ESTCP
Cost and Performance Report

(ER-200219)

Comparative Demonstration of Active and Semi-Passive In Situ Bioremediation Approaches for Perchlorate Impacted Groundwater: Active In Situ Bioremediation Demonstration

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ACRONYMS AND ABBREVIATIONS

AAL	Aerojet Analytical Laboratories
AEL	Aerojet's Environmental Laboratory
Aerojet	Aerojet General Corporation
AFCEC	U.S. Air Force Civil Engineer Center
BAZ	biologically active zone
bgs	below ground surface
BOD	biological oxygen demand
btoc	below top of casing
CDG	chlorine dioxide generator
CDWR	California DUSEPArtment of Water Resources
CEL	CalScience Environmental Laboratory
ClO_4^-	perchlorate
CLS	California Laboratory Services
cm/sec	centimeters per second
COD	chemical oxygen demand
EC	degrees Celsius
DCE	dichloroethene
DNA	deoxyribonucleic acid
DO	dissolved oxygen
DOD	U.S. DUSEPArtment of Defense
EISB	enhanced *in situ* bioremediation
ENSR	ENSR International Corporation
USEPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
EVO	emulsified vegetable oil
EW	extraction well
ft	feet/foot
ft/day	feet per day
ft/ft	feet per feet
ft/yr	feet per year
ft^2	square feet
ft^2/day	square feet per day
Geosyntec	Geosyntec Consultants
g/mol	grams per mole
gpm	gallons per minute
GW	groundwater
HPLC	high-performance liquid chromatography

ACRONYMS AND ABBREVIATIONS (continued)

IRCTS	Inactive Rancho Cordova Test Site
ITRC	Interstate Technology & Regulatory Council
K	hydraulic conductivity
L	liter
µg/L	micrograms per liter
µmol/L	micromoles per liter
m	meters
m/yr	meters per year
m^2	square meters
MCL	maximum contaminant level
mg/L	milligrams per liter
mL	milliliter
MNA	monitored natural attenuation
mV	millivolts
MW	monitoring well
NASA	National Aeronautics and Space Administration
NFESC	Naval Facilities Engineering Service Center
NPV	net present value
O&M	operation and maintenance
ORP	oxidation reduction potential
OSWER	Office of Solid Waste and Emergency Response
P&T	pump and treat
PCR	polymerase chain reaction
PQL	practical quantitation limit
PRG	preliminary remediation goal
psi	pounds per square inch
ROI	radius of influence
RW	Recharge Well
SERDP	Strategic Environmental Research and Development Program
TCE	trichloroethene
TDS	total dissolved solids
UV	ultraviolet
VC	vinyl chloride
VFA	volatile fatty acid

VOA	volatile organic analysis
VOC	volatile organic compound
WNN	Western Non-Aerospace Non-Industrial

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

Perchlorate is an inorganic anion that consists of chlorine bonded to four oxygen atoms. It is a primary ingredient in solid rocket propellant, exhibits high solubility and mobility in water, and has been identified in groundwater at numerous sites across the United States. Enhanced in situ bioremediation (EISB) of perchlorate-affected groundwater offers the potential to treat and destroy perchlorate in the subsurface. This report describes work conducted to demonstrate/validate the use of an active EISB approach at the Western Non-Aerospace Non-Industrial (WNN) Easement of the Inactive Rancho Cordova Test Site (IRCTS) in Rancho Cordova, CA.

The overall objective of this work was to demonstrate the efficacy of the active approach to EISB. The demonstration was designed to evaluate performance objectives, which are as follows:

- Ease of installation of system components;
- Ease of electron donor delivery events;
- Enhancement of microbiological activity;
- Ease of performance monitoring and validation;
- Reduction in perchlorate concentrations; and
- Radius of influence (ROI) and distance for degradation.

TECHNOLOGY DESCRIPTION

The active EISB approach involves ongoing groundwater recirculation and delivery of an electron donor to create a biologically active zone (BAZ) or biobarrier across a perchlorate plume, for the purposes of promoting perchlorate biodegradation and controlling plume migration. The active EISB test consisted of an active biobarrier, whereby groundwater containing perchlorate was extracted from the shallow aquifer, amended with a carbon-based electron donor (ethanol), and recharged to the shallow aquifer to promote in situ biodegradation of the perchlorate.

DEMONSTRATION RESULTS

Based on the experience and observations made during the demonstration, all of the performance objectives for the demonstration were achieved. Sampling of performance monitoring wells demonstrated that the average perchlorate concentrations were reduced to below the practical quantitation limit (PQL) of 4.0 micrograms per liter (µg/L) during the operating period. The average perchlorate concentrations measured in MW-1, from day 29 to the end of amendment injection period (2.6 µg/L), and STSW-138A from day 85 to the end of amendment injection period (2.9 µg/L), were all less than 4.0 µg/L.

An assessment of the costs to implement EISB for perchlorate-affected groundwater using the active approach was also conducted. A cost model was developed for a template site based on a typical site with perchlorate-affected shallow groundwater. Cost estimates were also

prepared for other approaches to EISB and a conventional pump and treat system. The cost model focused on treatment of a contaminated plume of groundwater and did not include costs for possible source zone treatment. The cost assessment includes estimates of the net present value (NPV) of future costs to help assess the life cycle costs.

The capital and operation and maintenance (O&M) cost for the active EISB system and for a comparable pump and treat (P&T) system at the template site are presented in the table below.

	Active Biobarrier	P&T
Capital Costs	$430,000	$490,000
Annual O&M Costs	$60,000	$74,000
NPV of 30 Years of O&M Costs	$1,200,000	$1,470,000
NPV of 30 Years of Total Remedy Costs	$1,980,000	$2,310,000
Total 30-Year Remedy Costs	$2,700,000	$3,160,000

The active remedial approach could be used in a modified configuration to treat source areas below the water table. This active source area treatment approach could be coupled with monitored natural attenuation (MNA) of the downgradient plume and could have the benefit of a significantly reduced time frame for operation than that of a system that simply treats a downgradient plume of perchlorate. Applying an active approach in the source area would have a higher initial capital cost and annual O&M costs but overall savings may be achieved because of a shorter duration of operation.

IMPLEMENATION ISSUES

Many guidance documents are available from organizations such as the U.S. Environmental Protection Agency (USEPA), Interstate Technology & Regulatory Council (ITRC), and U.S. Air Force Civil Engineer Center (AFCEC) dealing with EISB for perchlorate and chlorinated solvents. Many design issues with EISB for chlorinated solvents are also common to perchlorate. Strategic Environmental Research and Development Program (SERDP)/Environmental Security Technology Certification Program (ESTCP) recently published a monograph titled "In Situ Bioremediation of Perchlorate in Groundwater." This monograph contains information on the various options for treatment of perchlorate-affected groundwater.

Key implementation matters that need to be considered with this technology are regulatory issues, end-user issues, and design issues. The implementation of EISB in most jurisdictions requires a groundwater reinjection permit. End-users will have an interest in the technology because of its ability to treat groundwater in situ at an overall cost less than for conventional P&T remediation approaches. End-users and other stakeholders may have concerns regarding (1) the effectiveness of the technology in reducing concentrations of target compounds below appropriate criteria; and (2) potential negative impacts of excess electron donor on water quality downgradient of the treatment zone. Design issues to be considered include treatment of sites with the following characteristics:

- Low hydraulic conductivity;
- Significant variations in hydraulic conductivity;
- High concentrations of competing electron acceptors; and
- High concentrations of naturally occurring metals in the subsurface soil.

1.0 INTRODUCTION

This Cost and Performance Report has been prepared by Geosyntec Consultants (Geosyntec) for the Environmental Security Technology Certification Program (ESTCP) to present a summary of the results of the active enhanced in situ bioremediation (EISB) demonstration that was conducted at the Western Non-Aerospace Non-Industrial (WNN) Easement of the Inactive Rancho Cordova Test Site (IRCTS) in Rancho Cordova, CA (the "Site") in 2003 and 2004. This work was conducted as part of ESTCP Project ER-200219, "Comparative Demonstration of Active and Semi-Passive In Situ Bioremediation Approaches for Perchlorate Impacted Groundwater." Additional details of the demonstration test are presented in the "Final Report, Comparative Demonstration of Active and Semi-Passive In Situ Bioremediation Approaches for Perchlorate Impacted Groundwater: Active Bioremediation Demonstration" (the "Final Report;" Geosyntec, 2012).

This report is composed of the following sections:

- Section 1 presents background information and summarizes the objectives of the demonstration.
- Section 2 describes the active bioremediation technology demonstrated in this work.
- Section 3 presents the performance objectives for the demonstration.
- Section 4 presents information on the IRCTS where the demonstration was conducted.
- Section 5 presents the test design and results of the demonstration.
- Section 6 presents the results of the performance assessment.
- Section 7 presents the results of a cost assessment of the technology.
- Section 8 discusses potential implementation issues with the technology.

1.1 BACKGROUND

Perchlorate is an inorganic anion that consists of chlorine bonded to four oxygen atoms (ClO_4^-). It is a primary ingredient in solid rocket propellant and has been used for decades by U.S. Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and the defense industry in the manufacturing, testing, and firing of rockets and missiles. On the basis of 1998 manufacturer data, it is estimated that 90 percent of the several million pounds of perchlorate produced in the United States each year is used by the military and NASA. Private industry has used perchlorate to manufacture products such as fireworks, safety flares, automobile airbags, and commercial explosives.

Perchlorate exhibits high solubility and mobility in water and is stable, being degraded only under anaerobic conditions. Consequently, when perchlorate is released into a typical groundwater or surface water environment, it tends to persist and can migrate to great distances (many miles) in groundwater, as has been observed at many sites.

Conventional technologies for the treatment of perchlorate-affected groundwater are expensive. In California alone, the costs for remediation of perchlorate-impacted groundwater are expected to be in the billions of dollars, the cost of which may jeopardize major DoD and propulsion contractor production programs. Of the technologies being developed, bioremediation is among

the most promising because it has the potential to destroy perchlorate rather than transferring it to another waste stream (e.g., impacted resin or brine) requiring costly treatment or disposal.

One of the main factors that affects the success and cost of in situ bioremediation systems is the effectiveness of nutrient (electron donor) delivery and mixing in the subsurface. A variety of active, semipassive, and fully passive electron donor delivery systems have been employed to promote contaminant biodegradation. As further discussed in Section 2, each of these delivery configurations has associated benefits and limitations with respect to ease of implementation and cost. This report describes work conducted to demonstrate and validate the use of an active EISB approach at the IRCTS in California. The results of a separate demonstration of the use of a semipassive EISB approach are presented in separate reports (Geosyntec, 2009a and 2009b). The goal of the program is to demonstrate the efficacy of both approaches at a scale that is large enough to generate accurate full-scale design and cost information for widespread technology consideration and application at DoD and related sites.

1.2 OBJECTIVES OF THE DEMONSTRATION

The specific performance objectives for the demonstration were achieved as discussed below.

1. **The ease of installation of electron donor injection components –** This objective was achieved during the demonstration based on experience with the actual installation of the electron donor delivery system at the IRCTS. The equipment required for the active recirculation and injection of electron donor were all readily available through local drillers and plumbing suppliers. The ClO_2 biofouling control system was also available and straightforward to install. The procedures used to install the equipment were standard and well established procedures for local drillers and the procedures were simple enough to be conducted by field technicians with training in basic plumbing techniques.
2. **The ease of electron donor delivery –** This objective was achieved during the demonstration based on experience of field staff with the actual operation of the system. The activities and procedures required for the recirculation of groundwater and addition of electron donor delivery were simple enough to be conducted by field staff with minimal specialized training and effort. It is believed that the pulsed injection of electron donor over 1 hour each day followed by an injection of ClO_2 was an effective operating strategy for controlling biofouling of the injection well.
3. **The enhancement of microbiological activity –** This objective was achieved based on the results of chemical and geochemical characterization. Groundwater monitoring data for chemical and geochemical parameters demonstrated that electron donor addition enhanced microbiological activity in the treatment zone. Significant and sustained reductions in oxidation reduction potential (ORP) and reductions in perchlorate concentrations provided evidence that biological activity was enhanced by the addition of electron donor.
4. **The ease of performance monitoring and validation –** This objective was achieved during the demonstration based on the data obtained during the demonstration. The quality of the data obtained and the ability to interpret this data and quantify

biodegradation with confidence demonstrated that the performance monitoring network allowed for straightforward data collection, interpretation, and validation.

5. **The reduction of perchlorate concentrations in groundwater –** This objective was achieved based on groundwater sampling of performance monitoring wells. Sampling results demonstrated that the average perchlorate concentrations were reduced to below the practical quantitation limit (PQL) of 4 micrograms per liter (µg/L) during the operating period.
6. **The radius of influence (ROI) and distance for degradation of perchlorate –** This objective was achieved during the demonstration based on groundwater sample results from performance monitoring wells following system operation. These results show that the ROI for electron donor extends to the performance monitoring wells and that perchlorate was degraded before groundwater reached downgradient performance monitoring wells.

1.3 REGULATORY DRIVERS

In 2009, the U.S. Environmental Protection Agency (USEPA) established an Interim Drinking Water Health Advisory for perchlorate of 15 µg/L. The Office of Solid Waste and Emergency Response (OSWER) has also established a preliminary remediation goal (PRG) at National Priorities List sites of 15 µg/L. Numerous states have promulgated enforceable standards for perchlorate in drinking water. For example, Massachusetts and California have established enforceable standards for perchlorate in drinking water of 2 µg/L and 6 µg/L, respectively. For this demonstration, the remediation target will be reduction of perchlorate concentrations to the current common PQL, which is 4.0 µg/L in most jurisdictions.

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2.0 TECHNOLOGY

This section describes the active EISB technology which is the subject of the demonstration described in this report. Section 2.1 provides a description of the technology, and Section 2.2 discusses the advantages and limitations of the technology.

2.1 TECHNOLOGY DESCRIPTION

EISB has proven to be a cost-effective approach for the treatment of perchlorate-affected groundwater under many different site conditions. Perchlorate biodegradation results from microbially mediated redox reactions, whereby perchlorate serves as an electron acceptor, and is reduced via chlorate to chlorite. Chlorite then undergoes a biologically mediated dismutation reaction, releasing chloride, oxygen, and carbon dioxide (CO_2). A variety of electron donors have been used to stimulate perchlorate reduction using pure or mixed microbial cultures, including alcohols (e.g., ethanol, methanol), organic acids (e.g., acetate, lactate, citrate, oleate), edible oils (e.g., canola oil) and some sugar mixtures (e.g., corn syrup). A variety of microorganisms have been identified as possessing the ability to reduce perchlorate (Coates et al., 1999), including various *Dechlorosoma*, *Dechloromonas*, *Rhodocyclus*, *Azospirillum*, and *Ferribacterium* species, and perchlorate-degrading bacteria have generally been shown to be ubiquitous in subsurface environments.

In 1999, three research groups, including Geosyntec, Envirogen, and the Southern Illinois University (Dr. John Coates) were awarded research grants under the DoD SERDP to evaluate the ubiquity of perchlorate-degrading bacteria and to assess the applicability of in situ bioremediation as a remediation technology for perchlorate-affected DoD sites. This research suggested that the key to successfully implementing in situ bioremediation of perchlorate is the addition of appropriate carbon substrates in adequate quantities to reduce competing electron acceptors present in the groundwater (e.g., oxygen and nitrate), and to promote the perchlorate reduction reaction.

One of the main factors that affects the success and cost of EISB systems is the effectiveness of nutrient (electron donor) delivery and mixing in the subsurface. A variety of active, semipassive and fully passive electron donor delivery systems have been employed to promote in situ biodegradation. Each of these delivery configurations has associated benefits and limitations with respect to ease of implementation and cost. Active EISB systems have been shown to be effective (Geosyntec, 2002) in providing migration control over reasonably wide (and deep) perchlorate plumes with only a few extraction/injection wells.

Active EISB of perchlorate involves ongoing groundwater recirculation and the addition of electron donor on a continuous basis to stimulate natural microbiological populations. Active EISB approaches are similar to semipassive approaches in that groundwater is recirculated between injection and extraction wells. However, with the semipassive approach, groundwater is recirculated for an “active phase” of a limited duration (e.g., several days to several weeks) to distribute the electron donor, and then the recirculation system is shut off for a “passive phase” of longer duration (e.g., several months).

Groundwater extracted from one well or several wells, is amended with the electron donor, and injected into other wells along the line of the biobarrier. Some of the injected water flows back to the extraction well or wells and some water moves out in other directions. The ambient flow of groundwater from upgradient of the biobarrier is collected in the extraction well and some of the flow is diverted around the ends of the biobarrier. The recirculation of groundwater is conducted on a continuous basis. The electron donor used for the active approach must be sufficiently mobile to travel some distance between the injection and extraction wells to achieve the desired electron donor coverage. Soluble electron donors such as sodium lactate, citric acid, or ethanol have been used in field applications, and it may be possible to use mobile forms of emulsified vegetable oil, methyl esters and other slower release forms of electron donor as well.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The active EISB technology or approach, which is the subject of this demonstration, can be used as an alternative to groundwater extraction and aboveground treatment (pump and treat [P&T]) or as an alternative to other EISB approaches (i.e., semipassive or passive). Advantages and limitations of the active EISB approach relative to each of these alternatives are discussed below.

The active EISB technology has the following advantages over P&T technologies, which involve long-term groundwater extraction and ex situ treatment typically using bioreactors (fluidized-bed or fixed-film) or ion exchange:

- Will destroy perchlorate rather than simply transferring it to another medium, similar to what is accomplished with aboveground treatment using ion exchange;
- Can directly treat perchlorate in source areas, as well as perchlorate-affected groundwater as it pasess through a linear biobarrier system; and
- Has the ability to treat co-contaminants such as trichloroethene (TCE) as part of a single treatment strategy, which is not possible with ex situ ion exchange or bioreactor technology.

The active EISB technology has the following limitations over P&T technologies:

- The effectiveness of active EISB may be limited by the occurrence of specific geochemical conditions (e.g., high sulfate) that may require larger quantities of electron donor and sulfide production.
- Active EISB has the potential to adversely impact secondary groundwater quality through mobilization of metals and production of sulfides or methane if excess amounts of electron donor are added.
- The effectiveness of active EISB may be limited by the presence of co-contaminants that may be inhibitory to biodegradation (e.g., chloroform, hydrogen sulfide).

The active EISB approach, with ongoing operation of a groundwater recirculation system, has the following advantages over passive EISB approaches:

- Active systems require fewer wells or injection points because the groundwater recirculation provides an induced flow to distribute electron donor across the natural flow of groundwater across greater distances.

- Active systems do not inject unduly high concentrations of electron donor at one time as is typical with passive systems.
- Active systems do not inject large volumes of oil emulsion that can reduce the hydraulic conductivity of the treatment zone and cause diversion of groundwater around the treatment zone.

The active approach has the following limitations relative to passive approaches:

- Active systems require the installation of permanent injection wells to allow for groundwater recirculation and amendment of electron donor.
- Active systems require ongoing groundwater recirculation and amendment with electron donor.

The active approach has one advantage relative to semipassive approaches. Specifically, the active approach results in less variation in the concentration of electron donor than semipassive and passive systems and variations in the concentration of electron donor can negatively impact secondary water quality characteristics.

The active approach, with continuous operation rather than periodic operation of a groundwater recirculation system, has the following disadvantages over semipassive approaches:

- The groundwater recirculation equipment of an active system needs to be dedicated to a specific set of injection and extraction wells and cannot be moved from one area to another in sequence, thus avoiding significant capital costs.
- The operating costs for active systems can be greater than for semipassive systems because (a) the active system is operated continuously, and (b) the injection wells can be more susceptible to biofouling because the injection of electron donor is done on a continuous rather than periodic basis; and
- The equipment required for active operation can be more complex and is more likely to require complex controls and permitting because of the continuous nature of the operation.

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3.0 PERFORMANCE OBJECTIVES

The performance objectives for this demonstration are shown in Table 1 and are discussed in more detail below.

Table 1. Performance objectives.

Performance Objective	Data Requirement	Success Criteria
Qualitative Performance Objectives		
1. Ease of installation of electron donor delivery components	Experience of demonstration operators; actual availability and costs of installed equipment.	Electron donor delivery system can be readily installed by standard industry procedures/contractors.
2. Ease of electron donor delivery events	Experience of demonstration operators and costs of events.	Electron donor delivery events can be conducted with minimal training and effort.
3. Enhancement of microbiological activity	Groundwater and soil analyses for geochemical characterization.	Electron donor addition enhances microbiological activity in the treatment zone.
4. Ease of performance monitoring and validation	Quality of data and ability to interpret and quantify biodegradation with confidence.	Performance monitoring network allows straightforward data collection, interpretation, and validation.
Quantitative Performance Objectives		
5. Reduction in perchlorate concentration	Groundwater sampling of performance monitoring wells.	Perchlorate concentrations reduced to practical quantitation limit of 4 µg/L.
6. Radius of influence and distance for degradation	Groundwater sampling of performance monitoring wells.	Radius of influence for electron donor addition will extend to target treatment area and perchlorate will be degraded before groundwater reaches the furthest downgradient performance monitoring wells.

Notes: µg/L – micrograms per liter

3.1 EASE OF INSTALLATION

The ease of installation of electron donor injection components is an important factor in maintaining low installation costs for the EISB technology. Ideally, the installation can be accomplished using standard, readily available materials and components by contractors without special training or knowledge. This criterion was evaluated based on the experience of demonstration operators and the actual availability and costs of installed equipment.

This objective was achieved during the demonstration based on experience with the actual installation of the electron donor delivery system at the IRCTS. The equipment required for the active recirculation and injection of electron donor were all readily available through local drillers and plumbing suppliers. The ClO_2 biofouling control system was also available and straightforward to install. The procedures used to install the equipment were standard and well established procedures for local drillers and the procedures were simple enough to be conducted by field technicians with training in basic plumbing techniques.

3.2 EASE OF ELECTRON DONOR DELIVERY EVENTS

The ease of electron donor delivery is an important factor in maintaining low operation and maintenance (O&M) costs. Ideally, the electron donor delivery can be conducted with minimal special training for operators conducting the events, with minimal special equipment and in a short period of time. This criterion was evaluated based on the experience of operators and the costs of operating the system.

This objective was achieved during the demonstration based on experience of field staff with the actual operation of the system. The activities and procedures required for the recirculation of groundwater and addition of electron donor delivery were simple enough to be conducted by field staff with minimal specialized training and effort. It is believed that the pulsed injection of electron donor over 1 hour each day followed by an injection of ClO_2 was an effective operating strategy for controlling biofouling of the injection well.

3.3 ENHANCEMENT OF MICROBIOLOGICAL ACTIVITY

The enhancement of microbiological activity is a critical factor to the success of the EISB technology because it is this activity that degrades the perchlorate in the subsurface. This criterion was evaluated based on the results of groundwater and soil analyses for geochemical parameters.

This objective was achieved based on the results of chemical and geochemical characterization. Groundwater monitoring data for chemical and geochemical parameters demonstrated that electron donor addition enhanced microbiological activity in the treatment zone. Significant and sustained reductions in ORP and reductions in perchlorate concentrations provided evidence that biological activity was enhanced by the addition of the electron donor.

3.4 EASE OF PERFORMANCE MONITORING AND VALIDATION

The ease of performance monitoring and validation is an important factor to demonstrate that the objective of perchlorate reduction has been accomplished. This criterion was evaluated by assessing the quality of data and ability to interpret and quantify biodegradation with confidence.

This objective was achieved during the demonstration based on the data obtained during the demonstration. The quality of the data obtained and the ability to interpret this data and quantify biodegradation with confidence demonstrated that the performance monitoring network allowed for straightforward data collection, interpretation, and validation.

3.5 REDUCTION IN PERCHLORATE CONCENTRATION

The reduction of perchlorate concentrations in groundwater is the most critical objective of demonstration. This is a quantitative objective of achieving an average concentration of perchlorate to the PQL of 4 µg/L. This criterion was assessed based on the results of chemical analysis of groundwater samples collected from performance monitoring wells.

This objective was achieved based on groundwater sampling of performance monitoring wells. Sampling results demonstrated that the average perchlorate concentrations were reduced to below the PQL of 4 µg/L during the operating period.

3.6 ROI AND DISTANCE FOR DEGRADATION

The ROI and distance for degradation of perchlorate is an important factor in determining the effectiveness of the electron donor distribution system. This criterion was assessed based on groundwater sampling of performance monitoring wells during the tracer test and following electron donor addition. The assessment demonstrated that the ROI for electron donor addition extends between injection and extraction wells and perchlorate is degraded before groundwater reaches downgradient performance monitoring wells.

This objective was achieved during the demonstration based on groundwater sampling results from performance monitoring wells following system operation. The sampling results demonstrated that the ROI for electron donor extends to the performance monitoring wells and that perchlorate was degraded before groundwater reached downgradient performance monitoring wells.

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4.0 SITE DESCRIPTION

This section presents information on the IRCTS where the demonstration was conducted. Section 4.1 describes the site location, Section 4.2 describes the site geology/hydrogeology, and Section 4.3 describes the contaminant distribution.

4.1 SITE LOCATION

The demonstration test area is located within Aerojet General Corporation's (Aerojet) 60-foot (ft) WNN easement on the western boundary of the original IRCTS configuration. The IRCTS was used between 1956 and 1969 for a variety of aerospace-related activities including testing of solid-rocket motors and liquid rocket engines.

4.2 SITE GEOLOGY/HYDROGEOLOGY

The site is situated on a dissected alluvial plain in the southeastern margin of the Sacramento Valley. The area is underlain by over 1000 ft of sediments that include the following, from youngest to oldest:

- Quaternary South Fork Gravels;
- Quaternary-Tertiary Laguna Formation;
- Tertiary Mehrten, Valley Springs, and Ione Formations; and
- Cretaceous Chico Formation (California DUSEPArtment of Water Resources [CDWR], 1964 and 1974).

Groundwater at the site occurs in various hydrostratigraphic units within the Laguna and Mehrten Formations. The Laguna Formation is described as a predominately fine-grained, non-volcanic fluvial deposit. Contact with the underlying Mehrten Formation is gradual, and a 60- to 100-ft transition zone has been defined in the general area of the IRCTS and areas to the west (ENSR, 2001).

The transition zone has been identified by the presence of intercalated brown and black sands of volcanic origin and lower natural gamma response (ENSR, 2001). Underlying the transition zone, the Mehrten Formation consists of interbedded black sands and gravels with occasional thin silts and clays. A blue clay is present under these sands and gravels, which represents the top of the underlying Valley Springs Formation. In the vicinity of the demonstration test area, the top of the Mehrten Formation is shown to be at an elevation of approximately -100 ft below sea level or a depth of about 250 ft below ground surface (bgs) (CDWR, 1964).

Groundwater flow in the region is primarily to the west-southwest under horizontal gradients between 0.0027 and 0.0032 feet per foot (ft/ft) (ENSR, 2001). Vertical gradients across the site range from no gradient to downward gradients of up to 0.12 ft/ft. Pumping tests were performed at RW-1 in 2003. Results of the pumping tests indicated that the hydraulic conductivity of the shallow aquifer ranges from 65 to 100 ft per day (ft/day). Figure 1 shows the layout of monitoring wells and the direction of groundwater flow in the vicinity of the demonstration test area.

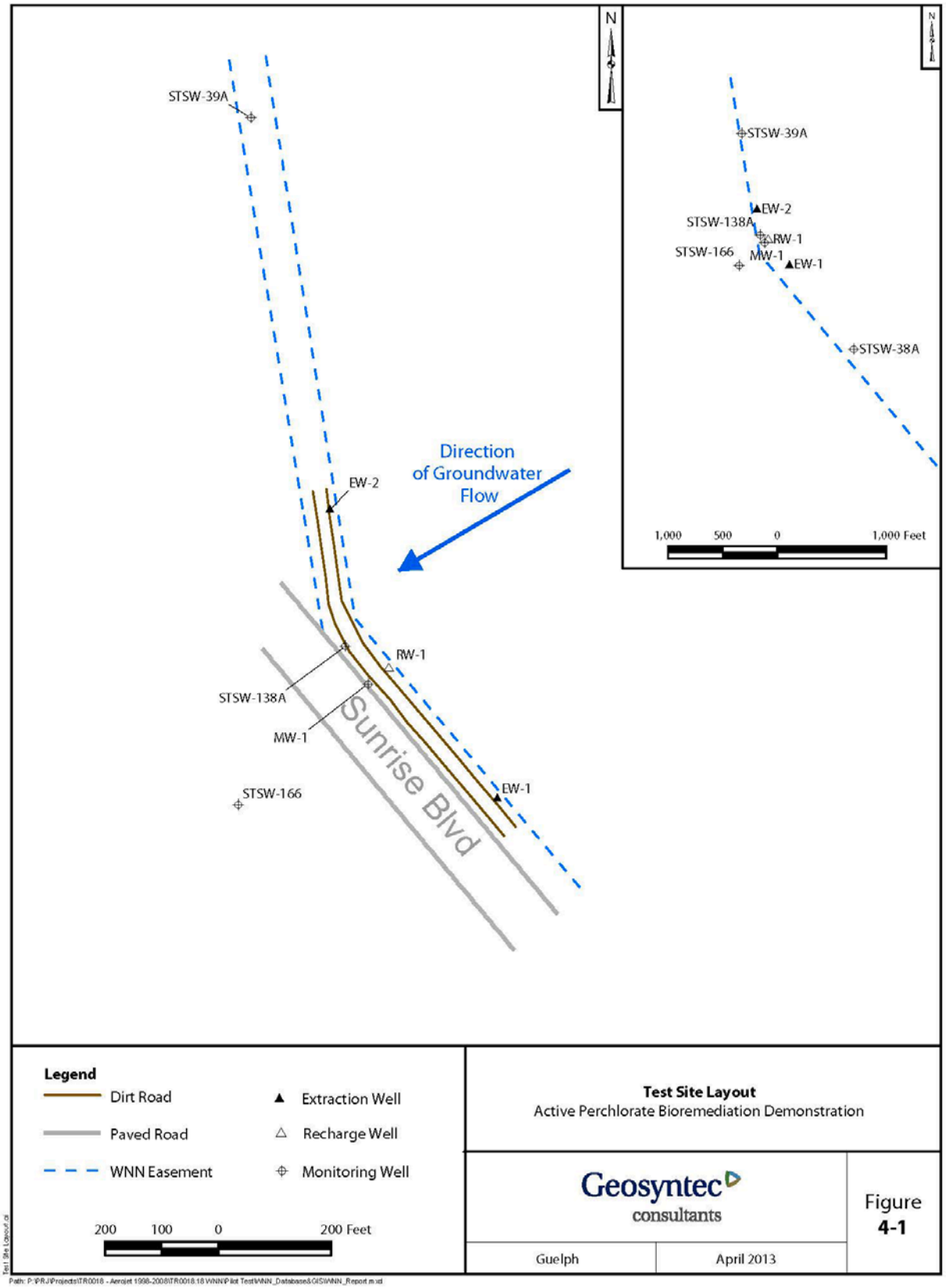

Figure 1. Test site layout.

In the vicinity of the test site, undifferentiated quaternary deposits are present from ground surface to approximately 100 ft bgs, which is underlain by a low permeability layer of silty clay (10 to 75 ft), before encountering the Laguna formation. The demonstration test was conducted in the shallowest aquifer of the local Laguna Formation, which extends from 120 to 182 ft bgs (thickness of 62 ft). In the demonstration test area the Laguna formation consists of gravel and silty and clayey sands. Another low permeability silty clay layer is present below the Laguna formation, followed by the Laguna-Mehren transition zone to a depth of approximately 250 ft bgs. Depth to groundwater was approximately 122 ft bgs before the initiation of the pilot test, which suggests that aquifer is unconfined or partially confined because the water level is near the top of the aquifer.

4.3 GROUNDWATER CHEMISTRY

The wells in the vicinity of the test area produce a calcium-magnesium bicarbonate groundwater with a total dissolved solids (TDS) concentration of approximately 160 milligrams per liter (mg/L). Before the test was initiated, the water contained perchlorate and TCE at concentrations of up to 4600 µg/L and 17 µg/L, respectively. The concentrations of cis-1,2-dichloroethene (DCE) and vinyl chloride (VC) were below their PQLs, indicating intrinsic TCE biodegradation was negligible. Nitrate and sulfate concentrations were low (maximums of 2.1 and 11 mg/L, respectively). Dissolved oxygen (DO) concentrations in the various wells ranged from 0.86 to 4.55 mg/L, which suggests aerobic conditions. However, ORPs ranged from –128 to 188 millivolts (mV), which suggests some variability in baseline redox conditions in the demonstration test area. Measurements of general indicators of biological activity, including volatile fatty acid and dissolved hydrocarbon gas testing, biochemical oxygen demand (BOD) and chemical oxygen demand (COD), and testing for general bacterial deoxyribonucleic acid (DNA), indicated limited biological activity in the groundwater.

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5.0 TEST DESIGN

This section describes the design and the results of the demonstration test.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

In concept, the active biobarrier approach involved the use of alternating extraction and injection (recirculation) wells installed across a perchlorate plume. To add and mix the electron donor across the plume, groundwater was extracted, amended with electron donor, and recharged to the aquifer to promote in situ biodegradation of perchlorate and prevent migration of perchlorate beyond the biobarrier.

The active biobarrier consisted of two groundwater extraction wells (EW) (EW-1 and EW-2) and a single central electron donor delivery/recharge well (RW)-1. These wells were oriented along a line approximately perpendicular to the prevailing direction of groundwater flow and were located within the WNN easement. The EWs and RWs are all screened within the shallow aquifer: EW-1 is screened from 146 to 176 ft bgs; EW-2 is screened from 147 to 187 ft bgs; and RW-1 is screened from 140 to 180 ft bgs. During demonstration test operation, groundwater was extracted from EW-1 and EW-2, combined, amended with electron donor (ethanol), and recharged via RW-1. Demonstration test performance (hydraulic and biodegradation) was monitored using three performance monitoring wells in the test area (MW-1, STSW-138A, and STSW-166). MW-1 was installed in April 2003, is located approximately 50 feet downgradient from RW-1, and is screened from 145 to 185 ft bgs. STSW-138A is located approximately 85 feet transgradient from RW-1 and is screened from 160 to 180 ft bgs. STSW-166 was installed in January 2004, is located approximately 350 feet downgradient from RW-1, and is screened from 120 to 180 ft bgs. Figure 1 presents the site layout and the locations of these well.

5.2 BASELINE CHARACTERIZATION

Hydraulic characterization within the vicinity of the demonstration test was performed through pump testing and tracer testing. These activities are described below.

Hydraulic testing was conducted at recharge well RW-1 before the EWs were installed to characterize the hydraulic properties of the shallow aquifer in the vicinity of the demonstration test. Two pumping tests were conducted by GeoTrans, Inc.: (1) a step-drawdown test to evaluate the specific capacity of each well, and (2) a constant-rate test to determine the transmissivity and storage coefficient of the shallow zone of the aquifer.

The step-drawdown test consisted of five sequential 2-hour periods of constant-rate pumping at increasingly higher pumping rates. The five flow rates ranging from 30 gallons per minute (gpm) to 200 gpm. Drawdown was measured at RW-1 and used to determine the specific capacity of the well. Based on these data, the recharge capacity of RW-1 was then determined using the method of Driscoll (1986).

The constant-rate test was conducted at a pumping rate of 151 gpm for 25.5 hours. This rate was near the sustainable well yield for RW-1. Drawdown was measured in MW-1 and STSW-138A. The data were analyzed using the Cooper-Jacob straight line method, and the Hantush method

for leaky aquifers, to determine the transmissivity, hydraulic conductivity, and storativity of the aquifer.

A numerical groundwater flow model was previously created with Visual MODFLOW™ to simulate the flow conditions in the vicinity of the biobarrier. After the pumping test results were analyzed, the data were used in combination with lithological data from the wells to refine the groundwater model. The refined model was then used to predict the capture zones and to optimize spacing and pumping rates for the extraction wells.

A conservative tracer test was conducted in August 2003 to (1) evaluate groundwater flow patterns in the test area; and (2) confirm groundwater flow velocities and system residence times. Baseline groundwater conditions were determined from sampling activities conducted in the spring and summer months preceding implementation of demonstration test activities.

Samples were collected from wells RW-1, MW-1, STSW-138A, STSW-39A/B, STSW-38A, and STSW-166. These samples were submitted to (depending on the analyte) either Aerojet's Environmental Laboratory (AEL), SiREM Laboratories, Calscience Environmental Laboratories and/or California Laboratory Services for analysis by the methods listed in Table 2.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

This section describes the design and layout of the technology components.

5.3.1 System Infrastructure

The demonstration test infrastructure was installed and instrumented during the spring of 2003 and was completed in August 2003. The only exception to this statement was monitoring well STSW-166, which was installed in January 2004. Well installations (RW-1, EW-1, EW-2, MW-1 and STSW-166) were completed by WDC Exploration and Wells by GeoTrans, Inc. or Kleinfelder. Aerojet used various contractors to install piping and electrical controls between the wells, the instrumentation of the electron donor delivery and biofouling control systems, and the construction of a secure control facility. Figure 1 presents the layout of the groundwater extraction, electron donor delivery and monitoring wells in the demonstration test area. Aerojet removed the aboveground facilities after completion of the test operations.

5.3.2 Basis for Electron Donor Addition Rates

Ethanol was used as the electron donor because of its efficiency in promoting perchlorate degradation and because it does not adversely impact groundwater quality (other than a transient redox and alkalinity shift). Calculations to determine the electron donor demand for perchlorate and TCE in the groundwater at the demonstration test area are presented in Table 3.

Table 2. Summary of laboratory analytical methods.

Parameter	Analytical Method	Method	Analytical Laboratory	Quantitation Limit	Sample Container	Preservative	Holding Time
Field Parameters (pH, DO, ORP, temperature)	Field instrumentation	Field	NA	Varies	NA	NA	NA
Perchlorate, chlorate	Ion chromatography	USEPA 314, 300	AAL, CLS	4 µg/L, 0.02 µg/L	120 mL plastic	cool to 4EC	14 days
Volatile Organic Compounds (VOC)	Gas chromatography/ mass spectrometry	USEPA 601, 602	AAL	0.25 to 20 µg/L	2 x 40 mL VOA	HCl, cool to 4EC	14 days
Metals (dissolved)	Ion chromatography (field filtered)	SW-846, 6010	AAL	See Table 4B	500 mL plastic	cool to 4EC	28 days
Anions (bromide, chloride, nitrate, nitrite, sulfate, phosphate)	Ion chromatography	USEPA 300	AAL	0.03 to 0.05 mg/L	120 mL plastic	cool to 4EC	2 to 28 days
Ethanol	Gas chromatography/ mass spectrometry	SW-846, 8260M	CEL	0.5 µg/mL	2 x 40 mL VOA	HCl, cool to 4EC	7 days
VFAs (butyric, proprionic, lactic, acetic, and pyruvic acids)	High-performance liquid chromatography (HPLC)/ultraviolet (UV)	HPLC/UV	CEL	0.5 to 1 mg/L	250 mL amber glass	phosphoric acid, cool to 4EC	14 days
DHGs (ethene, ethane, methane)	Gas chromatography/ flame ionizing detector	RSK-175	CEL	1 mg/L	250 mL amber glass	HCl, cool to 4EC	7 days
Sulfide	Titrimetry, potentiometry	NB 3653:139, USEPA 376.2	CEL	0.05 mg/L	250 mL plastic	zinc acetate, sodium hydroxide to pH>9, cool to 4EC	7 days
BOD	Oxygen electrode	USEPA 405.1	CEL	1.0 mg/L	1000 mL plastic	cool to 4EC	2 days
COD	Titrimetry	USEPA 410.4	CEL	5.0 mg/L	250 mL plastic	sulfuric acid to pH<2, cool to 4EC	28 days
Dehalococcoides	Polymerase chain reaction (PCR) assay	NA	SiREM	NA	2 x 1L plastic	cool to 4EC	30 days

AAL – Aerojet Analytical Laboratories, Rancho Cordova, California
CLS – California Laboratory Services, Rancho Cordova, California
CEL – CalScience Environmental Laboratory, Garden Grove, California
SiReM – SiREM Laboratories, Guelph, Ontario
NA – Not Applicable
DO – Dissolved oxygen
BOD – biological oxygen demand
mL – milliliter
L – liter
EC – degrees Celsius
ORP – oxidation reduction potential
VOA – volatile organic analysis
HCl – hydrochloric acid
COD – chemical oxygen demand

Table 3. Electron donor demand calculations.

Electron Acceptor	Chemical Formula	Stoichiometry[a]	Ethanol Balanced Redox Reaction[b]	Molar Ratio[c]
Oxygen (O_2)	O_2	$O_2 + 4H^+ + 4e^- = 2H_2O$	$C_2H_6O + 3O_2 = 2CO_2 + 3H_2O$	1/3
Nitrate ($NO_3\Gamma$)	$NO_3\Gamma$	$2NO_3^- = 12H^+ + 10e^- = N_2 + 6H_2O$	$5C_2H_6O + 12NO_3^- + 12H^+ = 6N_2 + 10CO_2 + 21H_2O$	5/12
Sulfate (SO_4^{2-})	SO_4^{2-}	$SO_4^{2-} + 10H^+ + 8e^- = H_2S + 4H_2O$	$2C_2H_6O + 3SO_4^{2-} + 6H^+ = 3H_2S + 4CO_2 + 6H_2O$	2/3
Perchlorate ($ClO_4\Gamma$)	$ClO_4\Gamma$	$ClO_4^- + e^- = ClO^- + 2O_2$	$2C_2H_6O + 3ClO_4^- = 3Cl^- + 4CO_2 + 6H_2O$	2/3
TCE (C_2HCL_3)	C_2HCL_3	$C_2HCl_3 + 6e^- + 3H^+ = C_2H_4 + 3Cl^-$	$C_2H_6O + 2C_2HCl_3 + 3H_2O = 2C_2H_4 + 2CO_2 + 6H^+ + 6Cl^-$	1/2

Electron Acceptor	Molecular Weight (g/mol)	In Situ Concentrations[d] (mg/L)	Molar Ratio	Ethanol Demand (mg/L)
Oxygen (O_2)	32.0	4.0	1/3	1.9
Nitrate ($NO_3\Gamma$)	62.0	1.0	5/12	0.3
Perchlorate ($ClO_4\Gamma$)	99.5	1.0	2/3	0.3
Sulfate (SO_4^{2-})	96.1	11	2/3	3.5
TCE (C_2HCL_3) (TCE)	131.4	0.02	1/2	0.004
Electron Donor Demand to Reduce Oxygen, Nitrate, and Perchlorate				**2.5**
Electron Donor Demand to Reduce Oxygen, Nitrate, Perchlorate, Sulfate, and TCE				**6.0**

Notes:
[a]Complete mineralization to the appropriate end products was assumed.
[b]Balanced redox reactions using ethanol were developed by adding the appropriate constituent half-reactions with the half-reaction for ethanol; whereby the ethanol (C_2H_6O) half-reaction is given by: $C_2H_6O + 3H_2O = 2CO_2 + 12H^+ + 12e^-$ (solutions are non-unique).
[c]Molar ratio is the number of moles of electron donor consumed per mole of constituent.
[d]Baseline perchlorate and trichloroethene results from STSW-39A measured from November 2000 to July 2001.
Oxygen, nitrate and sulfate results estimated from pervious microcosm studies for Alpha and Sigma Complex and former GET F Sprayfield.

Degradation of perchlorate requires the addition of sufficient electron donor to reduce oxygen and nitrate before perchlorate reduction; whereas, degradation of TCE requires the reduction of oxygen, nitrate, perchlorate, and sulfate prior to TCE reduction. The 24-hour time-weighted average electron donor concentration was initially 6 mg/L from demonstration test initiation through 16 March 2004, and 18 mg/L for the remainder of the pilot test. The initial concentration reflected the amount of electron donor stoichiometrically required to degrade perchlorate and TCE without excess. Following 16 March 2004, the concentration was increased 3-fold to provide excess electron donor to enhance the rate and extent of TCE dechlorination. Electron donor demand was calculated based on baseline concentrations of 0.02 mg/L TCE, 11 mg/L of sulfate, 1 mg/L perchlorate, 1 mg/L nitrate, and 4 mg/L DO. Electron donor addition was achieved through 1-hour daily pulse additions of 2580 mL pure ethanol at 43 mL/minute (for the period of to 16 March 2004) and 4,150 mL pure ethanol at 69 mL/minute (for the remainder of the demonstration test). The schedule of electron donor addition concentrations is presented in Table 4.

Additional electron donor was added immediately before each bioaugmentation event to provide suitable conditions for introduction of the dehalorespiring bacteria, as described in Section 5.3.3.

5.3.3 Bioaugmentation

Two sUSEPArate bioaugmentation events were conducted to evaluate the potential to enhance TCE bioremediation. The first event (Bioaugmentation A) was conducted on 10 November 2003 (day 63 of the demonstration test); the second event (Bioaugmentation B) was conducted on 24 March 2004 (day 198). Both events consisted of amending the shallow aquifer with approximately 40 L of KB-1 (provided by SiREM Laboratories), a microbial consortium that contains the dehalorespiring bacteria *Dehalococcoides*.

5.4 FIELD TESTING

The demonstration system was operated from September 2003 to April 2004. The activities conducted during the operation are described in the following subsections.

5.4.1 System Operation and Monitoring

5.4.1.1 <u>System Operation</u>

The system was initially operated by extracting groundwater from wells EW-1 and EW-2 at rates of approximately 20 gpm and 40, gpm respectively, beginning on 08 September 2003. On 16 March 2004, the flow rate at EW-1 was increased to 30 gpm to improve groundwater capture at this well. The demonstration test was terminated on 30 April 2004 (day 238). The extraction wells were equipped with submersible pumps set at 140 ft below top of casing (btoc). Pressure transducers with a pressure range of 10 pounds per square inch (psi) were set at 133 ft btoc. Level controls were set at 130 ft btoc for low-level shutoff to limit drawdown and protect the pump and at 122 ft btoc for high-level “on” (assuming a static water level of 120 ft btoc). However, to the extent possible, the flow rate from each well was maintained at a sustainable flow rate that did not induce cycling of the pump.

Table 4. Electron donor addition schedule.

Date Range	Start Day	End Day	24-Hour Time-Weighted Average Electron Donor Concentration Added (mg/L)	Stoichiometric Demand to Reduce Oxygen, Nitrate, and Perchlorate (mg/L)	Increase Over Stoichiometric Demand	Stoichiometric Demand to Reduce Oxygen, Nitrate, Perchlorate, Sulfate, and TCE (mg/L)	Increase Over Stoichiometric Demand	Flow from EW-1 (gpm)	Flow from EW-2 (gpm)
8-Sep-03 to 18-Dec-03	0	104	6	2.5	2.4X	6	1X	20	40
18-Dec-03 to 3 Jan-04[1]	104	120	0	2.5	0X	6	0X	1	0
3-Jan-04 to 16-Mar-04	120	193	6	2.5	2.4X	6	1X	20	40
16-Mar-04 to 30-Apr-04	193	238	18	2.5	7X	6	3X	30	40

Notes:
[1]System was shut down for holidays

The recharge well, RW-1, was operated at a flow rate of approximately 60 gpm, for the period up to 16 March 2004, and at a rate of approximately 70 gpm for the remainder of the demonstration test. RW-1 contained a back pressure valve at the wellhead and a pressure transducer with a range of 50 psi set at 122 ft btoc. A static water level of 120 ft btoc was assumed, thus level controls were set with a high-level shutoff at 92 ft btoc and a low-level "on" at 118 ft btoc. The high-level/pump-shutoff would prevent overflow in the event of well fouling (biological or mineral).

Groundwater from both extraction wells was combined and then directed through a filter system to remove particulates. The filter system was equipped with two sets of filters in parallel to allow filter change out without system shutdown. Following filtration, in-line flow sensors installed in each flow stream were used to continuously measure the flow rate of extracted groundwater from the individual wells. These data were logged automatically at 5-minute intervals. The flow from the two streams was then combined at a manifold "tee" and flowed through a third flow sensor. This latter sensor provided feedback control to the pumps to maintain steady extraction/recharge rates and controlled the delivery of tracer and/or electron donor solution to maintain a fixed concentration of these components in the amended groundwater to the recharge well. Following this third flow sensor, a Signet model 3-8750-1 probe continuously measured pH and ORP in the extracted groundwater, logging data at 5-minute intervals. The combined groundwater was then amended with electron donor (see Section 5.5) using a chemical metering pump, and passed through an in-line mixer before recharge to the shallow aquifer via a submerged delivery line in the recharge well RW-1.

The system operation was controlled using a programmable logic controller connected to a personal computer. The control system recorded the groundwater extraction rate and total volume, individual electrode measurements, and water levels in the extraction and recharge wells at 5-minute intervals.

5.4.1.2 System Maintenance and Monitoring

O&M activities included the following:

- Inspection of the groundwater circulation system;
- Dosing of the RW-1 with chlorine dioxide for biofouling control;
- Filling of electron donor and tracer supply tanks as needed;
- Replacement of filters as needed;
- Sampling and chemical analysis; and
- Periodic downloading of automated data collection systems.

5.4.1.3 Biofouling Control

Chlorine dioxide gas was used to control biofouling of the electron donor delivery/RW. The chlorine dioxide generator (CDG) from CDG Technologies, Inc., used a pre-blended compressed gas cylinder to supply a pressurized mixture of nitrogen and chlorine gas (96% nitrogen, 4% chlorine), which was passed through a cylinder of sodium chlorite ($NaClO_2$) within the unit housing, generating 8% chlorine dioxide gas (ClO_2) in nitrogen. The amount of chlorine dioxide delivered during each dosing event was regulated by the gas flow rate, and the gas was piped

directly into the recharge water at the well-head to control biofouling within RW-1. Chlorine dioxide dosing was accomplished by adding daily one-hour doses of 1 mg/L of ClO_2.

5.4.1.4 Performance Monitoring

Performance monitoring of groundwater chemistry at demonstration test wells consisted of weekly to monthly measurements of field parameters, perchlorate and other electron acceptors, and bioremediation parameters.

Monitoring at injection well RW-1 was conducted by collecting samples from a sample valve located within the treatment system after electron donor addition and before the chlorine dioxide unit. Data provided for RW-1 represent the concentrations and chemistry of the water being injected into RW-1. These data provide background data to measure changes in groundwater chemistry and concentration between RW-1 and MW-1 that can be used to evaluate the effectiveness of the treatment system.

5.5 SAMPLING METHODS

Depending on the analytical parameter, samples were submitted to either AEL, SiREM Laboratories, CEL, and/or CLS for analysis by the methods listed in Table 2.

5.6 SAMPLING RESULTS

This section presents the results obtained during the demonstration.

5.6.1 Baseline Conditions

This section presents the results of baseline monitoring conducted prior to the injection of electron donor at the site.

The key baseline groundwater chemistry can be summarized as follows:

- Baseline DO concentrations ranged from 0.86 to 4.55 mg/L. Baseline ORP values ranged from –128 to 188 mV.
- The groundwater pH was near-neutral, ranging from 6.9 to 7.8.
- Perchlorate concentrations ranged from nondetect (STSW-38A) at a PQL of 4 µg/L) to 2600 µg/L (wells EW-2 and STSW-138A). Outside the demonstration test area, perchlorate concentrations ranged up to 4300 µg/L, with the highest concentration detected at well STSW-39A.
- Chlorate concentrations ranged from nondetect at a PQL of 0.02 mg/L to 0.32 mg/L.
- Chloride was detected in the demonstration test area at concentrations in the range of 2 to 4 mg/L.
- Nitrate concentrations were low and ranged from nondetect to 1.7 mg/L.

- Sulfate was detected in all wells at concentrations of 9 to 10 mg/L. Sulfide was not detected in any of the wells, at a PQL of 0.05 mg/L.
- Trichloroethene was detected in all wells except for EW-1. Concentrations ranged from 0.74 to 23 µg/L. The compounds cis-1,2-DCE and VC, and potential intermediate products of TCE dechlorination, were not detected above their PQL of 0.5 µg/L.
- Ethene and ethane, potential end products of TCE dechlorination, were not detected. Similarly, methane, an indicator of microbial (anaerobic) activity was not detected in these wells. The PQL for these dissolved hydrocarbon gases was 1 µg/L.
- Manganese was detected in STSW-138A, STSW-38A, STSW-39A, and STSW-39B at concentrations from 0.009 to 0.034 mg/L. Iron was only detected in groundwater from STSW-39B (0.74 mg/L) and was not detected in the other wells above a PQL of 0.3 mg/L.
- *Dehalococcoides* presence was tested for groundwater samples from extraction wells EW-1 and EW-2. *Dehalococcoides* were detected in EW-2 at low levels.
- Acetic acid was detected in EW-1, MW-1 and STSW-138A at concentrations ranging from 1.8 to 3.7 mg/L. Propionic acid was only detected in STSW-138A at a concentration of 2.9 mg/L.
- BOD and COD concentrations were below PQLs of 1 and 5 mg/L, respectively, at all wells.

5.6.2 Pump Testing and Groundwater Modeling

The step-drawdown test of RW-1 established a linear relationship between discharge and drawdown, and therefore RW-1 was an efficient well for the discharge rates of the test. A specific capacity of 10 gallons per minute per foot of drawdown (gpm/ft) was obtained, which indicates a transmissivity of approximately 2700 square ft (ft^2) per day (ft^2/day). Driscoll (1986) states that the addition of positive head in a recharge well should not exceed one-fifth of the depth from the ground surface to the top of screen to minimize the potential for fracturing the formation and/or damaging the hydraulic conductivity of the aquifer. This distance is 28 ft in RW-1; therefore, the theoretical recharge capacity of RW-1 was 280 gpm. However, based on Aerojet experience and the potential for fine-grained materials to reduce the capacity of a recharge well, a conservative estimated recharge capacity for RW-1 was assumed to be 140 gpm.

The constant-rate drawdown data were analyzed using the Cooper-Jacob straight-line method and the Hantush method for leaky aquifers. The resultant transmissivity and hydraulic conductivity values were 2600 to 2900 ft^2/day and 65 to 73 ft/day respectively.

The site-specific information generated by the pumping tests and lithologic data from the wells were used to refine a numerical groundwater flow model previously created with Visual MODFLOW to simulate the pilot project flow conditions. The revised model was used to estimate optimal pumping rates for the two extraction wells and recharge for RW-1, and to estimate the capture zone of this system. Based on these analyses, a spacing of 600 ft was selected for the extraction wells (300 ft north and 300 ft south of RW-1). This spacing allowed flexibility in achieving adequate hydraulic capture through adjustment of flow rates as

operational data were collected pertaining to well capacity, aquifer hydraulic parameters, and bromide tracer recovery. Simulations of particle tracking indicated this configuration would create a nominal 800-foot wide biobarrier with pumping rates as low as 20 gpm per well for an extraction/recharge zone transmissivity of 2,600 ft^2/day. However, the well capacities provided a safety factor in case the flow rate needed to be higher based on operations data.

The refined flow model from the pre-test analysis was calibrated to water levels measured during the constant-rate pumping test and the tracer test. The model layers included an aquitard above and below the pumped aquifer and included simulated leakage through the aquitards. To minimize boundary effects, the upgradient and downgradient boundaries were changed from constant-head boundaries to general-head boundaries. The modeled drawdown matched the observed drawdown for the following input parameters:

- Hydraulic conductivity = 65 ft/day
- Aquifer thickness = 40 ft
- Aquitard vertical hydraulic conductivity = 0.0035 ft/day
- Storativity = $4x10^{-6}$

This combination of hydraulic conductivity and aquifer thickness corresponds to a transmissivity of 2,600 ft^2/day, which is comparable with the results from the analysis of specific capacity and the Cooper-Jacob method.

The design recommendations that were implemented based on the modeling included (1) extraction well spacing of 600 ft with RW-1 located equidistant (300 ft) from EW-1 and EW-2; (2) initial extraction rates at EW-1 and EW-2 of 20 gpm and 40 gpm (respectively); and (3) initial recharge rate at RW-1 of 60 gpm. The extraction rate at EW-2 was higher than at EW-1 because the aquifer is thicker at EW-2 than at EW-1. An illustration of this scenario created by the numerical model is presented on Figure 2.

5.6.3 Tracer Testing

Figure 3 shows the results of the bromide tracer test of demonstration test area hydraulics. Maximum breakthrough concentrations at MW-1 occurred on 11 September 2003 (day 24 of the tracer test), with a concentration of 24 mg/L. This maximum breakthrough concentration was 96% of the 25 mg/L time-weighted average injection concentration. The average travel time for groundwater from RW-1 to MW-1 was approximately 16 days.

Breakthrough at the transgradient monitoring well STSW-138A reached a maximum concentration of 17 mg/L by 22 September 2003 (day 35 of the tracer test). This breakthrough concentration constituted approximately 68% of the injection concentration of bromide. The average travel time for groundwater from RW-1 to STSW-166 was approximately 23 days.

Bromide breakthrough was observed in both EWs. Breakthrough at EW-1 was observed on 16 December 2003 (day 120 of the tracer test) at a concentration of 0.05 mg/L or 0.2% of the injection concentration. Breakthrough at EW-2 was observed by 7 October (day 50 of the tracer test) at concentrations of 0.097 to 0.690 mg/L or 0.4 to 2.8% of the injection concentration.

These results provide confidence that the biobarrier was providing some capture across the full 600 ft reach of the biobarrier.

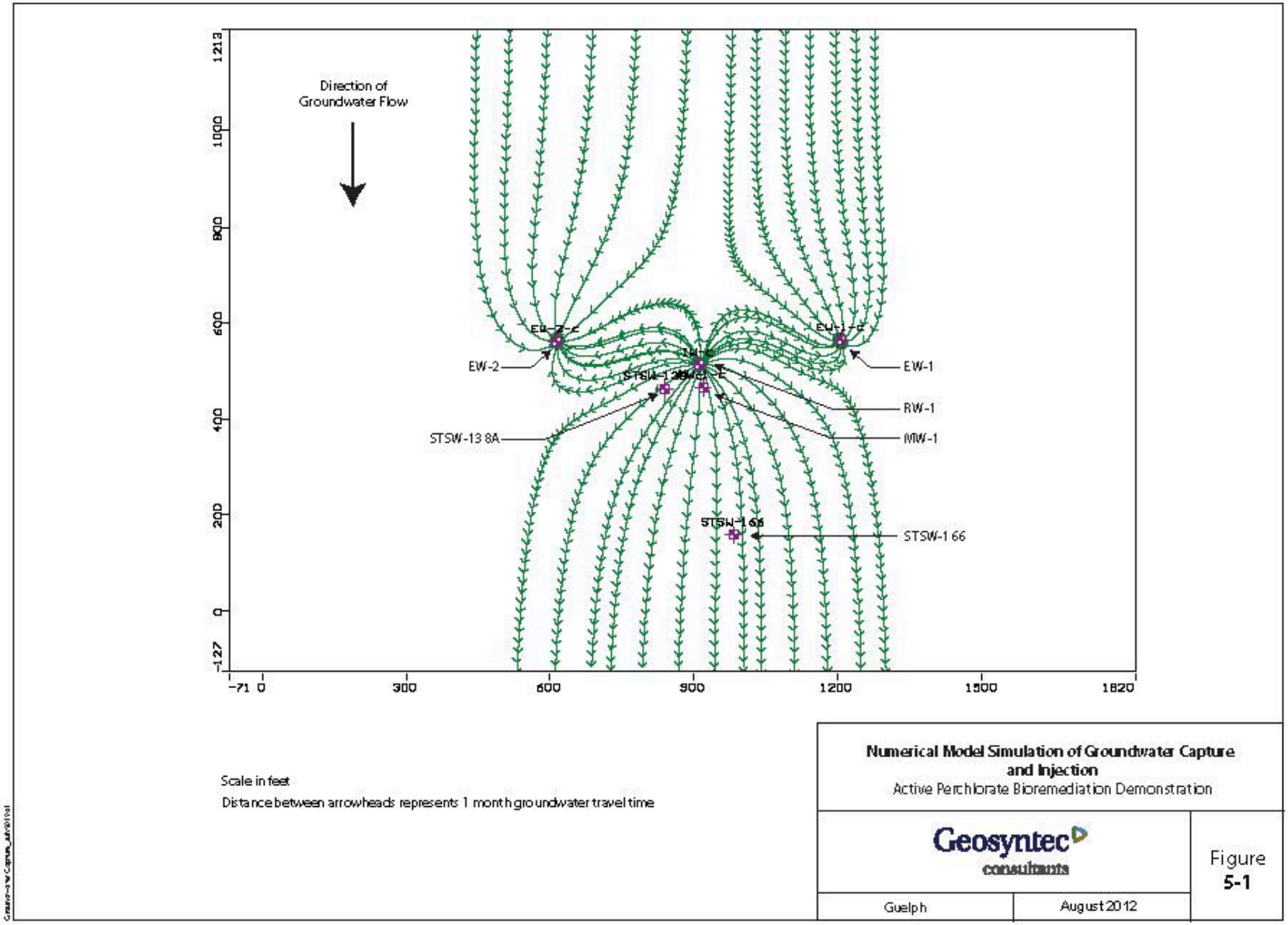
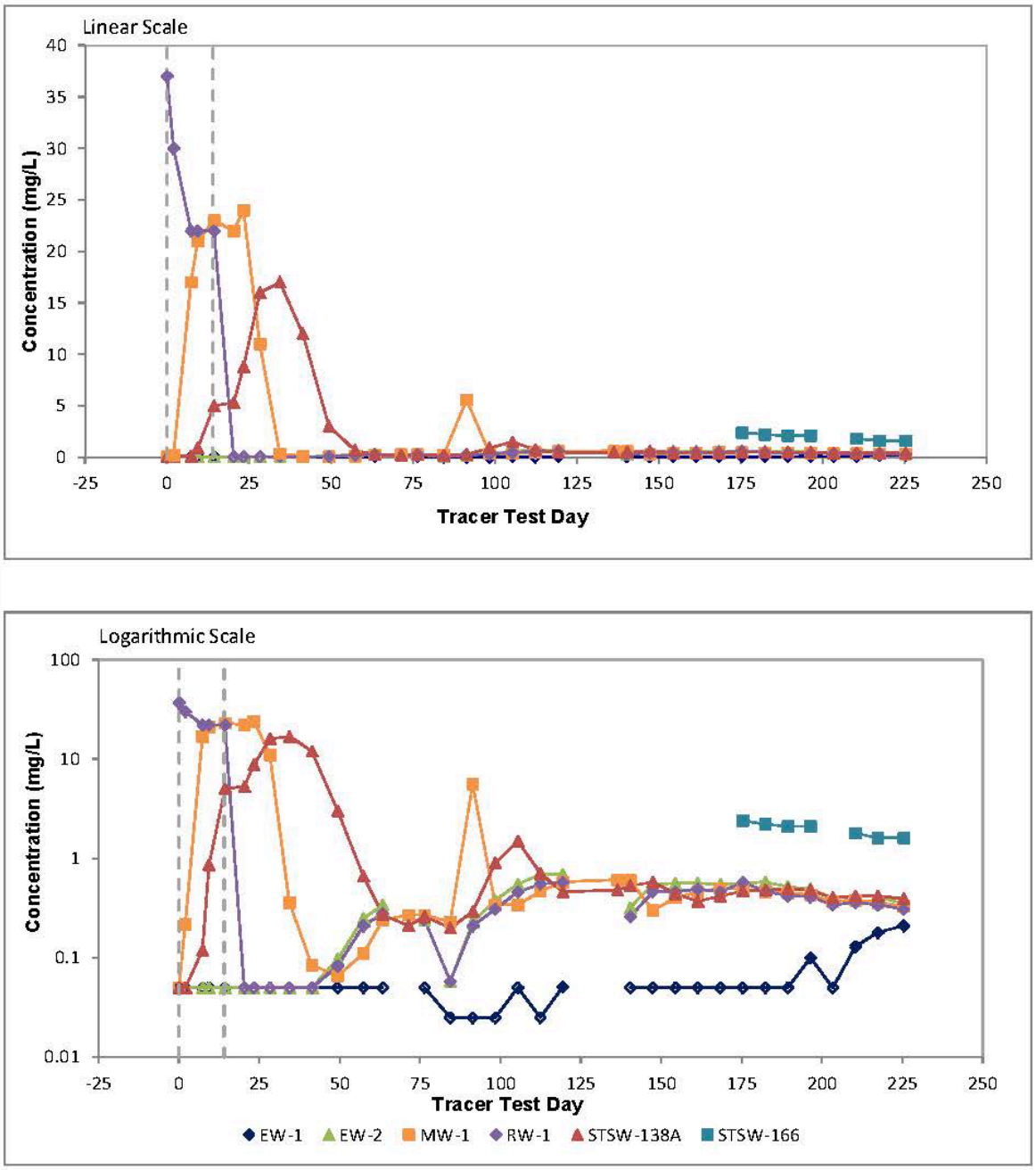


Figure 2. Numerical model simulation of groundwater capture and injection.



Open symbols represent non-detect values (plotted at the detection limit)

Note: Day "0" = 19-Aug-03

Bromide Tracer Testing Results
Active Perchlorate Bioremediation Demonstration

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Figure 5-2

Figure 3. Bromide tracer testing results.

The numerical flow model was also used to simulate the transient flow field during the tracer test and was coupled with a transport model to simulate the breakthrough of bromide in the MWs and EWs. The following input parameters resulted in a reasonable match between observed and modeled concentrations at MW-1 and STSW-138A, and EWs EW-1 and EW-2:

- Hydraulic gradient = 0.005
- Longitudinal dispersivity = 5 ft
- Transverse dispersivity = 0.5 ft
- Effective porosity = 0.28

5.6.4 Redox and pH Trends

Figure 4 presents trends in ORP and DO conditions in the test area over the duration of the demonstration test. The extracted groundwater from EW-1 and EW-2 was typically aerobic and oxidizing, with median DO values of 2.9 and 2.3 mg/L, respectively, and median ORP values of 93 and 78 mV, respectively. Following addition of electron donor, the redox conditions at the monitoring wells MW-1 and STSW-138A declined, and DO was typically below 1 mg/L and negative ORP. The pH of the test area groundwater generally remained stable and generally neutral throughout the pilot test.

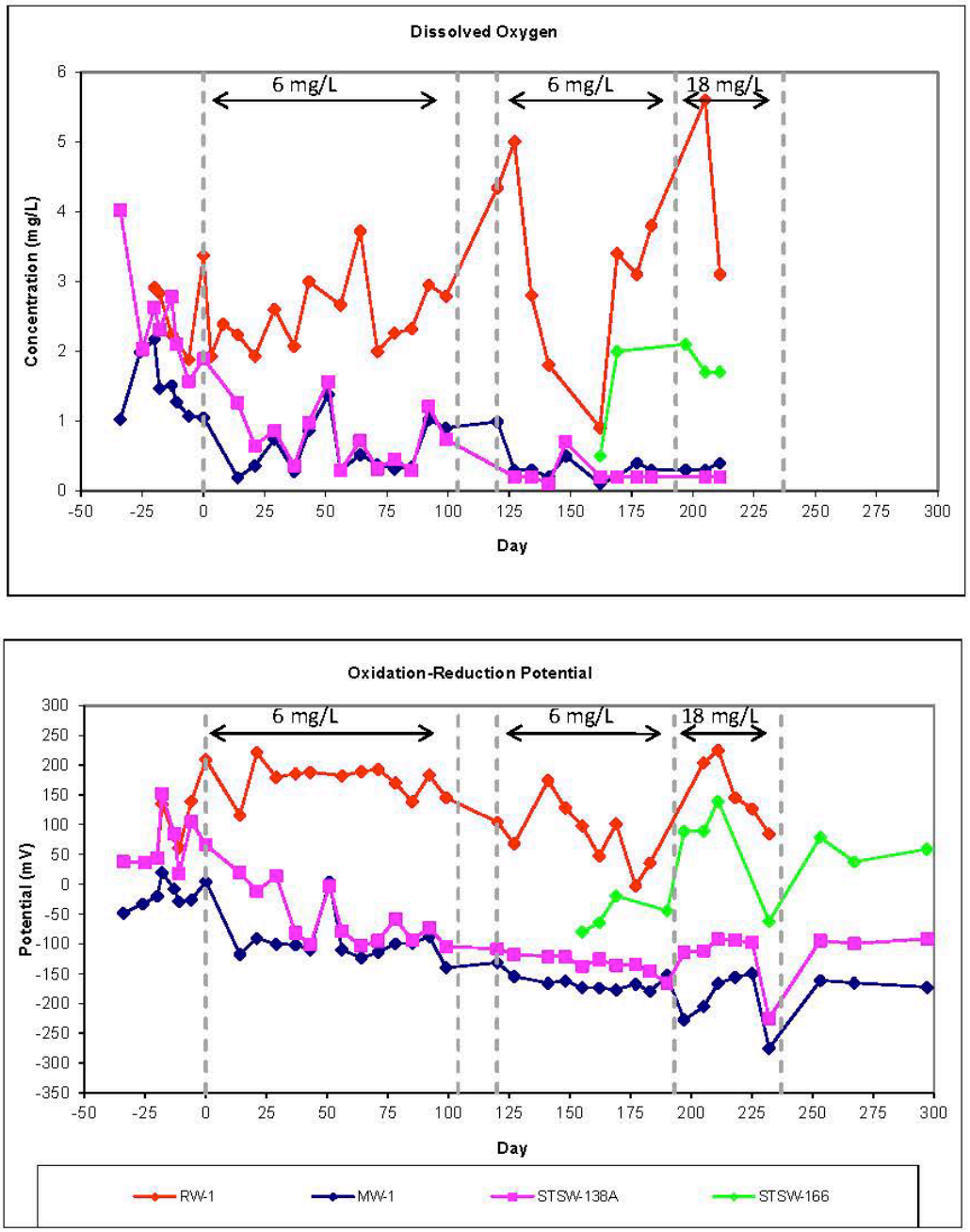
5.6.5 Results of Perchlorate Analysis

Figure 5 presents trends in perchlorate concentrations in the demonstration test area groundwater over the duration of the demonstration test.

Perchlorate concentrations were quite different in the extraction wells, which included relatively low and increasing concentrations at EW-1 and much higher, but declining, concentrations at EW-2.

Perchlorate varied from 250 to 480 µg/L at EW-1 (median: 350 µg/L) and from 1900 to 3000 µg/L at EW-2 (median: 2400 µg/L). Influent concentrations at RW-1 tracked EW-2 concentrations and typically ranged from 1300 to 2500 µg/L over the course of the study (median: 1900 µg/L, excluding a questionable nondetect and two anomalously low values).

Following electron donor addition, perchlorate concentrations declined rapidly in monitoring well MW-1 and reached nondetect on 7 October 2003 (day 30). Concentrations generally remained nondetect throughout the remainder of the pilot test and for over 2 years after the test. Moreover, “normal” perchlorate concentrations (~1500 µg/L) had not returned to MW-1 (~70 µg/L) by late 2009. An evaluation of the perchlorate concentrations at MW-1 indicates that there was little acclimation period before perchlorate degradation occurred following addition of the electron donor. Based on the data for MW-1, the half-life for perchlorate biodegradation can be calculated as 1.1 days, which is consistent with perchlorate biodegradation half-lives measured for other perchlorate sites (Cox et al., 2001).



Dissolved Oxygen and Oxidation-Reduction Potential Trends

Active Perchlorate Bioremediation Demonstration

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Figure 5-3

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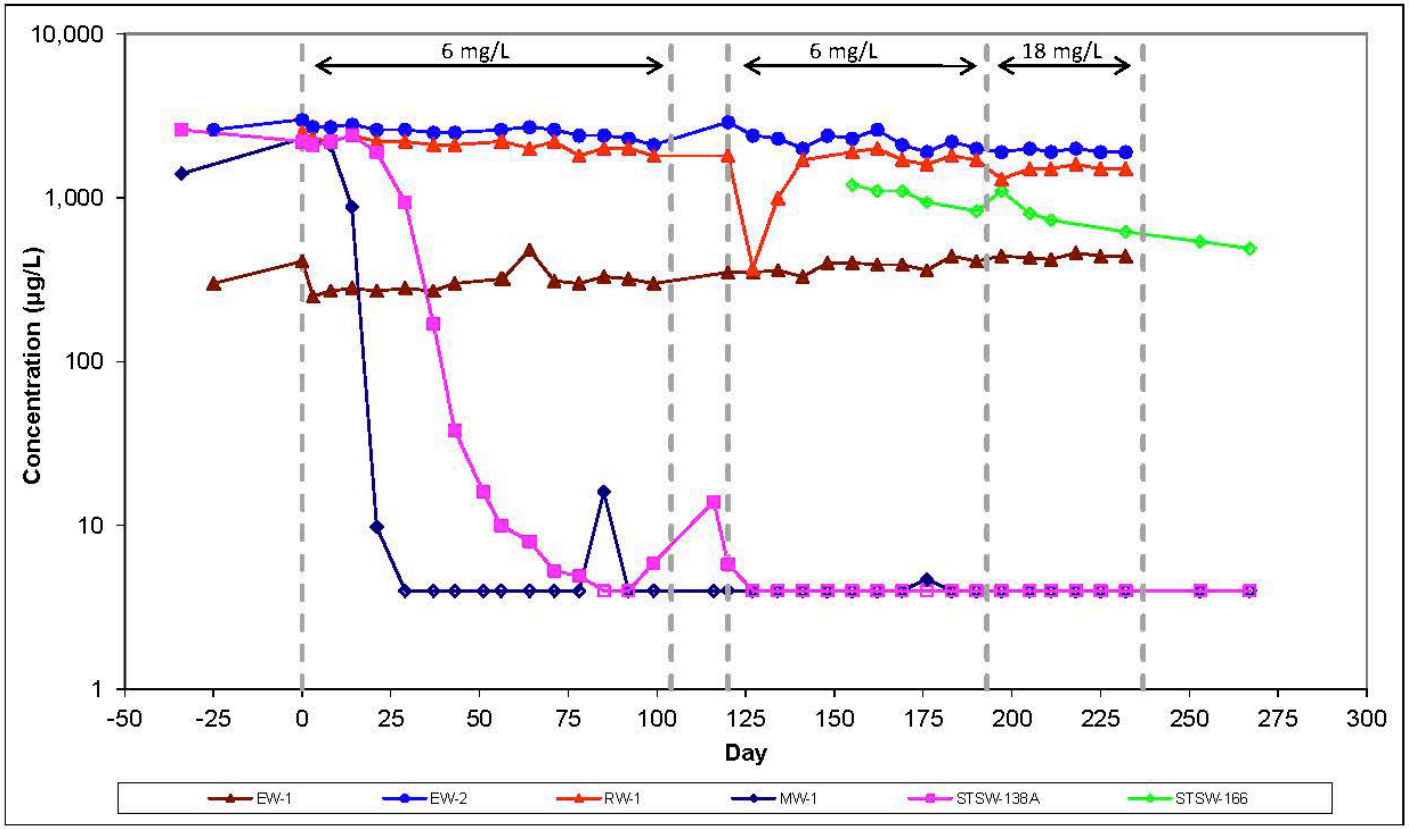
Notes:
Day "0" = 8-Sep-03
"6 mg/L" - dose rate of ethanol

Figure 4. DO and ORP trends.



Notes:
Open symbols represent non-detects
Day "0" = 8-Sep-03
"6 mg/L" - dose rate of ethanol

Perchlorate Biodegradation Results
Active Perchlorate Bioremediation Demonstration

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Figure 5-4

Figure 5. Perchlorate biodegradation results.

At monitoring well STSW-138A, perchlorate concentrations declined to non-detect on 2 December 2003 (day 86) and generally remained non-detect throughout the remainder of the pilot test, and for approximately five months after the test. Normal perchlorate concentrations returned to STSW-138A during late 2005, approximately one year after perchlorate was detected again.

Perchlorate biodegradation was able to continue after the demonstration test because the ethanol dosing was able to create and sustain a large mass of bacteria within a biologically active zone (BAZ) between RW-1 and MW-1. Without ethanol, the bacterial mass would have declined and living bacteria would feed on dead bacteria while consuming perchlorate, nitrate, and dissolved oxygen in the groundwater flowing into the bacterial mass. MW-1 was probably located near the center of this biomass and was able to maintain the degradation of perchlorate much longer than the peripheral location of STSW-138A. The locations of these wells suggest a maximum BAZ width between 150 and 200 ft for the 7.8-month test. The BAZ continued to reduce perchlorate concentrations around MW-1 for over 5 years after the test.

Perchlorate at STSW-166 was found to be declining during the latter third of the test (new well) and for over 6 months after the test. Normal perchlorate concentrations probably returned to STSW-166 during 2008. These data show that treated groundwater migrated downgradient of the BAZ into the vicinity of STSW-166.

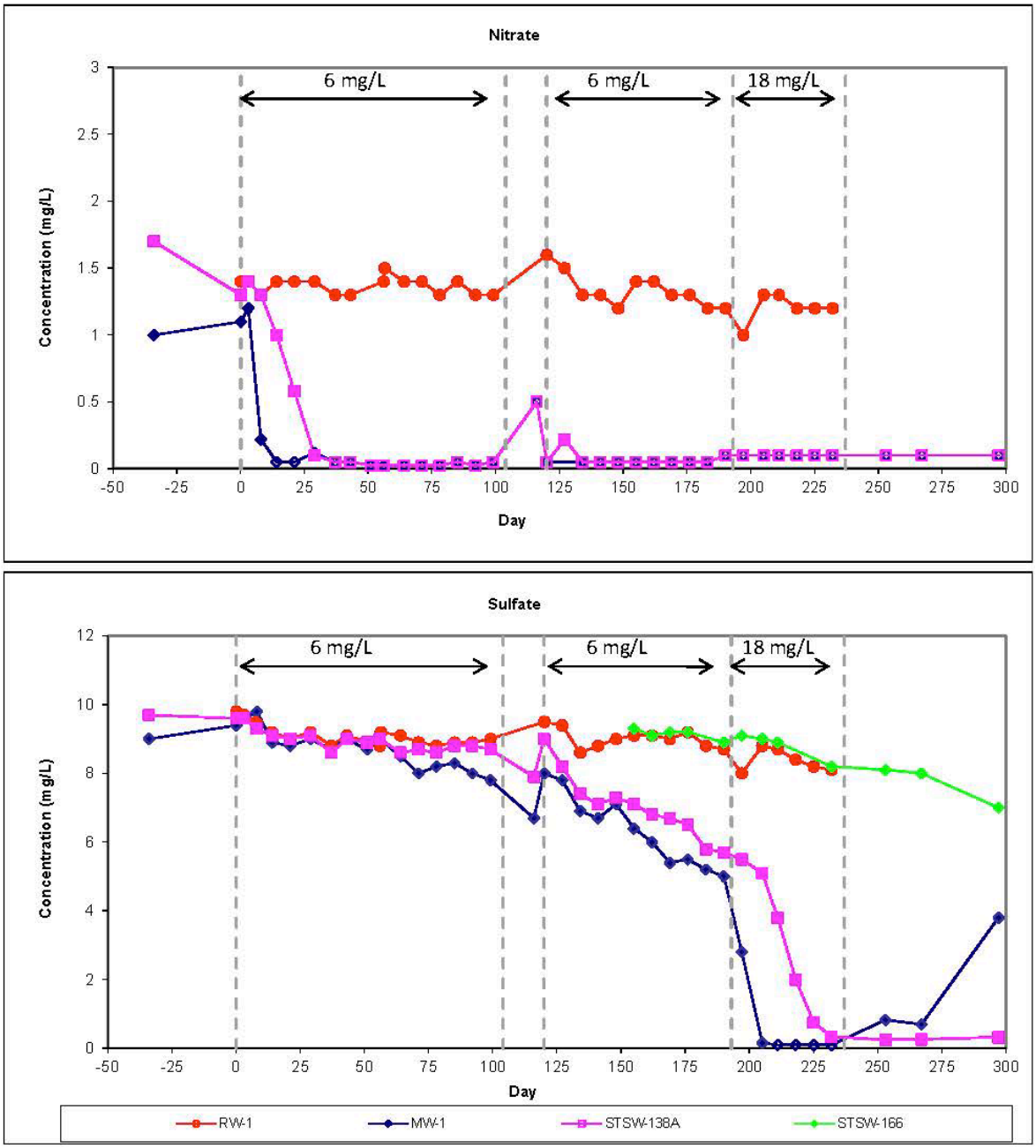
5.6.6 Results of Supporting Groundwater Chemistry

The following sections summarize the inorganic results for key supporting geochemical parameters, including nitrate, sulfate, DHGs, dissolved metals, and VOCs.

5.6.6.1 Nitrate and Sulfate

Figure 6 presents the trends in the concentrations of nitrate in the demonstration test area groundwater. Nitrate concentrations in the extraction and recharge wells EW-1, EW-2, and RW-1 remained relatively stable throughout the pilot study, and ranged between 1.0 and 1.9 mg/L. Some reduction is noticeable at EW-2 and RW-1 toward the end of the test, as more water affected by the addition of electron donor was circulated to these wells. Nitrate concentrations in groundwater at monitoring well MW-1 declined from a background of approximately 1.0 mg/L to nondetect at a PQL of 0.05 mg/L within 14 days of electron donor addition. Nitrate was still nondetect approximately 2.5 years after the test. Similarly, nitrate concentrations in the transgradient monitoring well STSW-138A declined from approximately 1.3 mg/L to <0.05 mg/L within 37 days after the addition of electron donor. Nitrate had recovered at STSW-138A to pre-test concentrations after approximately 1 year. At STSW-166, nitrate declined during the latter part of the pilot test and continued to decline for a year after the test. Moreover, nitrate concentrations have recovered slowly since the well continues to receive groundwater from the vicinity of MW-1.

Figure 6 also presents the trends in the concentrations of sulfate in the demonstration test area groundwater. Sulfate concentrations remained relatively stable during the period when the electron donor concentration was constrained to one-times the stoichiometric demand. Sulfate concentrations decreased rapidly in MW-1 following the second bioaugmentation event, when



Nitrate and Sulfate Concentration Trends
Active Perchlorate Bioremediation Demonstration

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Figure 5-5

Notes:
Open symbols represent non-detects
Day "0" = 8-Sep-03
"6 mg/L" - dose rate of ethanol

Figure 6. Nitrate and sulfate concentration trends.

the electron donor concentration was increased to three-times the stoichiometric demand and were nondetect until the end of the test. Similarly, sulfate decreased at STSW-138A but was delayed slightly and the decrease was less. Sulfate also declined at STSW-166 as groundwater from the MW-1 flowed past STSW-166. The overall sulfate data confirm that perchlorate degradation can be accomplished without sulfate reduction, through control of electron donor addition, but that electron donor addition levels required for TCE reduction cause sulfate reduction.

Sulfate recovered to normal concentrations within approximately 15 months at STSW-166 and with approximately 22 months at STSW-138A. Conversely, sulfate at MW-1 rebounded within 5 months to twice the pretest concentrations and then declined to near-normal concentrations by December 2006.

5.6.6.2 Dissolved Hydrocarbon Gases

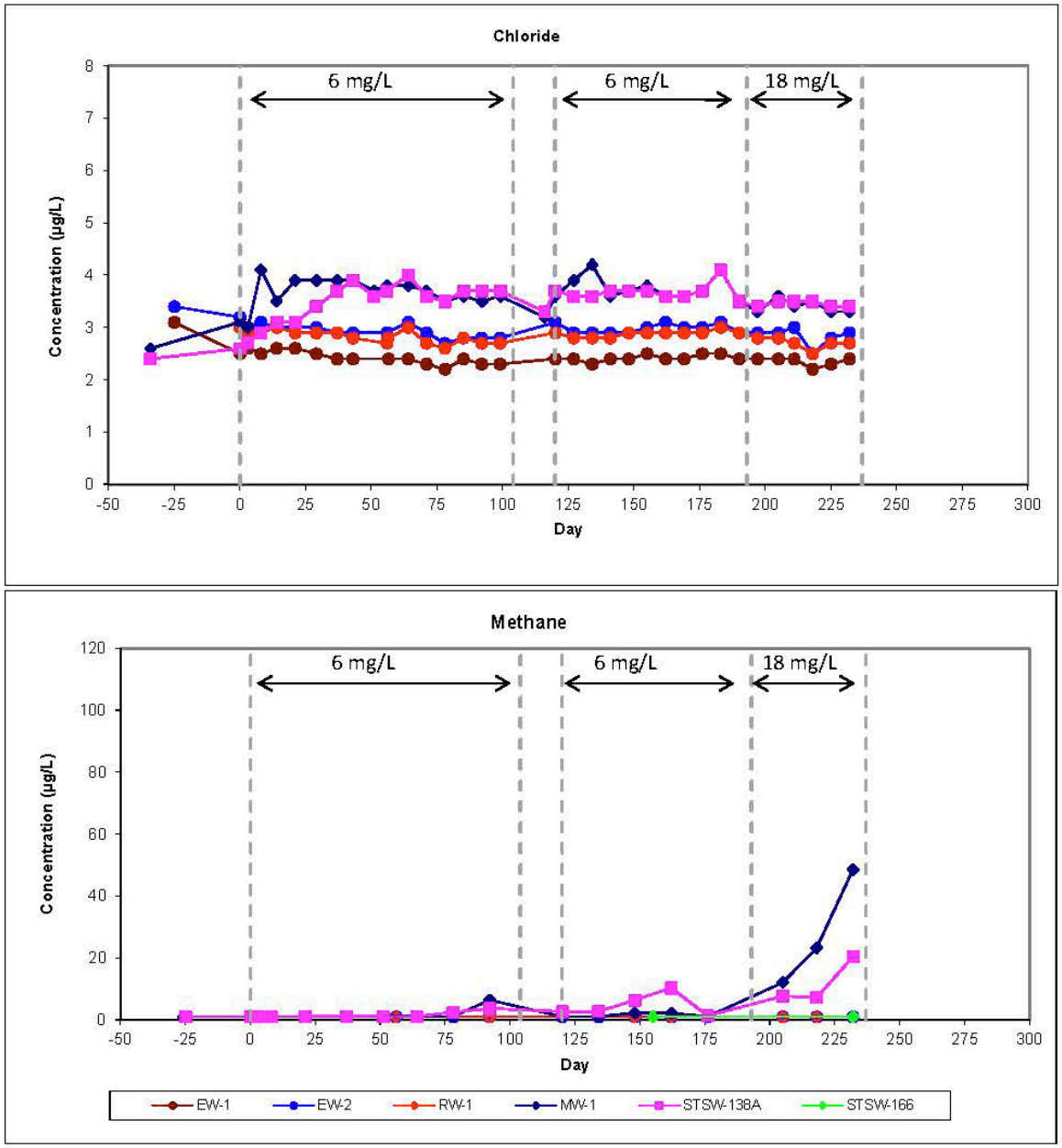
Ethane and ethene were not detected throughout the pilot test in all wells. Similarly, methane was not detected at EW-1, EW-2, RW-1 or STSW-166, although methane concentrations increased at wells MW-1 and STSW-138A, particularly in response to the second bioaugmentation event and associated increase in electron donor dose rate. Figure 7 presents methane concentration trends.

5.6.6.3 Dissolved Metals

Figure 8 presents the concentration trends for dissolved iron and dissolved manganese, which are two metals known to be mobilized under anaerobic conditions. Iron was present at monitoring well MW-1 before the test, showed some fluctuations during the pilot test, and then declined after the test until December 2005 when concentrations began to increase. Conversely, iron at STSW-138A was not detected until over 3 weeks after starting the demonstration test and then rose quickly before leveling off. Iron concentrations rose slightly near the end of the test, possibly as a result of the higher ethanol dosing in the last period of the test. Iron at STSW-138A remained relatively high for several months after the test and then iron was nondetect by August 2005. Iron concentrations at downgradient monitoring well STSW-166 were virtually nondetect, based on a PQL of 0.3 mg/L, which also is the secondary maximum contaminant level (MCL) for iron. The high iron in MW-1 groundwater appeared to have attenuated before arriving at STSW-166 until late 2006, as shown by the steady iron nondetects, but then increased thereafter, which was similar to active values of the pilot test.

Manganese concentrations increased in monitoring wells MW-1 and STSW-138A following the initiation and subsequent increases in electron donor delivery. Concentrations in MW-1 appeared to be less than 0.1 mg/l before the test and then increased steadily to nearly 0.2 mg/L during the perchlorate degradation period. After the bioaugmentation of MW-1 in late March 2004, manganese concentrations increased again to nearly 0.6 mg/l shortly after the termination of the test. Manganese at MW-1 decreased slightly thereafter, but has remained at approximately 0.5 mg/l though September 2009. Importantly, manganese concentrations at well STSW-138A remained below the secondary MCL for manganese (0.05 mg/L) throughout the study. Manganese concentrations at downgradient monitoring well STSW-166 were below the secondary MCL during the latter portion of the pilot test and were nondetect for nearly 1 year

thereafter. However, manganese has been detected at STSW-166 at concentrations below the secondary MCL.



Notes:
Day "0" = 8-Sep-03
"6 mg/L" - dose rate of ethanol

Chloride and Methane Concentration Trends
Active Perchlorate Bioremediation Demonstration

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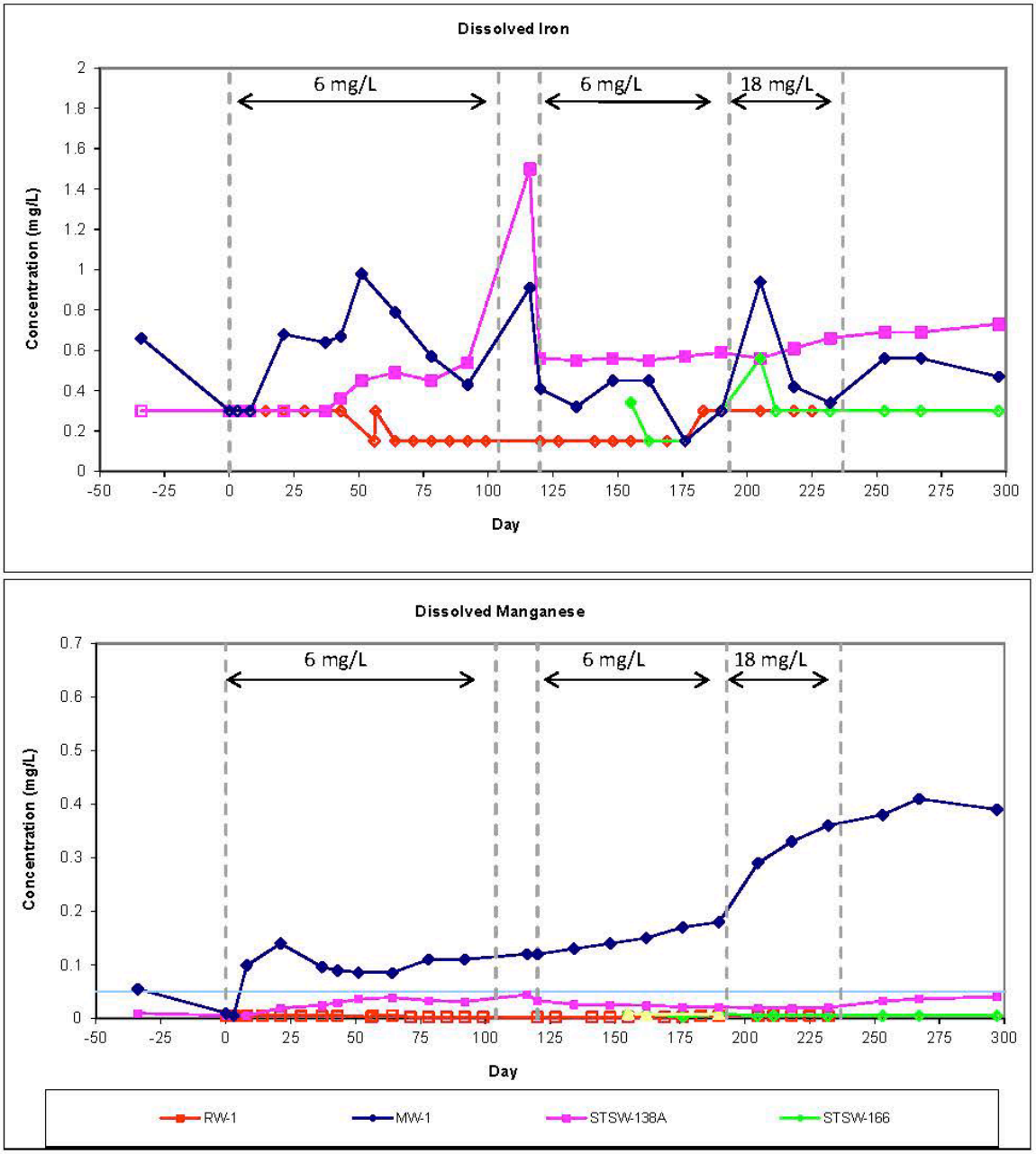
Figure 5-6

Figure 7. Chloride and methane concentration trends.



Dissolved Iron and Manganese Concentration Trends
Active Perchlorate Bioremediation Demonstration

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Figure 5-7

Notes:
Open symbols represent non-detects
Day "0" = 8-Sep-03
"6 mg/L" - dose rate of ethanol

Figure 8. Dissolved iron and manganese concentration trends.

6.0 PERFORMANCE ASSESSMENT

The performance objectives and results for this demonstration are shown in Table 5 and are discussed below.

6.1 EASE OF INSTALLATION

The ease of installation of electron donor delivery components was evaluated based on the experience of field staff and the actual availability and costs of installed equipment. The success criterion for this objective is that the electron donor delivery system can be readily installed using standard industry procedures and contractors.

This objective was achieved based on experience with the actual installation of the groundwater recirculation and electron donor delivery systems at the IRCTS. The equipment required for the active groundwater recirculation and injection of electron donor was all readily available through local drillers and plumbing suppliers. The ClO_2 biofouling control system was also available and straightforward to install. The procedures used to install the equipment were standard and well established procedures for local drillers and the procedures were simple enough to be conducted by field technicians with training in basic plumbing techniques.

6.2 EASE OF ELECTRON DONOR DELIVERY EVENTS

The ease of electron donor delivery events was evaluated based on the experience of field staff who conducted the actual electron donor events. The success criterion for this objective is that electron donor delivery events can be conducted by field staff with minimal training and effort.

This objective was achieved based on experience of field staff with the actual electron donor delivery events. The activities and procedures required for the electron donor delivery events were simple enough to be conducted by field staff with minimal specialized training and effort.

Electron donor was added to the groundwater recirculation injection well on a daily basis. Commercially available ethanol was used as the electron donor. There were some safety issues to be addressed with the use of ethanol as a result of its flammability, but once the appropriate storage equipment and procedures were put in place there were no significant issues with the addition of electron donor.

The groundwater recirculation system was operated on a continuous basis and there were no indications that significant fouling was occurring in the groundwater injection well. The injection well was equipped with a high-level shutoff switch to shut off the recirculation of groundwater if the water level in the injection well rose indicating that the well was becoming fouled but no such events occurred during operation. It is believed that the pulsed injection of electron donor over 1 hour each day followed by an injection of ClO_2 was an effective operating strategy for controlling biofouling of the injection well.

Table 5. Performance objectives and results.

Performance Objectives	Data Requirement	Success Criteria	Results
Qualitative Performance Objectives			
1. Ease of installation of electron donor delivery components.	Experience of demonstration operators; actual availability and costs of installed equipment.	Electron donor delivery system can be readily installed by standard industry procedures/contractors.	Objective achieved – experience with system installation demonstrates that electron donor delivery system can be readily installed by standard industry procedures/contractors.
2. Ease of electron donor delivery events.	Experience of demonstration operators, and costs of events.	Electron donor delivery events can be conducted with minimal training and effort.	Objective achieved – experience of operators demonstrates that electron donor delivery events can be conducted with minimal training and effort.
3. Enhancement of microbiological activity.	Groundwater and soil analyses for geochemical characterization.	Electron donor addition enhances microbiological activity in the treatment zone.	Objective achieved – groundwater monitoring data demonstrates that electron donor addition enhances microbiological activity in the treatment zone.
4. Ease of performance monitoring and validation.	Quality of data and ability to interpret and quantify biodegradation with confidence.	Performance monitoring network allows straightforward data collection, interpretation, and validation.	Objective achieved – quality of data and ability to interpret and quantify biodegradation with confidence demonstrates that performance monitoring network allows straightforward data collection, interpretation, and validation.
Quantitative Performance Objectives			
5. Reduction in perchlorate concentration.	Groundwater sampling of performance monitoring wells.	Perchlorate concentrations reduced to practical quantitation limit of 0.004 mg/L.	Objective achieved – groundwater sampling of performance monitoring wells demonstrates that the average perchlorate concentrations were reduced to below the practical quantitation limit of 4 µg/L.
6. ROI and distance for degradation.	Groundwater sampling of performance monitoring wells.	ROI for electron donor addition will extend to target treatment area and perchlorate will be degraded before groundwater reaches the furthest downgradient performance monitoring wells.	Objective achieved – groundwater sampling of performance monitoring wells during tracer test and following electron donor addition demonstrate that the area of influence extends between injection and extraction wells and perchlorate was degraded before groundwater reaches downgradient performance monitoring wells.

Notes:
µg/L – micrograms per liter

6.3 ENHANCEMENT OF MICROBIOLOGICAL ACTIVITY

The enhancement of microbiological activity was evaluated using groundwater analysis for geochemical parameters. The success criterion for this objective is that electron donor addition enhances microbiological activity in the treatment zone.

This objective was achieved based on the results of chemical and geochemical characterization. Groundwater monitoring data for chemical and geochemical parameters demonstrated that electron donor addition enhanced microbiological activity in the treatment zone. Significant and sustained reductions in ORP were observed following the addition of electron donor and provide the first indication that biological activity was enhanced by the addition of electron donor. A statistical analysis of ORP data was conducted (Geosyntec, 2012) and shows a very high level of confidence that the injection of electron donor in the biobarrier resulted in significant reductions in ORP that are indicative of enhanced biological activity. The ORP values measured in monitoring wells MW-1 and STSW-138A were evaluated before (day -34 to day -6) and during amendment with electron donor (day 56 to day 232).

The mean and standard deviation of the ORP values from each monitoring well in each of the two time periods were calculated (Geosyntec, 2012). In addition, a one-tailed Student's t-test was conducted at a 5% level of significance and assuming equal sample variances. The null hypothesis of the t-test is that the mean ORP value for the time period following the amendment with electron donor was greater than or equal to the mean ORP value for the time period preceding the amendment, or the mean baseline ORP. The p-values from the t-tests for ORP data from MW-1 and STDW-138A were also calculated (Geosyntec, 2012). The p-value is the probability of obtaining a test statistic at least as extreme as the one observed. If the p-value is less than the specified alpha level, i.e., 0.05, then there is sufficient evidence to reject the null hypothesis. The p-values for the comparison of means from the period of time before amendment and after amendment for MW-1 and STSW-138A are 1.56×10^{-10} and 6.5×10^{-6}, respectively. As these values are significantly lower than 0.05, the null hypothesis is rejected and we can conclude that the mean ORP after amendment is statistically lower than that at the baseline. Therefore, the results of the t-test confirm that ORP concentrations did indeed decrease after amendment.

The reductions in perchlorate concentrations in groundwater observed following addition of the electron donor provide additional indications that biological activity was enhanced by the addition of the electron donor and that this biological activity included microorganisms capable of degradation of perchlorate. The reductions in perchlorate are discussed further in Section 6.5.

6.4 EASE OF PERFORMANCE MONITORING AND VALIDATION

The ease of performance monitoring and validation was evaluated based on the quality of the data obtained and the ability to interpret and quantify biodegradation with confidence. The success criterion for this objective is that the performance monitoring network and sampling conducted allows for straightforward data collection, interpretation, and validation.

This objective was achieved based on the data obtained during the demonstration. The quality of the data obtained and the ability to interpret this data and quantify biological activity (by the reduction in ORP) with confidence and reduction in perchlorate demonstrated that the performance monitoring network allowed for straightforward data collection, interpretation, and validation.

The monitoring well network installed for the demonstration allowed the collection of groundwater samples for measurement of field parameters and for chemical analysis from key locations in the demonstration test area.

Measurement of field parameters and analysis of samples collected from monitoring wells allowed for data to be collected that demonstrated significant reductions in ORP associated with the enhancement of biological activity resulting from the addition of electron donor. The reduction in ORP in samples from monitoring wells in the demonstration area provided a quantitative measure of the biological activity in the subsurface. The monitoring well network allowed for the collection of data that showed the reduction in perchlorate concentrations to validate the performance of the technology.

6.5 REDUCTION IN PERCHLORATE CONCENTRATION

The reduction in perchlorate concentrations was evaluated based on groundwater sampling of performance monitoring wells. The success criterion for this objective is that perchlorate concentrations are reduced to the practical quantitation limit of 4.0 µg/L. Figure 5 shows the concentration of perchlorate in key monitoring wells in the biobarrier over the course of the demonstration test. Appendix D presents the statistical analysis of the data to support this conclusion.

The concentrations of perchlorate in monitoring wells MW-1 and STSW-138A varied between 1400 µg/L and 2600 µg/L before operation of the groundwater recirculation and amendment addition system was initiated at day "0." The concentration of perchlorate in MW-1 dropped quickly and was nondetect (i.e., <4.0 µg/L) by day 29. The concentration remained less than 4.0 µg/L until the end of the test at day 232 with the exception of two excursions to 16 and 4.7 µg/L on day 85 and day 176.

The concentration of perchlorate in STSW-138A dropped more slowly than in MW-1 but was nondetect (i.e., <4.0 µg/L) by day 85. The groundwater recirculation and electron donor amendment system was shut off from day 104 to day 120. During this time period, the concentration of perchlorate in monitoring well STSW-138A increased up to 14 µg/L at day 116 but dropped to less than 4.0 µg/L on day 127 and remained less than 4.0 µg/L to the end of amendment injection period at day 232. It is likely that when the recirculation system was shut off at day 104, unamended groundwater from upgradient of STSW-138A began to flow into the monitoring well and resulted in the short-term increase in perchlorate concentrations in this monitoring well.

The average perchlorate concentrations measured in MW-1, from day 29 to the end of amendment injection period (2.6 µg/L), and STSW-138A, from day 85 to the end of amendment injection period (2.9 µg/L), were all less than 4.0 µg/L. The 95th percentile perchlorate

concentrations measured in MW-1, from day 29 to the end of amendment injection period (3.6 µg/L), and STSW-138A, from day 127 to the end of amendment injection period (2.0 µg/L), were all less than 4.0 µg/L.

This objective was achieved based on groundwater sampling of performance monitoring wells that demonstrated that the average perchlorate concentrations were reduced to below the PQL of 4.0 µg/L during the during the operating period.

6.6 ROI AND DISTANCE FOR DEGRADATION

The ROI and distance for degradation was evaluated based on the results of groundwater samples collected from the performance monitoring wells. The success criterion for this objective is that the ROI for electron donor addition will extend between recirculation wells and that perchlorate will be degraded before groundwater reaches the farthest downgradient performance monitoring well.

This objective was achieved based on groundwater sampling results from performance monitoring wells during the tracer tests and following electron donor delivery. These results demonstrated that the ROI of the system extends between the recirculation wells and that perchlorate was degraded before groundwater reached downgradient performance monitoring wells.

A summary of the results of the tracer test is shown on Figure 3. The figures show the tracer concentrations in wells in the demonstration test area. During the tracer test, groundwater was extracted from EW-1 at a rate of 20 gpm and from EW-2 at a rate of 40 gpm and all of the extracted groundwater was injected into RW-1. The tracer was observed in EW-2 after approximately 50 days demonstrating a hydraulic connection between the injection and extraction well. The tracer was observed at EW-1 with a lower extraction rate starting at about 200 days, which again demonstrates a hydraulic connection between the injection and extraction well.

The distance for degradation was demonstrated by the reductions in perchlorate in monitoring wells MW-1 and STSW-138A approximately 50 feet and 85 feet from the injection well RW-1. Degradation of perchlorate occurred in wells very close to the alignment of the biobarrier indicating that the degradation of perchlorate can occur within a short distance from the electron donor injection point.

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7.0 COST ASSESSMENT

This section presents the results of a cost assessment to implement EISB for perchlorate-affected groundwater using the active approach for the addition of electron donor. Section 7.1 describes a costing model that was developed for the application of EISB with a comparison to other approaches to implementing EISB and to a P&T system. Section 7.2 presents an assessment of the cost drivers for the application of the technology, and Section 7.3 presents the results of an analysis of the costing model.

7.1 COST MODEL

A cost model was developed for EISB for this report and for the recently released SERDP/ESTCP monograph on In Situ Bioremediation of Perchlorate in Groundwater (Stroo and Ward, 2009).

The cost model was developed for a template site based on a typical site with perchlorate-affected shallow groundwater. The specific site characteristics used are presented in Table 6 and an illustration of the plume and biobarrier are provided on Figure 9. Cost estimates were prepared for an active EISB remedy along with three other approaches to implementing EISB and for a conventional P&T system. Using the template site conditions, the cost model identifies the major cost drivers for the active approach and provides an estimate of costs for the capital, O&M, and long-term monitoring. Capital costs included design and permitting activities, mobilization, site preparation, well installation, chemical reagents, management, and derived waste disposal. O&M costs included mobilization, equipment replacement and supplies (e.g., electron donor). Long-term monitoring costs included field supplies, sampling equipment, laboratory analysis and regulatory reporting. Labor associated with the planning, procurement and implementation of all aspects of the active EISB approach is also included. Excluded from consideration are the costs of pre-remediation investigations (e.g., plume delineation, risk determination, and related needs), treatability studies, source zone treatment, and post remediation decommissioning activities.

The cost estimates focused on treatment of a contaminated plume of groundwater and costs for possible source zone treatment are not included. In reality, it may be appropriate to treat source areas that may contain a significant mass of perchlorate and contribute slowly to elevated concentrations in groundwater. A perchlorate "source" may take a variety of forms, including the following:

1. Perchlorate in the geological media above the water table (the vadose zone), which is carried into the groundwater by water infiltrating from the surface and flushing the perchlorate into the groundwater;
2. Perchlorate in the vadose zone, which dissolves into the groundwater as groundwater elevations increase (possibly on an intermittent basis) and saturate the vadose zone containing the perchlorate;
3. Perchlorate disposed of below the water table in a manner that allows the perchlorate to be releases into the groundwater over an extended period of time; and

Table 6. Site characteristics and design parameters for EISB of perchlorate-affected groundwater.

		Scenario/Case Description and Number												
Design Parameter	**Units**	**Base Case** Case 1	**Accelerated Clean Up Case** Case 2	**Low Perchlorate Conc. Case** Case 3	**High Perchlorate Conc. Case** Case 4	**Low Donor Demand Case** Case 5	**High Donor Demand Case** Case 6	**Low GW Velocity Case** Case 7	**High GW Velocity Case** Case 8	**Deep GW Case** Case 9	**Thin Interval Case** Case 10	**Thick Interval Case** Case 11	**Narrow Plume Case** Case 12	**Wide Plume Case** Case 13
Width of Plume	meters	120	120	120	120	120	120	120	120	120	120	120	30	240
	feet	400	400	400	400	400	400	400	400	400	400	400	100	800
Length of Plume	meters	240	240	240	240	240	240	240	240	240	240	240	240	240
	feet	800	800	800	800	800	800	800	800	800	800	800	800	800
Porosity		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Gradient		0.008	0.008	0.008	0.008	0.008	0.008	0.0008	0.0008	0.016	0.008	0.008	0.008	0.008
Hydraulic Conductivity*	cm/sec	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Upgradient Perchlorate Concentration	mg/L	2	2	0.4	10	2	2	2	2	2	2	2	2	2
Downgradient Perchlorate Conc.	mg/L	1.1	1.1	0.22	5.5	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Nitrate Conc.	mg/L	15	15	15	15	5	30	15	15	15	15	15	15	15
DO Conc.	mg/L	5	5	5	5	2	8	5	5	5	5	5	5	5
Depth to Water	m bgs	3	3	3	3	3	3	3	3	3	3	3	3	3
	ft bgs	10	10	10	10	10	10	10	10	100	10	10	10	10
Vertical Saturated Thickness	m	9	9	9	9	9	9	9	9	9	3	15	9	9
	ft	30	30	30	30	30	30	30	30	30	10	50	30	30
Cross Sectional Area of Plume	m^2	1080	1080	1080	1080	1080	1080	1080	1080	1080	360	1800	270	2160
	ft^2	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	4000	20,000	3000	24,000
GW SeUSEPAge Velocity	m/year	10	10	10	10	10	10	1	20	10	10	10	10	10
	ft/year	33	33	33	33	33	33	3.3	66	33	33	33	33	33
Perchlorate Treatment Objective	mg/L	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245
Assumed Number of Pore volumes to Flush Plume		2	2	2	2	2	2	2	2	2	2	2	2	2
Number of Barriers Perpendicular to GW Flow		1	5	1	1	1	1	1	1	1	1	1	1	1
GW travel time to barrier(s)	years	24	5	24	24	24	24	240	12	24	24	24	24	24
Years to clean up GW	years	48	10	48	48	48	48	480	24	48	48	48	48	48

Notes: *hydraulic conductivity based on uniform silty sand aquifer — input parameters changed from base case

bgs – below ground surface; cm/sec – centimeters per second; ft – feet
GW – groundwater; kg – kilogram; L – liters
m – meters; mg/L – milligrams per liter; Conc. – Concentration

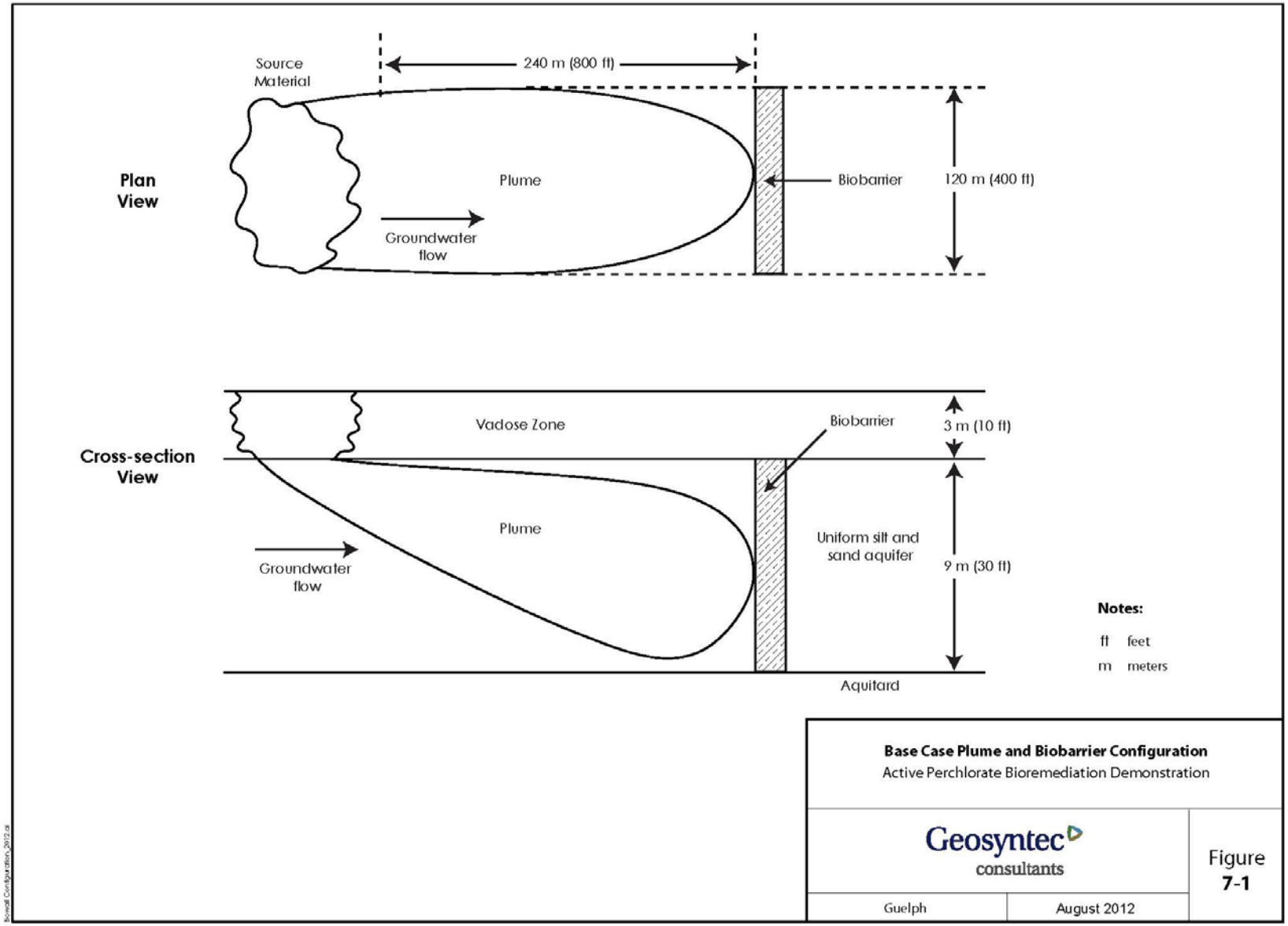


Figure 9. Base case plume and biobarrier configuration.

4. Perchlorate that was released into the groundwater at high concentrations and diffused into low hydraulic conductivity (K) units in the geological media and which continue to diffuse out of the low K units as the upgradient source of perchlorate is depleted.

If the "source" material is not treated, it may continue to feed the plume for an extended period of time and it may be necessary to treat the plume for a longer period of time until the source zone is sufficiently depleted. The active remedial approach could be used in a modified configuration to treat source areas below the water table. The benefits of an active approach in the source area would be that the time frame for operation could be significantly less than that for a system that simply treats a downgradient plume of perchlorate as it released from the source area. Applying an active approach in the source area would likely be more expensive than a downgradient barrier in terms of initial capital costs and annual O&M costs but overall savings may be achieved because of a shorter duration of operation. Costs for active treatment of source areas are discussed in Section 7.3. Sources of perchlorate above the water table may be treated using other approaches such as enhanced flushing of the vadose zone that are beyond the scope of the cost estimate presented in this chapter.

To obtain a clearer picture of life cycle costs for the various options, estimates include the NPV of future costs. The NPV calculations provide cash flow analysis for 30 years and show the costs by category for each year. The future costs are only carried forward for 30 years on the basis that the NPV of future costs beyond the 30-year time frame are small and the future costs beyond the 30-year time period are difficult to predict. O&M and long term monitoring costs are discounted at a rate of 3% to develop the NPV estimates of future costs (DoD, 1995). The rate of 3% is based on the U.S. government's Office of Management and Budget "Real Interest Rates on Treasury Notes and Bonds" for 20-year and 30-year notes and bonds of 2.8% (Office of Management and Budget, 2008).

The cost model also estimates the impact of changes in site characteristics and design parameters. Using the template site as a baseline condition, site characteristics and design parameters (e.g., depth to groundwater, contaminant plume width, and groundwater velocity) were varied individually and the twelve iterations are shown in Table 6. This specific analysis provides some insight into how capital, O&M, and long-term monitoring costs are affected by changing specific variables.

The base case assumes a homogenous silty sand aquifer from a depth of 3 meters (m) (approximately 10 ft) bgs to 12 m (40 ft) bgs with a hydraulic conductivity of 0.001 cm/sec, a horizontal gradient of 0.008 m/m and a porosity of 0.25. These aquifer characteristics result in a groundwater seUSEPAge velocity of approximately 10 m/year (yr) (33 ft/yr). The plume of perchlorate-affected groundwater extends along the direction of groundwater flow for 240 m (800 ft) and is 120 m (400 ft) in width. The concentration of perchlorate at the upgradient side of the plume is 2 mg/L and the concentration on the downgradient side is 1.1 mg/L. Oxygen and nitrate will contribute demand for electron donor and the assumed concentrations of DO and nitrate are 5 mg/L and 15 mg/L, respectively.

The base case also assumes that two pore volumes of clean water will need to flush through the affected areas to achieve the cleanup objectives. In reality, the number of pore volumes of clean

water required to flush through the subsurface to achieve target treatment objectives will be determined by a number of factors, such the degree of heterogeneity of the geological media. Variations in the K of the aquifer material can allow significant mass of perchlorate to diffuse into low K layers and then act as an ongoing source of perchlorate to the higher K zone as the perchlorate is flushed from the higher K zones. In most geological settings, more than two pore volumes will be required to achieve treatment objectives and longer-term operation of the remedial measures will be required. The assumption that two pore volumes of flushing are required to achieve treatment objectives could only be valid for situations where there is very uniform K of the geological media and is likely an optimistic assumption for most real world situations.

The base case design incorporates one biobarrier on the downgradient edge of the plume to treat water as it flows across the line of the biobarrier. Based on the groundwater seUSEPAge velocity of 10 meters per year (m/yr) (33 ft/yr), a plume that extends for 240 m (800 ft) along the direction of groundwater flow and the assumed need to flush two pore volumes of clean water through the affected aquifer to achieve cleanup standards, it would be expected to take approximately 48 years for the plume to be treated in the base case. If more than two pore volumes of flushing are actually required to achieve treatment objectives, the biobarrier would need to be operated beyond the 30-year time frame considered in this costing exercise, but the concentrations to be treated would likely be reduced significantly and operating requirements reduced. The costs of this potential future operation would be incurred more than 30 years into the future and the NPV of these costs would not be as significant as the costs incurred for operation in the near and medium term (i.e., less than 30 years).

The perchlorate treatment objective that was used for the template site was based on the chronic exposure reference dose (and the resulting drinking water equivalent concentration) selected by USEPA in 2005 (http://www.USEPA.gov/iris/subst/1007.htm) of 24.5 µg/L (0.0245 mg/L). A lower treatment objective would increase the costs associated with the implementation of the approaches presented here.

The active bioremediation approach considered can achieve low treatment criteria (i.e., below 0.004 mg/L). However, to achieve lower target treatment criteria, a higher safety factor will be required in the design and operation of each remedy so that pockets or layers of low K geological material containing untreated groundwater with some perchlorate do not remain or transmit perchlorate in groundwater following treatment. In addition, the system may need to be operated for a longer period of time. If a very low target treatment objective is required, even small pockets or layers of untreated groundwater could result in groundwater samples exceeding the target criteria. Layers of low K geological material exist at many sites where interbedded clay, silts, and sands are present and can serve as longer term repositories for perchlorate from which diffusion is the dominant transport mechanism. These pockets or layers may release perchlorate to flowing groundwater after treatment of perchlorate in the higher K units has been completed.

As discussed above, the presence of significant low K repositories of perchlorate and low target treatment concentrations would affect the assumption used in the base case that two pore volumes of groundwater need to be flushed through the plume to achieve the target treatment objectives. If additional clean groundwater needs to be flushed through the plume area to

achieve remedial action objectives, then the treatment system will need to be operated for a longer period of time and incur additional long-term O&M and monitoring costs. The additional safety factor in design and possibly longer-term operation will increase costs to achieve lower target treatment objectives. However, the impact of a specific change in the target treatment concentration is difficult to predict without extensive and very detailed site characterization and contaminant transport modeling.

The active biobarrier alternative assumes that a series of injection and extraction wells will be installed along the alignment of the biobarrier and a groundwater recirculation system will be constructed to recirculate groundwater and distribute electron donor across the biobarrier. Groundwater will be recirculated between injection and extraction wells and a soluble electron donor will be added to the water being recirculated to distribute the electron donor across the plume of perchlorate impacted groundwater. For the purpose of this cost model, it is assumed that this initial system installation is the same as would be used for a semipassive approach to the addition of electron donor. The costing has been developed based on circulating groundwater and adding electron on a continuous basis. The operating costs would be higher than for a semipassive system as a result of the increased operating requirements and increased potential for biofouling of injection wells.

The other EISB approaches considered here include passive electron donor injection, semipassive electron donor injection, and a trench biowall. The passive EISB system assumes that a series of injection wells are installed across the plume and that emulsified vegetable oil (EVO) is injected into these wells every 3 years. The semipassive system would be set up in a manner almost identical to the active system but would be operated on an intermittent rather than a continuous basis. The trench biowall EISB system assumes that a trench is excavated to intercept the plume of perchlorate-impacted groundwater and is backfilled with mulch and EVO. It is assumed that the biowall is rejuvenated by injecting additional EVO after 4 and 8 years and every 3 years thereafter.

The groundwater extraction and treatment or P&T system included for comparison would be similar to the biobarrier system. Specifically, a row of extraction and injection wells would be used to bring groundwater to the surface and to reinject the groundwater—but rather than amending the groundwater with electron donor, the groundwater would be treated to remove perchlorate before reinjection on a continuous basis. The groundwater treatment component of this system would be a small-scale bioreactor to degrade perchlorate.

A series of 12 variations in site conditions and/or design parameters were developed and the cost implications of these variations on the active EISB system were estimated. The first variation of the base case, Case 2: Accelerated Cleanup Case, uses five biobarriers aligned perpendicular to the direction of groundwater flow distributed every 48 m (160 ft) within the 240 m (800 ft) long plume. This process will provide treatment of the plume at one downgradient and four intermediate locations rather than just at the downgradient edge of the plume. Based on the seUSEPAge velocity of 10 m/yr (33 ft/yr) and the assumption that two pore volumes of clean water need to flow through the plume area to achieve cleanup, this case will require approximately 10 years to treat the groundwater rather than the 48 years of the base case.

The third and fourth cases incorporate reduced and elevated concentrations of perchlorate in groundwater as shown in Table 6. The fifth and sixth cases assume lower and higher concentrations of nitrate and dissolved oxygen that will result in a higher and lower demand for electron donor. The seventh and eighth cases incorporate lower and higher groundwater seUSEPAge velocities resulting from changes in the hydraulic gradient from the base case. The ninth case assumes that the depth to groundwater is 30 m (100 ft) rather than the 3 m (10 ft) in the base case. The tenth and eleventh cases assume thin and thick vertical interval of 3 m (10 ft) and 15 m (50 ft) rather than the 9 m (30 ft) of the base case. The twelfth and thirteenth cases assume a narrow plume (30 m [100 ft] in width) and a wide plume (240 m [800 ft] in width) rather than the 120 m (400 ft) width of the base case.

The costs of the base case and the variations are discussed in Section 7.3.

7.2 COST DRIVERS

The costs to implement EISB for perchlorate impacted groundwater using the active approach for the addition of electron donor will vary significantly from site to site. The key costs drivers are listed below followed by a brief discussion of the impact on cost.

- **Width of Plume (perpendicular to the direction of groundwater flow) –** Treatment systems for wider plumes require more recirculation wells, equipment, electron donor and labor to operate. Some system costs, such as design and mobilization will be relatively insensitive to the size of a system but many costs will increase in direct proportion with an increase in the width of the area to be treated.
- **Length of Plume to be Treated –** Treatment systems may be designed to treat the entire length of a plume in a shorter time period by installing recirculation wells at many locations along the length of the plume or they may be designed to treat a plume over a longer period of time as the groundwater flows through a few biobarriers aligned perpendicular to the direction of groundwater flow. In either case, the costs will be higher for plumes of greater length. Systems designed to treat plumes quickly will require more recirculation wells, more equipment, more electron donor, and more labor to operate than systems designed to treat perchlorate over a longer period of time. Systems designed to treat plumes as they flow through a small number of biobarriers will need to operate for longer periods of time if the plume to be treated has a greater length.
- **Vertical thickness of the area of impacted groundwater –** Systems designed to treat plumes with a greater vertical thickness will be more expensive as they will require longer screen in the recirculation wells, higher capacity pumps, piping and other equipment, more electron donor, and some additional labor to operate. As with the length of the plume, some system costs, such as design and mobilization costs, will be relatively insensitive to the size of a system but many costs will increase in direct proportion with an increase in the vertical thickness of the area to be treated.
- **Depth of the interval to be treated –** System designed to treat perchlorate at greater depths will be somewhat more expensive than shallow plumes as a result of the higher costs of installation recirculation wells. Most other capital and operating costs will not

be affected greatly by the need to treat deeper plumes of perchlorate-affected impacted groundwater.

- **The area of the plume of affected groundwater to be treated –** As discussed above, systems may be designed to treat the entire length of a plume on a short time frame by installing recirculation wells at many locations along the length of the plume or they may be designed to treat a plume over a longer period of time as the groundwater flows through a few biobarriers aligned perpendicular to the direction of groundwater flow. Treating the entire plume will increase the initial capital costs relative to treating the plume as water flows through a small number of biobarriers but the long-term costs will be less because treatment will be completed over a shorter period of time.

- **Ambient groundwater velocity –** Systems designed to treat higher ambient groundwater velocities will be more expensive because higher groundwater recirculation rates or additional recirculation wells will likely be required to distribute electron donor across the width of the plume. In addition, the higher groundwater velocities will result in greater demand for electron donor as higher quantities of perchlorate and other electron acceptors will be flowing through the target treatment zone. A higher groundwater velocity will, however, usually allow for cleanup criteria to be achieved in a shorter time period as water flows faster through the affected geological media.

- **Hydraulic conductivity (K) of the geological media containing the impacted groundwater –** Sites with a high K will generally have high groundwater velocities and associated higher costs as discussed above. Systems at low K sites will generally be less expensive because of the lower groundwater velocity. However, the amount of the costs savings may be reduced somewhat by the need for a greater number of recirculation wells that may be required to recirculate a sufficient amount of groundwater to maintain hydraulic control.

- **The variation in the K of different layers in the geological media –** Sites with a high degree of variation in the K of different layers in the geological media will have increases costs as a result of the greater number of pore volumes of clean water required to flush through the subsurface to achieve target treatment objectives. Variations in the K of the aquifer material can allow significant mass of perchlorate to diffuse into low K layers and then act as an ongoing source of perchlorate to the higher K zone as the perchlorate is flushed from the higher K zones. The need for more pore volumes of water to flush the subsurface will result in the need to operate the system for a longer period of time with an associated increase in O&M and monitoring costs.

- **Concentration of perchlorate in affected groundwater –** Higher concentrations of perchlorate may not impact the initial capital costs to a large extent but will increase O&M and monitoring costs for systems in two ways. First, higher concentrations of perchlorate will require more clean water to flush the perchlorate from the geological media and, therefore, a longer period of operation. Second, the higher concentrations will require more electron donor to degrade the perchlorate present, although the impact of this factor may be small at most sites where the total demand for electron donor is dominated by parameters such DO, nitrate, and sulfate rather than by the perchlorate concentration.

- **Target treatment concentration –** EISB can achieve low treatment criteria (i.e., below 4 µg/L). However, the lower the target treatment criteria, the higher the safety factor required in the design and operation of the system so that pockets or layers of low K geological material containing untreated groundwater with some perchlorate do not remain or transmit perchlorate in groundwater following treatment. If a very low target treatment objective is required, even small pockets or layers of untreated groundwater could result in groundwater samples exceeding the target criteria and operation of the system for a long period of time may be required. Layers of low K geological material exist at many sites where interbedded clay, silts, and sands are present and can serve as longer term repositories for perchlorate from which diffusion is the dominant transport mechanism. These pockets or layers may release perchlorate to flowing groundwater after substantial treatment of perchlorate in the higher K units has been completed.
- **Concentration of other electron acceptors –** High concentration of other electron acceptors such as DO and nitrate will increase the amount of electron donor required to degrade perchlorate. The increased electron donor demand will increase the operating costs somewhat for the system.

7.3 COST ANALYSIS

The detailed breakdown of the estimated capital costs, annual O&M costs, long term monitoring costs, and the NPV of these costs for the following are presented in the Final Report:

- Semipassive EISB;
- Passive EISB;
- Active EISB;
- Trench biowall EISB; and
- Equivalent P&T system.

A summary of these costs is presented in Table 7.

The capital cost, including design, installation of wells, installation of the groundwater recirculation and amendment system and system startup and testing for the active EISB system is approximately $430,000, and the annual O&M cost is estimated to be $60,000 per year. The NPV of the O&M represents an additional $1,200,000 of costs over a 30-year life. The NPV of the long term monitoring costs is estimated to be $350,000 to give a total current value cost for the alternative of $1,980,000. The total cost of the remedy over 30 years is estimated to be $2,700,000. The cross sectional area of the plume for this scenario is 1080 square meters (m^2) or 12,000 ft^2. The unit costs for capital and annual O&M are, therefore, $398/$m^2$ ($36/$ft^2$) and $56/m2 ($5/ft^2) respectively.

The capital cost for the P&T alternative is $490,000; this amount is somewhat higher than for the active biobarrier at $430,000. The O&M costs are estimated to be $73,000 per year versus $60,000 for the active biobarrier. The NPV of the O&M costs for the P&T approach are estimated to be $1,470,000, also higher than for the EISB alternative of $1,200,000. The NPV of the long term monitoring costs is estimated to be same as for the EISB alternative at $350,000 to give a total current value cost for the alternative of $2,310,000 versus $1,980,000 for EISB. The

total cost of the remedy over 30 years is estimated to be \$3,160,000 versus \$2,700,000 for EISB. The unit costs for capital and annual O&M for the P&T alternative is \$453/m^2 (\$41/ft^2) and \$68.5/m^2 (\$6.1/ft^2), respectively.

Table 7. Summary of costs for treatment of perchlorate-affected groundwater.

Alternative	Capital Costs ($)	Total O&M costs ($) (year 1 to 30)	Average Annual O&M Costs ($) (year 1 to 30)	NPV of 30 Years of O&M Costs ($)	NPV of 30 Years of Monitoring Costs ($)	NPVof 30 Years of Total Remedy Costs ($)	Total 30-year Remedy Costs ($)
Semi-passive biobarrier	430,000	1,160,000	38,700	780,000	350,000	1,560,000	2,060,000
Passive biobarrier	280,000	1,500,000	50,000	990,000	350,000	1,620,000	2,250,000
Active biobarrier	430,000	1,800,000	60,000	1,200,000	350,000	1,980,000	2,700,000
Trench biowall	320,000	1,250,000	41,700	780,000	350,000	1,450,000	2,040,000
P&T	490,000	2,200,000	73,300	1,470,000	350,000	2,310,000	3,160,000
Cross Section al Area of Biobarrier (m^2)	1080	1080	1080	1080	1080	1080	1080
Cross Sectional Area of Biobarrier (ft^2)	12,000	12,000	12,000	12,000	12,000	12,000	12,000
Unit Cost Basis ($ per m^2 of biobarrier)							
Semi-passive biobarrier	398	1100	36	720	324	1400	1900
Passive biobarrier	259	1400	46	920	324	1500	2100
Active biobarrier	398	1700	56	1110	324	1800	2500
Trench biowall	296	1200	39	720	324	1300	1900
P&T	454	2000	68	1360	324	2100	2900
Unit Cost Basis ($ per ft^2 of biobarrier)							
Semi-passive biobarrier	36	97	3.20	65	29	130	170
Passive biobarrier	23	125	4.20	83	29	140	190
Active biobarrier	36	150	5.00	100	29	170	230
Trench biowall	27	104	3.50	65	29	120	170
P&T	41	183	6.10	123	29	190	260

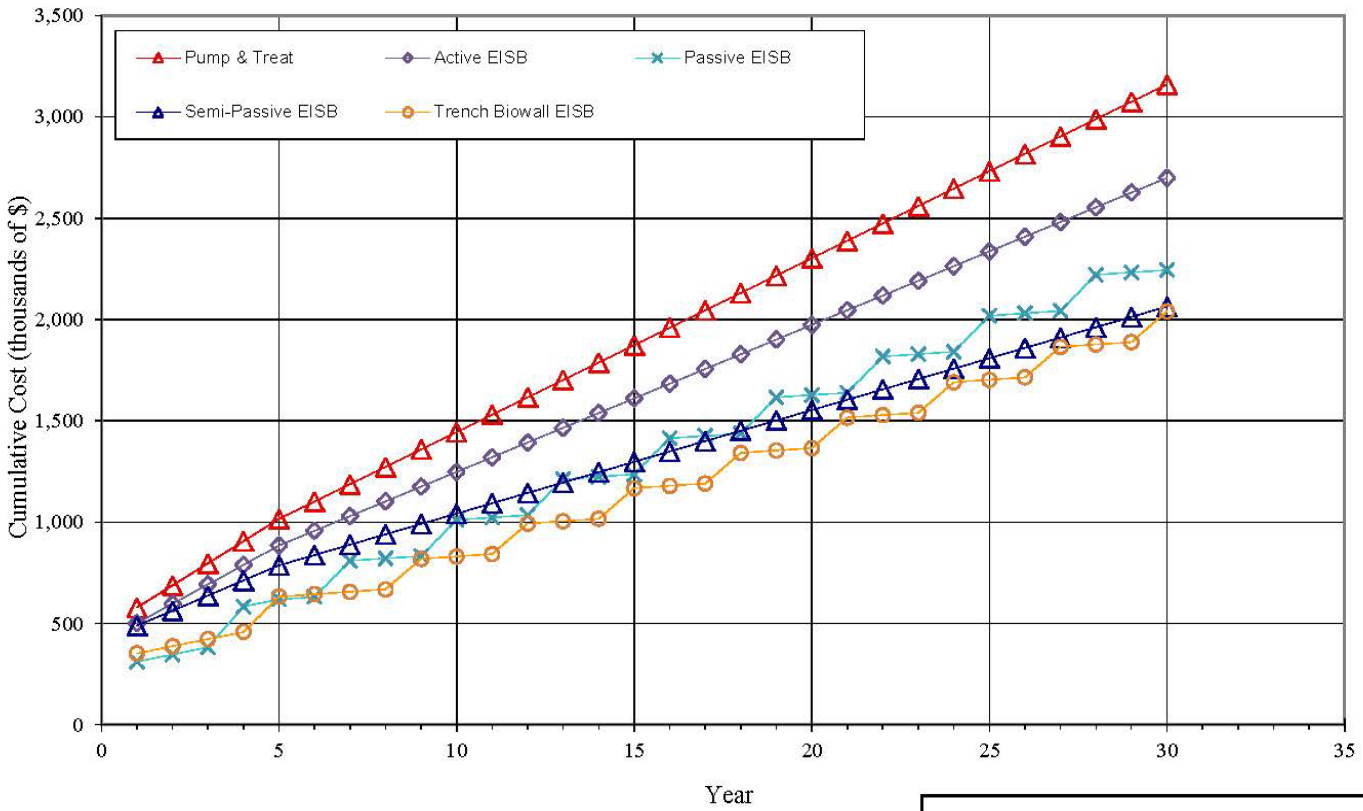
Figure 10 shows the cumulative costs by year for the EISB and P&T alternatives evaluated above.

Table 8 shows the estimates of the impact of variations in the site characteristics and design parameters on the costs for the EISB technology. Of the changes in site characteristics and design parameters considered in this evaluation, the most significant cost driver is the decision to accelerate the cleanup of the entire zone of perchlorate-affected groundwater rather than treating groundwater at the downgradient limit and allowing the affected groundwater to flow through this location over time. As a result of the size of the plume, a significant number of sUSEPArate biobarrier systems would be required to provide sufficient coverage of the affected groundwater to accelerate clean up.

As discussed earlier in Section 7.1, the active remedial approach could be used in a modified configuration to treat source areas below the water table. This active source area treatment approach could be coupled with MNA of the downgradient plume and could have the benefit of a significantly reduced time frame for operation than that of a system that simply treats a downgradient plume of perchlorate. Applying an active approach in the source area would have a higher initial capital cost and annual O&M costs; however, overall savings may be achieved because of a shorter duration of operation.

For example, if a source area can be treated over a period of 5 years with an active recirculation system costing 20% more than a single downgradient active barrier and the downgradient plume is small and can be addressed via MNA, the costs would be significantly less than for the 30-year treatment options described in Table 7. The capital costs for such a system would be $520,000, the annual O&M costs would be $72,000, and the system would operate for 5 years. The total NPV cost of this approach would be about $1,000,000, relative to a cost of $1,450,000 for a trench biowall, the least expensive barrier alternative, operated for 30 years.

The cost effective implementation of this approach could be limited by (1) the size of the source area (a larger source area would require additional costs to treat); and (2) the agreement of stakeholders to allow the downgradient plume of perchlorate to be addressed via MNA.



Notes: EISB - Enhanced *In Situ* Bioremediation

Cumulative Costs for Perchlorate Treatment
Active Perchlorate Bioremediation Demonstration

Geosyntec consultants

Guelph | August 2012

Figure **7-2**

Figure 10. Cumulative costs for perchlorate treatment.

Table 8. Impact of site characteristics and design parameters on costs for active EISB.

Cost Component	Base Case	Accelerated Clean Up Case		Low Perchlorate Concentration Case		High Perchlorate Concentration Case		Low Donor Dem and Case		High Donor Demand Case		Low GW Velocity Case	
	Case 1	Case 2		Case 3		Case 4		Case 5		Case 6		Case 7	
	Cost ($)	Factor	Cost ($)	Factor	Cost ($)	Factor	Cost ($)	Factor	Cost ($)	Factor	Cost ($)	Factor	Cost ($)
Capital Cost	430,000	4.50	1,935,000	0.98	421,400	1.05	451,500	0.95	408,500	1.15	494,500	0.90	387,000
NPV of O&M Costs	1,200,000	1.75	2,100,000	0.95	1,140,000	1.05	1,260,000	0.90	1,080,000	1.15	1,380,000	0.90	1,080,000
NPV of Monitoring Costs	350,000	1.25	437,500	1.00	350,000	1.00	350,000	1.00	350,000	1.00	350,000	1.00	350,000
NPV of Total Costs	1,980,000	2.26	4,472,500	0.97	1,911,400	1.04	2,061,500	0.93	1,838,500	1.12	2,224,500	0.92	1,817,000

Cost Component	High GE Velocity Case		Deep GW Case		Thin Interval Case		Thick Interval Case		Narrow Plume Case		Wide Plume Case	
	Case 8		Case 9		Case 10		Case 11		Case 12		Case 13	
	Factor	Cost ($)	Factor	Cost ($)	Factor	Cost ($)	Factor	Cost ($)	Factor	Cost ($)	Factor	Cost ($)
Capital Cost	1.15	494,500	1.25	537,500	0.90	387,000	1.15	494,500	0.35	150,000	1.85	795,500
NPV of O&M Costs	1.10	1,320,000	1.00	1,200,000	0.90	1,080,000	1.15	1,380,000	0.45	540,000	1.75	2,100,000
NPV of Monitoring Costs	0.90	315,000	1.00	350,000	1.00	350,000	1.00	350,000	0.50	175,000	1.50	525,000
NPV of Total Costs	1.08	2,129,500	1.05	2,087,500	0.92	1,817,000	1.12	2,224,500	0.44	865,500	1.73	3,420,500

Notes: All costs are in thousands of dollars
Factor – factor increase or decrease in costs relative to the Base Case
NF – not feasible, cost not estimated
NPV – Net Present Value
O&M – operation and maintenance
EISB – enhanced in situ bioremediation

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8.0 IMPLEMENTATION ISSUES

This section describes implementation issues with EISB using active addition of electron donor to treat perchlorate impacted groundwater.

8.1 ADDITIONAL SOURCES OF INFORMATION

Many guidance documents are available from organizations such as USEPA, ITRC, and AFCEC dealing with EISB for perchlorate and chlorinated solvents. Many design issues with EISB for chlorinated solvents are also common to perchlorate. A list of recent relevant guidance documents is presented below:

- SERDP/ESTCP Environmental Technology Series. H.F. Stroo and H.C. Ward Editors. 2009. In Situ Bioremediation of Perchlorate in Groundwater. Springer Publishing Company. http://www.springer.com/environment/environmental+management/book/978-0-387-84920-1
- ITRC Perchlorate Team. 2005. Perchlorate: Overview of Issues, Status, and Remedial Options. September 2005. http://www.itrcweb.org/Documents/PERC-1.pdf
- ITRC Perchlorate Team. 2008. Remediation Technologies for Perchlorate Contamination in Water and Soil. March 2008. http://www.itrcweb.org/Documents/PERC-2.pdf
- ITRC Bioremediation of DNAPLs Team. 2008. In Situ Bioremediation and Chlorinated Ethene: DNAPL Source Zones. June 2008. http://www.itrcweb.org/Documents/bioDNPL_Docs/BioDNAPL3.pdf
- ITRC Enhanced Attenuation: Chlorinated Organics Team. 2008. Enhanced Attenuation: Chlorinated Organics. April 2008 http://www.itrcweb.org/Documents/EACO-1.pdf
- ITRC In Situ Bioremediation Team. 2002. A Systematic Approach to In Situ Bioremediation in Groundwater. April 2002 http://www.itrcweb.org/Documents/ISB-8.pdf
- Permeable Reactive Barriers: Lessons Learned/New Directions. 2005. ITRC Permeable Reactive Barrier Team. February 2005 http://www.itrcweb.org/Documents/PRB-4.pdf
- Solutions EIS. 2006. Protocol for Enhanced In Situ Bioremediation Using Emulsified Vegetable Oil. Prepared for ESTCP. May 2006.
- http://www.estcp.org/viewfile.cfm?Doc=ER%2D0221%20Final%20Protocol%20V2%2Epdf
- USEPA. 2005. Perchlorate Treatment Technology Update – USEPA Federal Facilities Forum Issue Paper. USEPA – Solid Waste and Emergence Response. May 2005. http://www.clu-in.org/download/remed/542-r-05-015.pdf
- U.S. Air Force. 2007. Protocol for In Situ Bioremediation of Chlorinated Solvents Using Edible Oil. Prepared for AFCEC - Environmental Science Division –

Technology Transfer Outreach Office. October 2007. http://www.clu-in.org/download/remed/Final-Edible-Oil-Protocol-October-2007.pdf

- Hoponick, J. R. 2006. Status Report on Innovative In Situ Remediation Technologies Available to Treat Perchlorate-Contaminated Groundwater. Prepared for USEPA – Office of Superfund Remediation & Technology Innovation – Technology Innovation & Field Services Division. August 2006. http://www.clu-in.org/download/studentpapers/J_Hoponick_Final.pdf

8.2 POTENTIAL ENVIRONMENTAL ISSUES

8.2.1 Regulatory Issues

The implementation of EISB in most jurisdictions requires a groundwater reinjection permit. This permit must allow for extraction of groundwater, amendment with electron donor, and reinjection of the mixture. It is not normally difficult to obtain permits to implement such a program because (1) the groundwater that will be extracted will be injected again close to where it was extracted; (2) electron donors normally consist of innocuous organic compounds; and (3) bioaugmentation (addition of a microbiological culture) is seldom required for EISB for treatment of perchlorate.

Additional permits or other regulatory approvals may be if flammable electron donors, such as ethanol, are used or if chlorine gas is used to clean injection well screens.

8.2.2 Air Discharge

The EISB process described will not normally result in discharge of chemicals to the atmosphere.

8.2.3 Wastewater Discharge

The EISB process described will not normally result in the generation of wastewater streams. Extracted groundwater is normally reinjected into the injection wells. Some small quantities of wastewater may be generated during well installation and groundwater sampling events and must be managed as they would be for other investigation-derived waste.

8.2.4 Waste Storage, Treatment, and Disposal

The EISB process described will not normally result in the generation of significant waste streams. Some waste may be generated during well installation and must be managed as they would be for other investigation derived waste.

8.3 END-USER ISSUES

Potential end-users of this technology include responsible parties for contaminated sites where perchlorate is present in groundwater. End-users will have an interest in the technology because it can potentially treat groundwater in situ at an overall cost much less than for conventional P&T remediation approaches. End-users and other stakeholders may have concerns regarding

(1) the effectiveness of the technology in reducing concentrations of target compounds below appropriate criteria; (2) potential negative impacts of excess electron donor on water quality downgradient of the treatment zone; and (3) potential negative impacts of the electron donor addition on secondary water characteristics.

8.4 PROCUREMENT ISSUES

There are no specialized equipment components required to implement EISB using the active approach and no specialized services required. There are no significant procurement issues with the application of this technology.

8.5 DESIGN ISSUES

Based on the results of the demonstration conducted at the IRCTS and a review of other applications of the technology, potential design issue to be considered in the development of the design of active EISB systems were identified. These design issues are discussed below.

- **Sites with a low hydraulic conductivity –** It can be difficult to obtain high groundwater recirculation rates at sites where the hydraulic conductivity is low and, therefore, longer periods of time are required to distribute electron donor between injection and extraction wells. Sites with a low hydraulic conductivity also normally have a low groundwater velocity and therefore it will take a significant period of before electron donor or the impacts of electron donor move downgradient from the biobarrier.
- **Sites with significant variations in hydraulic conductivity –** It can be difficult or impossible to obtain a uniform distribution of electron donor at sites where there are significant variations in the hydraulic conductivity (i.e., significant interbedding of low K units). Electron donor will migrate much faster and further in higher K zones than in low K zones making it difficult to obtain uniform distribution of electron donor, however, because the flux of groundwater and of perchlorate in the higher K zones is higher than in low K zones, these higher K zones require more electron donor to degrade the perchlorate.
- **Sites with high concentrations of competing electron acceptors –** The requirements for electron donor will be high at sites with high concentrations of competing electron acceptors such as DO and nitrate in the groundwater. Costs for electron donor will be higher at these sites that at sites with low concentrations of competing electron acceptors.
- **Sites with high concentrations of naturally occurring metals in the soil –** Groundwater monitoring should be conducted following addition of electron donor at sites with high concentrations of naturally occurring metals in the soil to make sure that the addition of electron donor does not result in the mobilization of significant concentrations of metals to areas downgradient of where the electron donor is injected. Modest amounts of electron donor should be added initially to evaluate the potential to mobilize metals such as iron and manganese. Active approaches to EISB will have less potential to mobilize naturally occurring metals downgradient of the biobarrier than semipassive or passive EISB approaches.

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9.0 REFERENCES

California Deparrtment of Water Resources (CDWR), 1964. Folsom-East Sacramento Ground Water Quality Investigation, Bulletin 133.

CDWR, 1974. Evaluation of Ground Water Resources: Sacramento County, Bulletin 118-3.

Coates, J.D., U. Michaelidou, R. Bruce, S. O'Connor, J. Crespi, and L. Achenbach, 1999. Ubiquity and diversity of dissimilatory (Per)chlorate-reducing bacteria. Appl. Environ. Microbiol. 65:5234-5241.

Cox, E.E., M. McMaster, and S. Neville, 2001. Perchlorate in groundwater: Scope of the problem and emerging remedial solutions. Symposium of Engineering Geology & Geotechnical Engineering. March 2001, Las Vegas.

U.S. Deparrtment of Defense (DoD). 1995. DoD Instruction 7041.3: Economic Analysis for Decision-Making. November 17, 1995. http://www.dtic.mil/whs/directives/corres/pdf/704103p. pdf

Driscoll, F. G. 1986. Groundwater and Wells.

ENSR International Corporation (ENSR). November 2001. Draft – Soil Remedial Investigation and Baseline Risk Assessment: Alpha/IOC-1 Study Area.

Geosyntec Consultants. 2002. In Situ Bioremediation of Perchlorate-Impacted Groundwater Final Technical Report. Strategic Environmental Research & Development Program (SERDP). June 2002.

Geosyntec Consultants. 2009a. Final Report, Comparative Demonstration of Active and Semi-Passive In Situ Bioremediation Approaches for Perchlorate Impacted Groundwater (Longhorn Army Ammunition Plant). ESTCP Project ER-200219.

Geosyntec Consultants. 2009b. Cost and Performance Report, Comparative Demonstration of Active and Semi-Passive In Situ Bioremediation Approaches for Perchlorate Impacted Groundwater (Longhorn Army Ammunition Plant). ESTCP Project ER-200219.

Geosyntec Consultants, 2012. Final Report, Comparative Demonstration of Active and Semi-Passive In Situ Bioremediation Approaches for Perchlorate Impacted Groundwater Active In Situ Bioremediation Demonstration. ESTCP Project ER-200219.

Office of Management and Budget. 2008. Discount Rates for Cost-Effectiveness, Lease, Purchase and Related Analysis http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html

Stroo, H.F., and H.C. Ward. 2009. In Situ Bioremediation of Perchlorate in Groundwater. SERDP ESTCP Environmental Technology Series. Springer Publishing Company.

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APPENDIX A

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