALYSIS

Data Set: Q:\APPS\AQTW\PMW6.AQT
Date: 02/26/03 Time: 15:14:40

AQUIFER DATA

Saturated Thickness: 11. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
R-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ MW-6	5	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 0.4803 ft^2/min
S = 0.9857

For Official Use Only

Appendix C

RAINFALL DATA

MONTHLY CLIMATOLOGICAL SUMMARY for JUN. 2002

NAME: Weather 2001 CITY: Indain Head STATE: Maryland
ELEV: LAT: 38°,34',59 N LONG: 77°,11',35 W

TEMPERATURE (°F), RAIN (in), WIND SPEED (mph)

DAY	MEAN TEMP	HIGH	TIME	LOW	TIME	HEAT DEG DAYS	COOL DEG DAYS	RAIN	AVG WIND SPEED	HIGH	TIME	DOM DIR
1	80.9	90.2	5:45p	72.3	12:00m	0.0	16.3	0.00	3.8	27.0	12:30a	NW
2	78.0	86.5	4:00p	69.6	4:00a	0.0	13.0	0.00	12.3	43.0	2:15p	NW
3	71.5	79.7	6:15p	64.5	6:30a	0.0	7.1	0.00	5.3	29.0	12:15a	NNW
4	73.1	83.5	4:00p	62.2	7:30a	0.0	7.9	0.13	5.9	19.0	7:00p	ESE
5	80.0	91.6	5:45p	72.2	6:15a	0.0	16.9	0.00	3.7	35.0	8:15p	SE
6	76.5	90.0	2:15p	66.8	8:30p	0.0	13.4	0.29	6.2	45.0	6:45p	NW
7	66.9	73.0	4:30p	60.6	10:45p	0.0	1.8	0.00	8.2	25.0	1:30a	NNW
8	65.6	75.7	4:30p	56.0	5:15a	0.0	0.8	0.00	3.0	12.0	4:45p	SE
9	70.3	84.4	6:00p	57.0	5:30a	0.0	5.7	0.00	4.0	13.0	10:30a	SE
10	78.5	91.3	4:15p	65.8	5:15a	0.0	13.6	0.00	2.0	10.0	7:45p	WSW
11	80.8	95.5	5:15p	70.8	6:15a	0.0	18.2	0.00	2.9	14.0	4:45p	SE
12	81.0	89.8	3:15p	72.3	6:15a	0.0	16.1	0.00	4.4	31.0	6:00p	SW
13	72.9	82.6	11:45a	65.5	12:00m	0.0	9.0	0.74	1.9	16.0	3:15p	NE
14	67.4	72.1	5:15p	64.0	7:30a	0.0	3.0	0.03	2.4	11.0	1:15a	NE
15	70.5	78.3	5:00p	63.7	11:45p	0.0	6.0	0.12	7.8	31.0	4:45p	W
16	69.5	79.9	3:45p	61.8	1:00a	0.0	5.9	0.14	4.8	49.0	4:45p	SE
17	71.0	80.8	4:15p	59.8	6:15a	0.0	5.3	0.01	1.9	13.0	4:30p	NNW
18	71.7	83.4	3:45p	61.4	6:30a	0.0	7.4	0.00	3.8	31.0	11:45p	E
19	71.7	79.7	5:00p	61.4	12:30p	0.0	5.5	0.00	3.7	17.0	12:45a	E
20	73.5	84.0	3:45p	63.1	6:15a	0.0	8.5	0.00	2.8	12.0	2:45p	E
21	72.9	84.5	3:30p	60.1	4:45p	0.0	7.3	0.00	2.6	12.0	12:45p	ESE
22	74.2	84.6	6:15p	60.7	12:45a	0.0	7.6	0.00	2.9	12.0	11:00p	WNW
23	76.6	88.3	5:45p	65.1	5:15a	0.0	11.7	0.00	3.5	12.0	1:00p	SE
24	81.1	92.8	3:30p	69.8	5:45a	0.0	16.3	0.00	1.6	9.0	5:30p	WSW
25	82.0	92.7	4:00p	71.0	12:15a	0.0	16.8	0.00	2.3	11.0	5:00p	N
26	82.9	94.7	3:15p	71.3	7:00p	0.0	18.0	0.02	4.4	24.0	6:15p	S
27	80.3	93.0	4:15p	72.2	12:00m	0.0	17.6	0.13	4.8	41.0	6:30p	SSE
28	75.7	84.3	4:45p	71.7	6:30a	0.0	13.0	0.00	3.5	24.0	5:30p	WSW
29	78.9	88.8	4:45p	70.3	12:00m	0.0	14.6	0.00	3.4	13.0	2:30p	NNW
30	77.1	87.4	3:15p	64.7	6:45a	0.0	11.0	0.00	2.9	13.0	3:30p	ESE
	75.1	95.5	11	56.0	8	0.0	315.4	1.61	4.1	49.0	16	ESE

Max >= 90.0: 9
Max <= 32.0: 0
Min <= 32.0: 0
Min <= 0.0: 0
Max Rain: 0.74 ON 6/13/02
Days of Rain: 8 (>.01 in) 6 (>.1 in) 0 (>1 in)
Heat Base: 65.0 Cool Base: 65.0 Method: (High + Low) / 2

For Official Use Only

MONTHLY CLIMATOLOGICAL SUMMARY for JUL. 2002

NAME: Weather 2001 CITY: Indain Head STATE: Maryland
LEV: LAT: 38°,34',59 N LONG: 77°,11',35 W

TEMPERATURE (°F), RAIN (in), WIND SPEED (mph)

DAY	MEAN TEMP	HIGH	TIME	LOW	TIME	HEAT DEG DAYS	COOL DEG DAYS	RAIN	AVG WIND SPEED	HIGH	TIME	DOM DIR
1	79.9	89.8	5:45p	70.7	5:45a	0.0	15.3	0.00	4.2	13.0	5:00p	SE
2	82.6	92.8	5:00p	72.4	4:45a	0.0	17.6	0.00	2.3	9.0	1:00a	SE
3	86.5	99.3	6:30p	76.2	6:15a	0.0	22.8	0.00	2.4	13.0	9:15a	NW
4	88.9	99.0	4:15p	81.2	6:45a	0.0	25.1	0.00	4.8	16.0	8:45a	NW
5	86.4	94.1	4:00p	76.9	12:00m	0.0	20.5	0.00	8.3	25.0	12:15p	NW
6	78.6	88.5	4:15p	70.3	6:00a	0.0	14.4	0.00	6.9	23.0	10:45a	NNW
7	75.3	86.6	2:00p	63.6	6:15a	0.0	10.1	0.00	3.0	16.0	1:30p	NW
8	77.3	92.0	5:30p	62.9	5:45a	0.0	12.5	0.00	2.9	15.0	11:45p	E
9	83.5	94.8	5:00p	73.0	10:00p	0.0	18.9	0.28	6.0	28.0	9:00p	SW
10	77.9	83.3	6:15p	73.2	3:00p	0.0	13.3	0.55	3.0	21.0	2:30p	WNW
11	72.6	80.0	6:45p	63.1	12:00m	0.0	6.5	0.00	6.7	30.0	2:45a	NNE
12	70.6	83.5	5:45p	56.9	6:30a	0.0	5.2	0.00	2.8	13.0	3:45p	ESE
13	73.3	81.7	6:00p	67.0	6:15a	0.0	9.3	0.00	2.7	11.0	1:00a	SE
14	69.7	75.0	5:30p	66.4	5:00a	0.0	5.7	0.59	2.5	14.0	7:30p	E
15	77.1	87.6	5:15p	66.7	6:00a	0.0	12.1	0.00	3.2	12.0	2:00p	SW
16	82.1	90.8	3:30p	71.8	2:30p	0.0	16.3	0.00	7.7	29.0	2:45p	NW
17	80.8	92.8	5:00p	70.3	3:30a	0.0	16.6	0.00	2.6	11.0	4:00p	N
18	82.1	90.3	1:45p	74.3	4:30a	0.0	17.3	0.00	1.1	11.0	11:15p	ESE
19	82.3	88.9	1:00p	75.5	6:30a	0.0	17.2	0.00	4.4	21.0	7:15p	NW
20	81.3	89.4	4:00p	75.6	7:00a	0.0	17.5	0.00	4.4	15.0	1:30a	NNW
21	81.0	89.7	2:00p	73.5	6:30a	0.0	16.6	0.00	4.3	18.0	10:45p	SE
22	83.8	95.8	4:15p	72.1	6:00a	0.0	19.0	0.00	5.0	18.0	12:00p	SE
23	84.0	95.0	3:15p	76.4	6:00a	0.0	20.7	0.00	6.5	37.0	8:00p	SSW
24	77.3	84.8	4:15p	72.6	12:00m	0.0	13.7	0.00	5.3	19.0	2:30a	N
25	74.1	78.7	4:30p	71.5	6:30a	0.0	10.1	0.00	4.6	17.0	9:15a	E
26	68.9	71.7	12:15a	65.4	8:15a	0.0	3.5	0.54	3.5	13.0	1:00a	E
27	74.3	80.5	2:30p	69.5	12:15a	0.0	10.0	0.54	2.7	42.0	3:45p	ESE
28	82.4	94.1	4:15p	72.7	7:00a	0.0	18.4	0.01	2.4	15.0	7:00p	SW
29	84.0	92.6	3:15p	77.7	5:30a	0.0	20.1	0.43	3.5	46.0	4:30p	SW
30	83.3	91.0	5:30p	75.0	6:15a	0.0	18.0	0.00	8.3	31.0	11:45a	WNW
31	83.9	93.2	4:15p	75.6	2:45a	0.0	19.4	0.00	3.9	18.0	11:15a	NW
	79.5	99.3	3	56.9	12	0.0	463.7	2.94	4.3	46.0	29	NW

Max >= 90.0: 15
Max <= 32.0: 0
Min <= 32.0: 0
Min <= 0.0: 0
Max Rain: 0.59 ON 7/14/02
Days of Rain: 6 (>.01 in) 6 (>.1 in) 0 (>1 in)
Heat Base: 65.0 Cool Base: 65.0 Method: (High + Low) / 2

For Official Use Only

MONTHLY CLIMATOLOGICAL SUMMARY for AUG. 2002

NAME: Weather 2001 CITY: Indain Head STATE: Maryland
LEV: LAT: 38°,34',59 N LONG: 77°,11',35 W

TEMPERATURE (°F), RAIN (in), WIND SPEED (mph)

DAY	MEAN TEMP	HIGH	TIME	LOW	TIME	HEAT DEG DAYS	COOL DEG DAYS	RAIN	AVG WIND SPEED	HIGH	TIME	DOM DIR
1	82.9	94.6	5:00p	73.2	7:15p	0.0	18.9	0.91	4.4	52.0	7:15p	NW
2	83.3	94.7	2:15p	72.1	6:15a	0.0	18.4	0.00	2.4	11.0	1:00a	ESE
3	81.7	94.4	3:45p	74.9	12:00m	0.0	19.7	0.00	4.0	23.0	4:15p	SE
4	82.5	94.6	5:45p	73.2	7:00a	0.0	18.9	0.00	3.9	12.0	9:45p	WSW
5	83.3	96.6	4:00p	75.8	7:00a	0.0	21.2	0.03	4.3	46.0	6:00p	SW
6	78.6	83.6	4:15p	73.8	11:45p	0.0	13.7	0.00	10.8	31.0	8:15a	NNW
7	72.9	81.8	4:15p	63.2	7:00a	0.0	7.5	0.00	7.0	25.0	1:15a	N
8	73.7	84.2	5:30p	63.3	1:15a	0.0	8.7	0.00	5.4	21.0	11:30a	NNW
9	75.4	87.8	6:15p	62.9	4:45a	0.0	10.4	0.00	3.2	13.0	12:15p	NNW
10	77.0	90.2	5:15p	63.3	6:45a	0.0	11.7	0.00	4.7	14.0	2:30p	SE
11	79.5	92.9	5:00p	68.4	6:45a	0.0	15.7	0.00	3.3	12.0	1:30a	SE
12	82.8	96.3	4:30p	70.4	6:45a	0.0	18.4	0.00	2.6	11.0	7:15p	SE
13	86.0	97.8	5:15p	75.8	5:15a	0.0	21.8	0.00	2.9	13.0	11:45p	ESE
14	86.7	98.9	4:00p	78.9	7:15a	0.0	23.9	0.00	6.1	19.0	5:00p	ESE
15	84.3	93.6	3:45p	77.0	6:45a	0.0	20.3	0.00	5.4	18.0	12:00p	WSW
16	82.9	91.9	4:15p	75.6	6:30a	0.0	18.8	0.00	3.3	16.0	2:00a	SSE
17	84.6	93.9	3:45p	78.5	6:45a	0.0	21.2	0.00	2.0	15.0	5:00p	S
18	85.6	95.6	4:30p	76.8	7:00a	0.0	21.2	0.00	3.1	12.0	3:30a	WSW
19	86.4	95.4	6:15p	79.4	3:30a	0.0	22.4	0.00	3.1	11.0	6:30a	N
20	85.4	93.5	4:30p	79.2	7:00a	0.0	21.3	0.00	7.3	20.0	1:45p	NW
21	81.6	90.7	4:00p	74.7	5:15a	0.0	17.7	0.00	4.6	16.0	10:00p	ESE
22	82.7	93.9	3:30p	73.5	4:30a	0.0	18.7	0.00	4.2	16.0	12:45a	SE
23	85.2	93.8	5:00p	76.7	11:30p	0.0	20.3	0.04	4.7	21.0	1:30p	NW
24	77.9	89.2	3:30p	74.0	4:15p	0.0	16.6	0.78	3.3	50.0	3:45p	E
25	80.9	88.5	5:00p	74.8	7:15a	0.0	16.7	0.01	8.1	26.0	4:45a	NW
26	75.4	80.2	1:15p	70.7	5:30a	0.0	10.4	0.00	1.5	15.0	1:30p	ESE
27	76.5	82.8	1:15p	70.5	6:45a	0.0	11.7	0.00	1.5	9.0	1:00p	E
28	67.9	73.6	12:15a	64.5	12:00m	0.0	4.0	2.37	5.8	27.0	7:00p	NNE
29	66.5	71.4	4:15p	61.3	5:30p	0.0	1.4	0.19	7.3	21.0	9:30a	NNW
30	69.5	76.2	3:00p	63.6	6:15a	0.0	4.9	0.00	4.8	13.0	1:30a	N
31	70.2	76.0	2:30p	65.2	1:30a	0.0	5.6	0.00	4.2	20.0	9:45p	N
	79.7	98.9	14	61.3	29	0.0	481.9	4.33	4.5	52.0	1	NNW

Max >= 90.0: 19
Max <= 32.0: 0
Min <= 32.0: 0
Min <= 0.0: 0
Max Rain: 2.37 ON 8/28/02
Days of Rain: 6 (>.01 in) 4 (>.1 in) 1 (>1 in)
Heat Base: 65.0 Cool Base: 65.0 Method: (High + Low) / 2

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MONTHLY CLIMATOLOGICAL SUMMARY for SEP. 2002

NAME: Weather 2001 CITY: Indain Head STATE: Maryland
ELEV: LAT: 38°,34',59 N LONG: 77°,11',35 W

TEMPERATURE (°F), RAIN (in), WIND SPEED (mph)

DAY	MEAN TEMP	HIGH	TIME	LOW	TIME	HEAT DEG DAYS	COOL DEG DAYS	RAIN	AVG WIND SPEED	HIGH	TIME	DOM DIR
1	66.2	68.2	6:45p	63.3	7:45a	0.0	0.7	0.41	8.4	31.0	1:15p	NNW
2	69.0	76.0	6:30p	64.0	12:00m	0.0	5.0	0.00	6.1	17.0	12:45a	NNW
3	74.5	88.3	5:30p	62.9	6:45a	0.0	10.6	0.00	3.1	12.0	2:00p	N
4	79.1	87.9	4:15p	66.4	4:30p	0.0	12.2	0.00	4.7	18.0	11:30a	NW
5	75.6	85.2	5:15p	67.8	7:30a	0.0	11.5	0.00	5.0	15.0	6:30p	NW
6	71.7	81.3	5:00p	64.1	9:15p	0.0	7.7	0.00	3.2	14.0	8:45a	N
7	70.7	83.2	3:45p	60.7	7:00a	0.0	6.9	0.00	3.0	16.0	2:30p	E
8	71.1	81.3	3:45p	61.3	7:45p	0.0	6.3	0.00	2.9	10.0	12:15p	ESE
9	73.1	89.0	5:00p	60.6	7:00a	0.0	9.8	0.00	2.4	13.0	12:45p	E
10	78.0	89.7	5:00p	59.8	10:30a	0.0	9.7	0.00	3.0	13.0	5:30p	N
11	76.8	80.8	12:45p	69.7	12:00m	0.0	10.3	0.00	16.4	44.0	11:00a	NW
12	69.4	78.8	5:45p	60.7	12:00m	0.0	4.8	0.00	6.7	22.0	4:30a	NW
13	70.4	83.9	5:00p	57.5	7:00a	0.0	5.7	0.00	4.1	16.0	12:45p	SE
14	73.7	82.9	3:30p	66.3	6:00a	0.0	9.6	0.13	4.5	27.0	7:15p	SE
15	74.4	78.9	4:30p	63.0	1:00p	0.0	6.0	0.07	4.8	26.0	11:30p	SE
16	75.0	83.1	3:45p	71.1	4:45a	0.0	12.1	0.28	3.2	19.0	12:30a	WSW
17	72.9	82.9	4:15p	57.8	8:15p	0.0	5.4	0.00	2.4	14.0	12:45a	NW
18	72.8	83.6	4:15p	64.1	6:30a	0.0	8.8	0.00	2.7	10.0	3:00p	SSW
19	73.3	82.1	3:45p	67.6	4:45a	0.0	9.8	0.00	3.9	12.0	2:15p	ESE
20	75.7	84.8	4:45p	68.9	5:00a	0.0	11.9	0.00	4.1	14.0	9:15p	ESE
21	77.4	87.6	4:00p	68.7	7:00a	0.0	13.1	0.00	4.8	15.0	8:30a	SE
22	76.9	85.5	3:00p	70.6	7:30a	0.0	13.0	0.00	4.8	16.0	12:00m	ESE
23	71.4	77.5	5:30p	64.5	12:00m	0.0	6.0	0.02	11.7	32.0	6:15a	NNW
24	67.4	79.1	5:15p	57.9	5:30a	0.0	3.5	0.00	4.2	14.0	6:00p	NNW
25	67.6	75.1	1:15p	58.9	4:00a	0.0	2.0	0.00	3.1	17.0	10:15a	NNE
26	65.4	67.9	12:30a	63.1	8:30p	0.0	0.5	0.75	4.6	17.0	2:45p	NNE
27	72.7	83.2	5:45p	52.8	11:30a	0.0	3.0	0.04	4.8	20.0	3:30p	SE
28	72.5	79.3	12:15a	62.4	12:00m	0.0	5.9	0.01	11.0	35.0	2:00a	NNW
29	66.3	76.8	4:45p	58.6	5:00a	0.0	2.7	0.00	2.6	11.0	11:00a	NNW
30	68.1	77.9	4:00p	59.3	1:00a	0.0	3.6	0.00	2.7	9.0	3:15a	ESE
	72.3	89.7	10	52.8	27	0.0	218.1	1.71	5.0	44.0	11	SE

Max >= 90.0: 0
Max <= 32.0: 0
Min <= 32.0: 0
Min <= 0.0: 0
Max Rain: 0.75 ON 9/26/02
Days of Rain: 7 (>.01 in) 4 (>.1 in) 0 (>1 in)
Heat Base: 65.0 Cool Base: 65.0 Method: (High + Low) / 2

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MONTHLY CLIMATOLOGICAL SUMMARY for OCT. 2002

NAME: Weather 2001 CITY: Indain Head STATE: Maryland
ELEV: LAT: 38°,34',59 N LONG: 77°,11',35 W

TEMPERATURE (°F), RAIN (in), WIND SPEED (mph)

DAY	MEAN TEMP	HIGH	TIME	LOW	TIME	HEAT DEG DAYS	COOL DEG DAYS	RAIN	AVG WIND SPEED	HIGH	TIME	DOM DIR
1	71.7	82.6	4:15p	63.0	2:30a	0.0	7.8	0.00	3.2	14.0	12:30p	E
2	73.8	86.1	3:00p	64.1	7:00a	0.0	10.1	0.00	1.4	10.0	2:45p	SSE
3	75.7	87.8	3:15p	66.8	7:30a	0.0	12.3	0.00	0.1	4.0	8:45a	S
4	76.3	84.5	4:00p	69.7	4:45a	0.0	12.1	0.00	5.3	22.0	10:45p	SE
5	78.1	87.7	3:15p	66.9	12:00m	0.0	12.3	0.00	7.6	34.0	6:45p	NNW
6	67.1	74.5	4:45p	59.4	7:15a	0.0	2.0	0.00	5.4	21.0	1:15a	SE
7	69.7	78.7	1:30p	58.1	11:45a	0.0	3.4	0.00	6.6	23.0	2:45p	NNW
8	58.2	66.3	3:30p	46.8	10:45a	8.4	0.0	0.00	5.4	21.0	1:00a	N
9	59.4	64.4	5:00p	51.4	2:45a	7.1	0.0	0.00	0.9	6.0	10:15a	E
10	64.1	67.2	2:30p	61.3	5:00a	0.8	0.0	0.23	1.9	12.0	11:00a	N
11	67.5	70.5	3:00p	65.0	6:00a	0.0	2.8	0.66	1.0	12.0	3:30p	N
12	68.4	73.7	3:00p	54.7	3:00p	0.8	0.0	0.00	4.9	15.0	4:30p	N
13	65.6	69.0	5:15p	61.3	12:00m	0.0	0.1	0.00	5.4	31.0	11:15p	NE
14	55.5	61.6	3:00p	45.8	12:00m	11.3	0.0	0.00	7.8	24.0	8:45a	NNW
15	52.9	60.4	4:00p	43.6	6:00a	13.0	0.0	0.04	3.1	20.0	10:15p	NNE
16	58.3	61.0	5:45p	54.4	10:45p	7.3	0.0	1.33	9.9	27.0	11:00a	N
17	56.2	61.8	3:45p	50.6	8:00a	8.8	0.0	0.03	5.9	30.0	11:30p	NW
18	52.1	62.1	5:00p	41.0	7:30a	13.5	0.0	0.00	5.3	23.0	12:15a	ESE
19	58.0	66.0	4:30p	48.0	5:00a	8.0	0.0	0.00	5.4	24.0	4:30p	SE
20	58.7	64.0	12:15a	56.0	12:00m	5.0	0.0	0.00	2.5	12.0	9:45a	NNW
1	54.8	61.9	5:15p	46.0	11:45p	11.0	0.0	0.00	3.4	13.0	12:15p	N
22	51.1	63.7	4:45p	42.9	5:15a	11.7	0.0	0.01	2.1	7.0	2:45p	E
23	54.7	66.8	2:15p	44.1	7:30a	9.5	0.0	0.00	4.7	18.0	2:15p	ESE
24	50.7	54.3	12:15a	46.8	12:00m	14.5	0.0	0.00	4.6	17.0	7:45a	NE
25	50.3	55.5	11:30p	45.5	3:00a	14.5	0.0	0.56	3.6	16.0	12:15a	N
26	57.7	66.6	4:00p	53.0	7:30a	5.2	0.0	0.11	3.4	16.0	5:30p	NW
27	57.5	67.4	4:30p	48.6	8:00a	7.0	0.0	0.00	2.5	20.0	12:30p	NW
28	51.3	56.2	12:15a	47.8	6:15p	13.0	0.0	0.15	2.1	10.0	1:45a	N
29	45.7	50.9	1:15a	42.1	12:00m	18.5	0.0	0.86	5.7	19.0	5:15a	NNE
30	41.8	43.1	3:30p	40.6	6:30a	23.2	0.0	0.52	9.1	26.0	6:45p	NNW
31	45.0	50.3	4:00p	41.1	5:15a	19.3	0.0	0.02	9.7	25.0	12:15a	NNW
	59.6	87.8	3	40.6	30	231.3	62.8	4.52	4.5	34.0	5	N

Max >= 90.0: 0
Max <= 32.0: 0
Min <= 32.0: 0
Min <= 0.0: 0
Max Rain: 1.33 ON 10/16/02
Days of Rain: 11 (>.01 in) 8 (>.1 in) 1 (>1 in)
Heat Base: 65.0 Cool Base: 65.0 Method: (High + Low) / 2

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MONTHLY CLIMATOLOGICAL SUMMARY for NOV. 2002

NAME: Weather 2001 CITY: Indain Head STATE: Maryland
ELEV: LAT: 38°,34',59 N LONG: 77°,11',35 W

TEMPERATURE (°F), RAIN (in), WIND SPEED (mph)

DAY	MEAN TEMP	HIGH	TIME	LOW	TIME	HEAT DEG DAYS	COOL DEG DAYS	RAIN	AVG WIND SPEED	HIGH	TIME	DOM DIR
1	46.9	56.1	1:00p	35.7	7:00a	19.1	0.0	0.00	8.8	33.0	9:45p	W
2	43.5	52.3	3:30p	34.9	11:45p	21.4	0.0	0.00	8.4	31.0	2:30a	WNW
3	44.4	54.8	4:15p	34.1	12:30a	20.6	0.0	0.00	4.0	16.0	7:15a	NW
4	47.9	57.1	4:00p	42.4	12:15a	15.3	0.0	0.00	3.3	16.0	6:45p	SE
5	46.9	52.5	11:30a	40.7	7:15a	18.4	0.0	0.60	3.5	14.0	1:30a	ESE
6	50.1	56.7	1:30p	46.6	2:45a	13.4	0.0	0.15	13.7	46.0	4:45p	WNW
7	48.2	53.0	3:30p	39.7	10:45p	18.6	0.0	0.00	12.0	35.0	3:00a	WNW
8	50.4	65.6	3:00p	37.2	6:00a	13.6	0.0	0.00	4.0	15.0	3:30p	SE
9	58.2	69.3	3:00p	44.8	7:00a	7.9	0.0	0.00	4.6	16.0	12:45p	SE
10	67.7	74.1	12:45p	59.3	6:00a	0.0	1.7	0.00	6.1	25.0	10:45a	SE
11	66.0	72.1	6:00a	58.4	9:15p	0.0	0.3	0.48	3.6	27.0	6:00a	SE
12	54.5	60.5	12:30a	51.3	5:00p	9.1	0.0	0.80	7.7	28.0	3:15p	NNW
13	49.1	52.1	1:45p	39.4	11:45p	19.3	0.0	0.01	11.0	36.0	11:15a	NW
14	49.7	63.5	3:00p	36.7	7:00a	14.9	0.0	0.00	2.9	13.0	10:00a	SE
15	52.1	61.9	3:30p	43.9	6:00a	12.1	0.0	0.00	2.4	11.0	2:00a	SE
16	51.6	53.2	1:15p	49.6	12:00m	13.6	0.0	1.34	4.7	18.0	11:30p	N
17	45.3	49.7	12:15a	42.3	10:00p	19.0	0.0	0.53	11.9	34.0	7:45p	NNW
18	45.3	52.1	2:45p	36.9	12:00m	20.5	0.0	0.00	11.9	34.0	10:30a	W
19	43.2	55.9	3:45p	31.5	6:15a	21.3	0.0	0.00	3.0	16.0	10:30a	E
20	43.9	59.8	3:30p	34.5	4:45a	17.9	0.0	0.00	2.3	12.0	4:30p	SE
21	47.3	52.3	12:45p	40.3	4:15a	18.7	0.0	0.00	0.7	7.0	8:45a	ESE
22	48.3	51.1	12:45p	43.9	10:00p	17.5	0.0	0.02	8.6	44.0	11:15p	W
23	44.0	49.0	3:15p	39.8	7:30a	20.6	0.0	0.00	17.9	60.0	2:15a	WNW
24	44.5	61.3	4:15p	32.0	7:00a	18.4	0.0	0.00	1.1	6.0	9:45a	SSW
25	45.7	59.3	3:15p	34.5	7:00a	18.1	0.0	0.00	1.5	15.0	12:00m	N
26	45.7	50.0	12:15a	42.6	7:00p	18.7	0.0	0.01	5.0	21.0	4:45a	N
27	40.5	43.7	1:00p	34.9	12:00m	25.7	0.0	0.01	15.3	35.0	9:45a	NW
28	35.4	42.5	3:45p	29.0	6:45a	29.3	0.0	0.00	6.0	20.0	5:30p	NW
29	41.2	50.7	4:30p	29.7	5:30a	24.8	0.0	0.00	6.9	25.0	8:15p	S
30	47.4	56.4	2:00p	39.0	11:45p	17.3	0.0	0.07	12.7	54.0	8:45p	S
	48.2	74.1	10	29.0	28	504.9	1.9	4.02	6.8	60.0	23	SE

Max >= 90.0: 0
Max <= 32.0: 0
Min <= 32.0: 4
Min <= 0.0: 0
Max Rain: 1.34 ON 11/16/02
Days of Rain: 8 (>.01 in) 6 (>.1 in) 1 (>1 in)
Heat Base: 65.0 Cool Base: 65.0 Method: (High + Low) / 2

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MONTHLY CLIMATOLOGICAL SUMMARY for DEC. 2002

NAME: Weather 2001 CITY: Indain Head STATE: Maryland
ELEV: LAT: 38°,34',59 N LONG: 77°,11',35 W

TEMPERATURE (°F), RAIN (in), WIND SPEED (mph)

DAY	MEAN TEMP	HIGH	TIME	LOW	TIME	HEAT DEG DAYS	COOL DEG DAYS	RAIN	AVG WIND SPEED	HIGH	TIME	DOM DIR
1	35.1	39.4	12:15a	28.0	11:00p	31.3	0.0	0.00	15.0	42.0	7:00a	WNW
2	41.9	51.8	1:45p	28.8	6:30a	24.7	0.0	0.00	5.0	20.0	5:45p	S
3	31.9	43.5	2:45a	26.3	9:30p	30.1	0.0	0.00	14.7	43.0	4:30a	NNW
4	28.1	33.9	8:00p	23.5	6:30a	36.3	0.0	0.00	4.2	20.0	1:00a	NNW
5	29.2	31.7	9:00p	26.4	1:45a	36.0	0.0	0.00	8.6	24.0	11:45a	NNW
6	30.1	36.1	11:45a	19.6	12:00m	37.2	0.0	0.18	6.2	29.0	12:15p	NW
7	28.8	42.4	3:45p	14.7	7:15a	36.5	0.0	0.20	3.6	14.0	11:30a	NE
8	37.1	50.5	3:00p	25.5	7:30a	27.0	0.0	0.01	6.5	34.0	8:45p	SSE
9	30.6	38.2	12:15a	22.7	5:45p	34.5	0.0	0.00	6.2	29.0	12:15a	N
10	31.5	37.3	3:00p	24.8	12:15a	34.0	0.0	0.00	2.1	10.0	10:15p	E
11	34.7	36.7	12:00m	32.4	4:45a	30.4	0.0	1.37	6.9	22.0	6:45p	NNW
12	34.1	36.7	12:15a	31.8	5:30a	0.0	0.0	0.00	3.1	9.0	1:45a	SW
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												
31												
	32.8	51.8	2	14.7	7	357.9	0.0	1.76	6.8	43.0	3	NW

Max >= 90.0: 0
Max <= 32.0: 1
Min <= 32.0: 11
Min <= 0.0: 0
Max Rain: 1.37 ON 12/11/02
Days of Rain: 3 (>.01 in) 3 (>.1 in) 1 (>1 in)
Heat Base: 65.0 Cool Base: 65.0 Method: (High + Low) / 2

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Applied Technology Department at the Indian Head Division, Naval Surface Warfare Center and Shaw Environmental, Inc., have just successfully completed a field demonstration of in situ bioremediation of a groundwater aquifer contaminated with perchlorate. Using a recirculation cell design, naturally occurring microorganisms were stimulated to degrade perchlorate by injecting a food source (lactate) and neutralizing the groundwater acidity with a carbonate buffer. Starting with perchlorate concentrations in excess of 210 mg/L, perchlorate levels were reduced by more than 95% in eight of the nine test plot monitoring wells over the 5 months of sampling. In two of the monitoring wells, the perchlorate levels were lowered to less than 5 ppb. In addition to the perchlorate levels and the pH, alkalinity, nitrate, and sulfate concentrations were measured. In situ bioremediation techniques are much less expensive and significantly lower in maintenance than traditional ex situ pump-and-treat systems. This is the first field trial conducted on the east coast of the United States, the first trial performed in an acidic aquifer, and the first demonstration of treating in situ perchlorate levels in excess of 200 mg/L. This project provides new and valuable information concerning the application of bioremediation for in situ perchlorate treatment.

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